National Park Service
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Natural Resource Stewardship and Science

Hydrology of the Sierra Nevada Network National Parks

Status and Trends

Natural Resource Report NPS/SIEN/NRR—2012/500

ON THE COVER
Upper Marble Fork of the Kaweah River, Sequoia National Park
Photo: Kevin Skeen

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Status and Trends

Natural Resource Report NPS/SIEN/NRR—2012/500

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Acronyms and Abbreviations

^{o}C	degrees Celsius
CD50	day of the water year when the accumulative runoff equals 50 percent of the annual runoff
CDEC	California Data Exchange Center
CDWR	California Department of Water Resources
DEPO	Devils Postpile National Monument
ENSO	El Niño-Southern Oscillation
FERC	Federal Energy Regulatory Commission
ft	feet
GCM	Global Circulation Model
GHG	greenhouse gases
I&M	Inventory & Monitoring
in	inches
IPCC	Intergovernmental Panel on Climate Change
LADWP	City of Los Angeles Department of Water and Power
mi	miles
NHST	null hypothesis significance testing
NPS	National Park Service
NWIS	National Water Information System
Pd	date precipitation
PDO	Pacific Decadal Oscillation
PG&E	Pacific Gas & Electric
PRISM	Precipitation-elevation Regressions on Independent Slopes Model
Q0.01/Q0.5	ratio of the flood equaled or exceeded 1% of the time to the flood equaled or exceeded 50% of the time
SCE	Southern California Edison
sec	second
SEKI	Sequoia and Kings Canyon National Parks
SIEN	Sierra Nevada Network
SNEP	Sierra Nevada Ecosystem Project
SWE	snow water equivalent
USGS	U.S. Geological Survey
VIC	variable infiltration capacity
WRC	Water Resources Council
WRCC	Western Regional Climate Center
WY	water year
YOSE	Yosemite National Park

Executive Summary

The purpose of this project was to inventory and analyze existing hydrologic data, primarily streamflow and snow course data, for the region encompassing Yosemite and Sequoia and Kings National Parks, and Devils Postpile National Monument in order to assist the Sierra Nevada Network (SIEN) Inventory and Monitoring Program in developing a protocol for monitoring streams and rivers. Important hydrological indicators include streamflow magnitude and timing and snow water content, all metrics derived from long-term monitoring at fixed station locations. In order to develop a monitoring protocol, it is helpful to first inventory existing regional data and monitoring locations. Because streamflow in the Sierra Nevada is dominated by snowmelt, inventory and analysis of snow course data are critical to understanding seasonal and long-term variations in streamflow. Results of these analyses can help to inform monitoring objectives, site selection, and analytical methods.

This project's objectives were to:

1. Review and summarize existing literature related to Sierra Nevada surface water and snow dynamics, with particular attention to interpretation of hydrologic changes in response to potential climate change scenarios.
2. Assemble, document, and analyze existing streamflow and snow course data in and near SIEN parks to inform the selection of sites and metrics for long-term monitoring.
3. Improve understanding of the annual and long-term dynamics of SIEN hydrologic systems through a literature review and analyses and compile data in a final report.

Recommendations are made regarding hydrological monitoring approaches, sites, and equipment.

The datasets analyzed for this study included: Twenty streamflow gaging station records from the U.S. Geological Survey's National Water Information System database that were determined to be essentially unimpaired and suitable length for all of the proposed analyses, seven additional gaging station records suitable or available for only partial analyses, and 68 snow courses with 25 years or more of record located within or adjacent to the SIEN. Analyses followed well-established, conventional methods for examining trends in hydrological data.

Major findings include the following:

- **Annual** mean discharges at streamgages included in these analyses are generally well-correlated, due to the similarities of geology, topography, and climate among drainage basins. Even streamgages separated by a substantial distance and on opposite slopes of the Sierra Nevada have quite high correlations. All streamgages considered in this study appear to be part of a well-defined hydrologic region.
- **Spring snowmelt runoff timing** was examined with these three metrics: 1) the percent of the annual discharge coming during the April through July (AMJJ) period; 2) the date to the runoff center of mass; and 3) the onset of snowmelt runoff. A statistically significant decreasing trend of the AMJJ/annual runoff ratio was found at 10 of the 20 west slope gaging stations analyzed. Further, at stations on the west slope of the Sierra, the center of mass, the date on which half of the total annual discharge has occurred, and the snowmelt onset are occurring earlier in the year on average. In contrast to the decreasing trend of AMJJ/annual runoff on the west side, on the east slope of the Sierra Nevada, there is a generally increasing trend.
- The most significant trends in **streamflow magnitude** among the 20 gaging stations studied were increasing winter low flows. A trend of increasing 7-day winter low flow was found for 15 of the

20 streamflow records, and for eight of the records, the trends are statistically significant at the 95% confidence limit.

- **Flow duration** indicates the percent of time a given flow has been equaled or exceeded during the period of record. A comparison of flow durations can be an efficient way to identify similarities and differences in watershed characteristics between multiple gages. The comparison is facilitated by dividing the range of discharges by the mean daily discharge over the period of record at each gage, resulting in a dimensionless decimal fraction of the mean daily discharge. Dimensionless flows equaled or exceeded more than 50 percent of the time are nearly identical for all 20 drainage basins in the south Sierra Nevada. The distinctive differences between southern Sierra Nevada streams and drainage basins are found in the relatively infrequent high flows whereas the frequent low flows are quite similar.
- Trends in **snow water equivalent** (SWE) measured at snow courses on or near April 1 of each year are consistent with a general regional warming of 0.8-1.0 ^{o}C. Snow courses located well west of the Sierra Nevada crest, and at relatively low elevations within the snow accumulation zone, tend to show trends of decreasing April 1 SWE. Conversely, snow courses located at relatively high elevations near the Sierra Nevada crest tend to show trends of increasing April 1 SWE. The crossover elevation from negative trends to positive occurs, on average, at about 8500 feet. Only two of the 68 snow courses have statistically significant trends at the 90 percent confidence limit.

Key recommendations for long-term hydrological monitoring in the SIEN are:

1) Essential information about the hydrology of the SIEN is provided by streamgages and snow courses, but many are located outside of the parks and operated by other agencies or organizations. Most of the gaging stations used for this study (more than half) and many of the snow courses are no longer active. National Park Service participation in the measurement and assessment of snowpack and streamflows throughout the southern Sierra Nevada region will be a cost-effective way to achieve a portion of the SIEN monitoring objectives for hydrology.
2) The existing network of streamgages currently operating does not adequately represent the diversity of drainage basins and elevations present in SIEN parks. Expanded monitoring, particularly at middle to high elevations, would provide hydrologic data with better spatial representation of these topographically diverse parks.
3) Many of the ecologically relevant questions concerning the temporal and spatial distribution of surface water across the SIEN can be evaluated and answered using less costly and more wilderness compatible methods and techniques than the streamflow gaging station. Several specific recommendations are provided.

Acknowledgements

While pursuing this study, I had the opportunity and pleasure of discussing aspects of Sierra Nevada hydrology with many of the most knowledgeable and experienced scientists and water managers in the field. I appreciated very much the generous offer of their time and many valuable insights. This study could not have been completed without their support and assistance. In order to identify and evaluate the hydrologic records that should be included in this study, I contacted each of the organizations that have collected long-term hydrologic records within and adjacent to the SIEN. Charles Parrett and Debra Curry, U.S. Geological Survey; Mike Higginbotham, City of Los Angeles Department of Water and Power; Brian McGurty, Southern California Edison Company; and Gary Freeman, Pacific Gas and Electric Corporation provided valuable information concerning the stream gages and snow courses they operate and helped to identify the appropriate records. Without their assistance, some hydrologic records would have been overlooked and some unsuitable records might have been included.

Peter Vorster, The Bay Institute, provided an informative discussion of the challenges and progress which has been made to the reconstruct unimpaired runoff into Mono Lake. Philip Mote provided valuable insights into the snow course database and the analysis snow course observations. The analysis presented in their report is, in large measure, an update of his important contribution. Bruce McGurk, City of San Francisco Department of Public Works, has a wealth of experience and knowledge concerning the snowmelt hydrology of the Sierra Nevada. I have enjoyed and benefitted from his expertise.

For the past six years, I have had the good fortune of participating in the Yosemite Hydroclimatology Project. My colleagues, Jessica Lundquist, University of Washington, David Clow, U.S Geological Survey, and and Michael Dettinger and Daniel Cayan, Scripps Institution of Oceanography and the U.S. Geological Survey, have been a continuing source of inspiration and insight concerning the hydrology and climate of the Sierra Nevada.

A draft report was reviewed by Michael Dettinger, (affiliation above), Roger Bales, University of California-Merced, Jim Roche and Jennie Skancke, Yosemite National Park and Sierra Nevada Network respectively, National Park Service. I appreciate very much their many comments and suggestions. They have contributed substantially to this report.

1. Introduction

In 1998, the U.S. Congress directed the National Park Service to implement a program of inventory and monitoring of National Park System resources to establish baseline information and to provide information on the long-term trends in the condition of National Park Service natural resources. To develop and implement this program, the National Park Service formed 32 networks of park units which share similar geography and natural resources. Yosemite, Kings Canyon, and Sequoia National Parks and Devils Postpile National Monument form the Sierra Nevada Network, henceforth referred to as the SIEN (Figure 1). Mutch et al. (2008) provide an in-depth overview of the SIEN and describes a detailed monitoring plan for the SIEN. The plan identifies 13 vital signs that were selected to provide a comprehensive, while cost-effective, assessment of the most significant and indicative characteristics of the SIEN ecosystem. The 13 vital signs are weather and climate, snowpack, surface water dynamics, water chemistry, invasive plants, forest stand population dynamics, landscape mosaics, fire regimes, wetland water dynamics, wetland plant communities, wetland macro-invertebrates, amphibians, and birds. Monitoring protocols are developed for each of the vital signs (Mutch et al. 2008).

This report was prepared at the request of the SIEN program to assist in the development of the hydrology monitoring protocols: snowpack and surface water dynamics. Other vital sign resources may be affected directly or indirectly, by appreciable changes in the hydrology of the SIEN. For example, changes in the hydrologic regime, i.e. magnitude and frequency of streamflows, water temperature, water chemistry, concentration of suspended sediment, etc., may influence the spread of non-native plants, alter the water balance of a wetland, or shift the balance between amphibians and their predators. The SIEN comprises an area of 658,000 hectares of which 89 percent is designated wilderness. A majority of the SIEN lies above 6000 feet elevation where winter precipitation falls predominantly as snow. The SIEN occupies the highest elevation portions of the Sierra Nevada. The SIEN and immediately adjacent areas encompass the region commonly termed the “High Sierra” (Secor 1992). There are 179 peaks in the Sierra Nevada that rise above 12,000 feet elevation, all of which lie to the south of the northernmost extent of the SIEN. Runoff from drainage basins within and adjacent to the SIEN contributes substantially to the water resources of California. The cities of Los Angeles and San Francisco, as well as irrigation districts in the San Joaquin Valley derive most of their water supplies from the rivers and streams draining the central and southern Sierra Nevada.

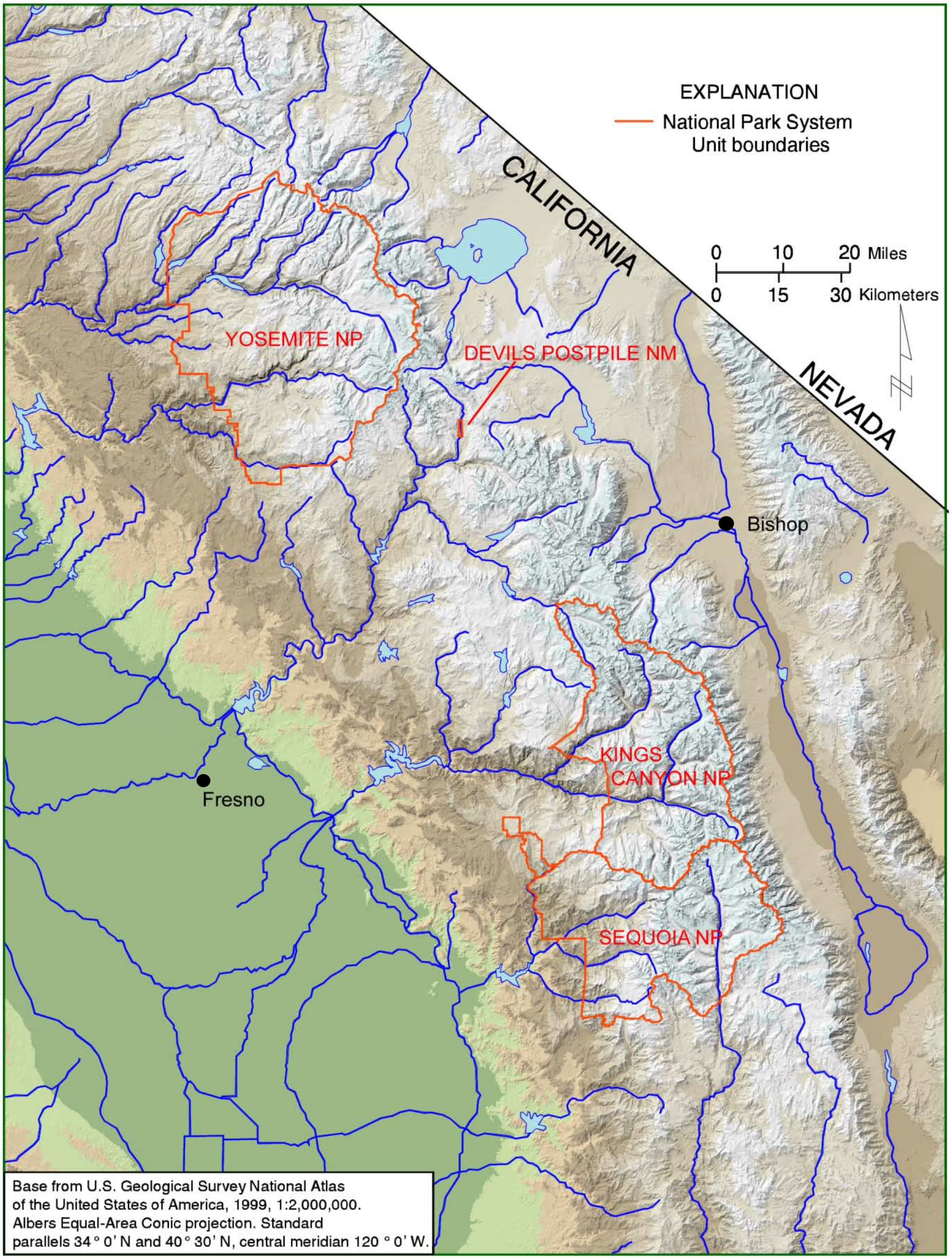


Figure 1. Relief map of the southern Sierra Nevada showing the Sierra Nevada Network national parks.

A comprehensive review and assessment of the Sierra Nevada ecosystem was completed during the mid-1990s - Sierra Nevada Ecosystem Project (SNEP) (1996) available at www.ceres.ca.gov/snep/pubs/. The three volume report contains articles by leading experts about the most significant issues facing the Sierra Nevada. The SNEP study addresses a broader geographical area and a greater variety of land-use activities than the SIEN. Even so, there is substantial agreement regarding the critical ecosystem and land stewardship issues. The primary difference, as much as anything, a shift in emphasis, is the growing awareness over the past decade that climate change, which has already began affecting the SIEN in subtle ways, may have profound impacts of the hydrologic regime by the end of this century. In particular, the manner in which the hydrology of the southern Sierra Nevada is viewed has shifted substantially. Previously, it had commonly been assumed that there was a “mean” condition which would be evident in hydrologic records of sufficient length. The assumption, typically made implicitly, was accepted in spite of large annual and decadal variations in the observation records, as well as evidence for even larger anomalies in temperature, precipitation, and runoff that have persisted for centuries over the past few thousand years (e.g. Meko et al. 2001). Today, we anticipate that the hydrology of the central and southern Sierra Nevada will be different a century from now than it has been over the past century. Some trends and patterns are already beginning to become apparent as will be discussed later. For the most part, however, it is still difficult to discern in the empirical hydrologic record the changes that our models tell us are coming.

The purpose of this report is to compile and assess the available information to guide and inform the design and establishment of a hydrologic monitoring protocol for SIEN Parks. The SIEN hydrologic monitoring protocol will be formulated subsequently by a diverse group of resource specialists, land managers, and scientists within the context and needs of the overall SIEN Vital Signs Monitoring Program. The report begins with a detailed review of the recent published literature concerning the hydrology of the southern Sierra Nevada, followed by an evaluation of long-term observations of streamflow and snowpack within and adjacent to the SIEN, and concludes with issues to consider in developing a hydrologic monitoring network for the SIEN. (Note: Most of the available studies and observational networks apply to a somewhat larger geographical area than the SIEN proper. The larger area, including the SIEN and adjacent areas, will be referred to as the southern Sierra Nevada.) A successful hydrologic monitoring protocol will be able to (1) resolve the spatial pattern of hydrologic trends across the SIEN, (2) be sufficiently flexible so that it can be adapted as needed, and (3) of a spatial scale and cost that can be sustained over decades. This report was prepared for an audience generally familiar with the Intergovernmental Panel on Climate Change (IPCC) 2007 report, a background in science and/or natural resources management, but not necessarily a specialty in hydrology or closely related fields.

2. State of Knowledge of Hydrology and Climate in the Sierra Nevada Inventory and Monitoring Network

2.1. Temperature and Precipitation

Edwards and Redmond (2011) provide a detailed description of the climate in the SIEN parks over the past century as well as an evaluation of the most likely changes in climate expected over the next century. Their report was prepared within the framework of the SIEN vital signs monitoring plan as is this report. The two reports are complementary with related objectives and topics. Twentieth-century precipitation and temperature, which are fundamental drivers of surface water hydrology, will be summarized only briefly herein, primarily as they provide a basis for understanding the current hydrologic regime of the SIEN parks and the greater southern Sierra Nevada. Readers interested in more detail concerning the observational network, analysis of the climate records as well as ongoing research to understand how the evolving global climate will be expressed specifically in and around the SIEN parks should consult Edwards and Redmond (2011).

Reliable, consistent observations of temperature and precipitation in the southern Sierra Nevada area began in the mid-1890s. A spatially-gridded database of historical climate has been constructed from the observational record using the Precipitation-elevation Regressions on Independent Slopes Model (PRISM), (Daly et al. 1994). Edwards and Redmond (2011) considered the variation of monthly mean temperature and precipitation for each of the six counties that encompass most of the SIEN parks. Significant, regionally consistent temporal variations in temperature and precipitation have occurred over past decadal periods. A prominent warming trend began about 1980 and continues. Annual mean temperatures during the past decade were 0.8–1.1°C above the 1895-2007 average and exceeded that of any previous 10 year period (Edwards and Redmond 2011). The increase is consistent with the magnitude of warming observed across the Western United States (IPCC 2007). Overall warming is due primarily to an increase of as much as 1.7°C in the minimum (nighttime) temperature while monthly mean maximum temperatures have increased only slightly since 1980 (Edwards and Redmond 2011). Due to the lack of long-term temperature records at elevations above 10,500ft., we do not have direct evidence concerning the magnitude of warming in the alpine zone relative to the lower elevations. Regional climate model studies based on downscaling of Global Circulation Models (GCM) indicate that temperatures have increased faster since 1980 in the alpine zone and will continue to do so in the future (Kim et al. 2002 and Snyder et al. 2002).

Spatially-averaged annual precipitation over the southern Sierra Nevada area has also varied substantially; the coefficient of variation exceeds 50 percent. In contrast to temperature, however, Edwards and Redmond (2011) found no appreciable trend of increasing or decreasing precipitation. Spatially-average precipitation for the Sierra Nevada Region for water years 1896-2010 is shown in Figure 2 (Western Regional Climate Center 2011). Linear regressions fit to spatially-averaged annual precipitation across the Sierra Nevada region for the period 1895-present as well as selected sub-periods show slight increasing trends. None of the trends, however, are statistically significant. Note that the 7 wettest years over the entire period of record have occurred since 1969. Similarly, two comprehensive reviews of statewide climate, the 2005 update of the California Water Plan (see Kiparsky and Gleich 2003) and the earlier Sierra Nevada Ecosystem Project (see Kattelman 1996), did not find evidence of a discernible trend in annual precipitation within or around the SIEN. Precipitation records are scrutinized intently, because any appreciable long-term change in annual precipitation over the Sierra Nevada, which contributes over 75 percent of California's water supply, would have far reaching consequences.

Karl and Knight (1998) and Groisman et al. (2001) found that annual precipitation has increased nationwide by about 10 percent, perhaps somewhat less over California, since 1910. Most of the increase in annual precipitation is due to an increase in the frequency and intensity of the upper 10 percentile of precipitation intensity. Statewide, greatest observed changes have been an increase in the frequency of the highest intensity (upper 5 percent) one day precipitation during the summer and autumn and about half as much increase during the winter and spring.

Whereas the temperature increases calculated by the most widely used global circulation models for various levels of greenhouse gas (GHG) emissions are in rather close agreement, the models provide rather disparate estimates, from –10 to as much as +20 percent changes, in annual precipitation over the southwest United States through 2100 (Kim et al. 2002, Snyder et al. 2002, and Dettinger 2005).

The total quantity of water available for runoff, plants and wildlife depends on precipitation minus evapotranspiration. Under the most likely global warming scenarios, evapotranspiration is estimated to increase by 3 to 15 percent by 2030 (IPCC 2001). Thus, even where precipitation may increase by a modest amount, the available water may decrease and result in an overall drier climate. Seager et al. (2007) examined projected changes in precipitation-evaporation over southwest North America including the southern Sierra Nevada, determined by the 19 climate models contributing to the Fourth Assessment Report of the IPCC (2007). A trend to a drier climate by 2098 was calculated by most models under most levels of GHG emissions. As noted above, there remains considerable uncertainty regarding the likely trend in annual precipitation as well as the annual water balance. We can anticipate that changes in the frequency, intensity, and distribution of precipitation throughout the year, a continuation of the types of changes, although not necessarily the same magnitude and direction as already described by Groisman et al. (2001) and Knowles et al. (2006), will affect the hydrologic regime of the SIEN area to a greater degree than trends in total precipitation.

There is some evidence that leads us to expect that hydrologic regimes will be relatively more affected by changes in precipitation than temperature. Karl and Riebsame (1989) examined the sensitivity of annual runoff to decadal variations in temperature and precipitation observed during the 20th century. Temperature variations of approximately ±1°C, the warming that has already occurred since 1980, and one-half to one-third of anticipated warming through the end of the 21st century, had very little effect on annual runoff. In contrast, decadal variations of ±10 percent in the annual precipitation produced responses in the annual runoff from 1 to 6 times larger. In short, annual runoff has been much more sensitive to variations in precipitation than temperature during the 20th century.

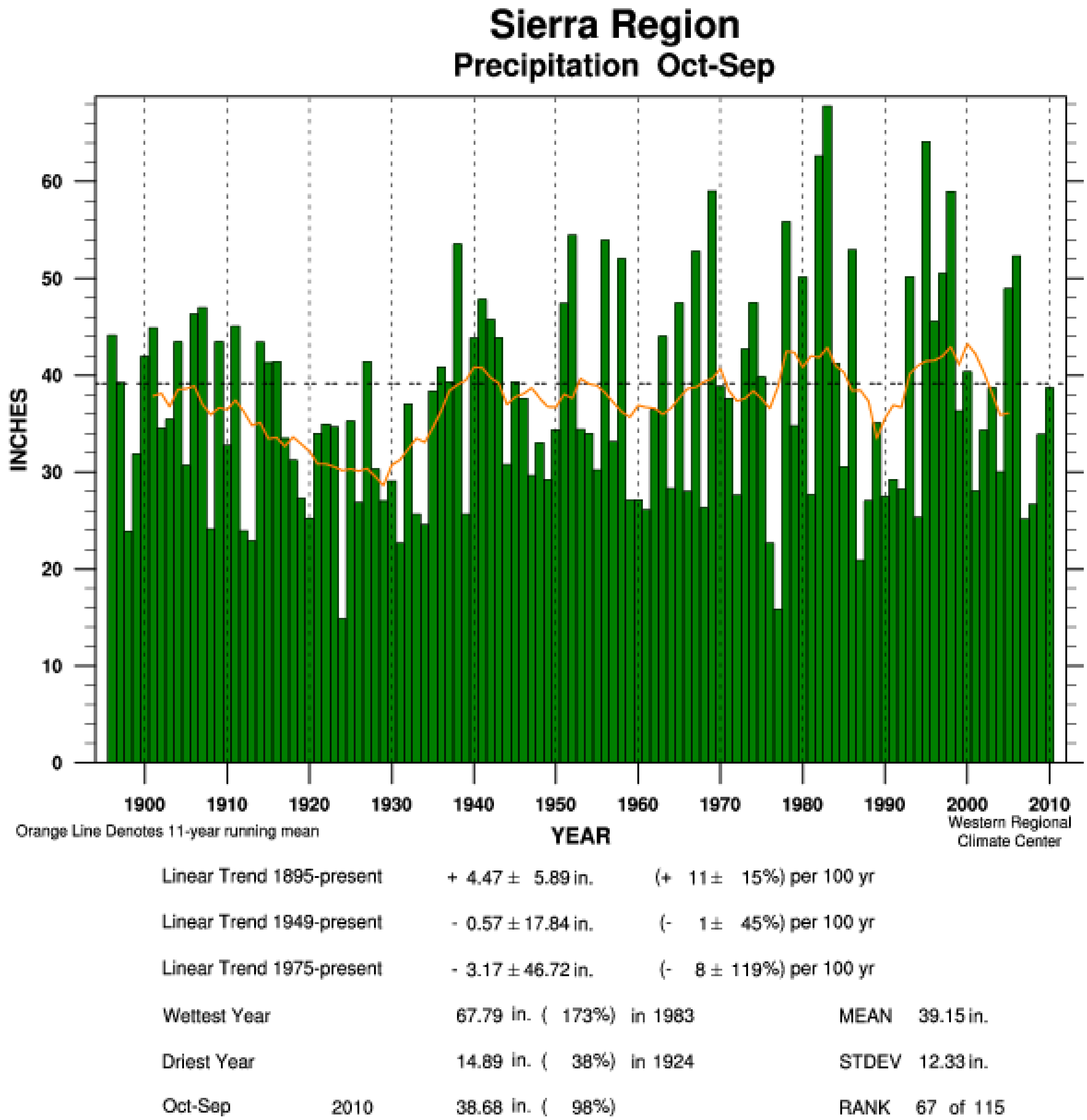


Figure 2. Spatially averaged Sierra Nevada annual precipitation. Values for the water-year (October-September) total precipitation, plotted in ending year, for period 1895/1896 thru 2009/2010. Statistics and trends shown below. *WRCC California Climate Tracker.*

Results obtained by downscaling predictions from several different global climate models with various scenarios of future greenhouse gas emissions for the southern Sierra Nevada region have found that annual total precipitation will not change appreciably from the 20th century. This view, however, is not universal. For example, Seager et al. (2007) concluded that a transition to a much drier climate across the southwest is imminent. Assuming annual total precipitation remains about the same, a number of studies (Gleick 1987; Dettinger and Cayan 1995; and Dettinger et al. 2004) have determined that annual runoff will not change appreciably either. The shift to a warmer climate, however, will substantially alter the annual pattern of streamflows.

Dettinger et al. (2004) concluded that the most significant change in the hydrology of the Merced River would be an approximately two-fold increase in mean flow during January to March.

2.2. Streamflow

Lins and Slack (1999) examined streamflows recorded at 395 gaging stations nationwide where the hydrologic regime has been relatively unaffected by storage, diversions, depletion, etc. The records span the 50-year period from 1944 to 1993, and 34 span the 80-year period from 1914–1993. They considered three long-term records of unimpaired streamflows in the southern Sierra Nevada - the Merced River at Happy Isles Bridge, Merced River at Pohono Bridge, and Bear Creek near Lake Thomas A. Edison. Their study found no trends at any gage in either the annual maximum daily discharge or the annual median daily discharge. Two of the three gages had statistically significant trends in the annual minimum daily discharge.

A principal consequence of the increase in annual mean temperature of about 1-2°F in recent decades has been that a smaller portion of the mean annual runoff comes during the April, May, June and July period (AMJJ). Melting of the accumulated snowpack has historically produced 60 or more percent of the annual runoff during the AMJJ period. Roos (1987, 1991) evaluated the ratio of AMJJ to annual discharge for the Sacramento River which receives runoff from the northern portion of the Sierra Nevada. Subsequently, Wahl (1991, 1992), Aguado et al. (1992), Dettinger and Cayan (1995), Lundquist et al. (2004), Stewart et al. (2004, 2005), McCabe and Clark (2006), Knowles et al (2006), Lundquist and Flint (2006), and Lundquist et al. (2009) have investigated various aspects of the phenomena in considerable detail, including the magnitude of change over time, the influence of drainage elevation, the regional pattern, and the role of large scale atmospheric circulation. Wahl (1992) examined runoff trends recorded at 58 long-term gaging stations in ten western states, including three gages located in the SIEN area, the Merced River at Happy Isles Bridge, Bear Creek near Lake Thomas A. Edison, and the Kern River near Kernville (The AMJJ/annual runoff ratios over the available period of record through 2009 are shown in Chapter 5 of this report). Wahl (1992) concluded that there were statistically significant trends towards a smaller AMJJ/annual runoff, with the runoff pulse occurring earlier in the year, in the Sierra Nevada, the Coast Range of California, Oregon, and Washington and the Cascade Range. The most significant decreasing trends have occurred in the lower drainage basins. Trends in the AMJJ/annual runoff ratio were muted or nonexistent at higher elevations and in the Rocky Mountains, where average spring temperatures are still well below freezing.

Wahl (1991, 1992) observed that a decreasing AMJJ/annual runoff ratio does not provide a definitive insight into the trends of AMJJ or annual runoff, only their relation. In fact, the relation appears to be rather complicated. His analysis of streamflows from southern Sierra Nevada drainage basins through 1991, found no trend in annual runoff at any of the three gages, and a weak decreasing trend in AMJJ runoff at the Merced River gage, and no trend in AMJJ runoff at the other two gages. Runoff during the fall and winter, however, increased at all three gages. These results appear to be conflicting. How could annual runoff remain unchanged when fall and winter runoff was increasing and spring and summer runoff unchanged? The annual and seasonal streamflows being considered were quite variable from year to year and the absolute magnitude of the trends was not particularly large compared to the variability. Furthermore, AMJJ runoff typically represents 70 percent or more of the annual runoff. A given increase in the magnitude of fall and winter streamflows would be more discernible than would be an equivalent volume increase in the annual runoff. An increase in fall and winter streamflows is consistent with an increasing portion of the cold precipitation falling as rain versus snow (Knowles et al. 2006). Finally, Wahl (1992) noted that most of the apparent trend disappeared when the period of streamflows analyzed was reduced by excluding the California drought years of 1987-1991.

Additional metrics have been formulated and applied to evaluate the temporal distribution of the spring snowmelt runoff. Cayan et al. (2001) calculated the onset of the spring snowmelt as the day when the cumulative departure from the mean flow, determined for the period from Julian Day 9 to Julian Day 208 reached its maximum value for the year. The calculation is illustrated in Figure 3 showing the hydrograph of the Marble Fork Kaweah River near Potwisha Camp for WY 1991. A second metric to describe the spring snowmelt runoff is the date of the runoff center of mass, developed by Stewart et al. (2005), also shown in Figure 3. The runoff center of mass (CM) was calculated as

$$CM = \frac{\sum_i (T_i Q_i)}{\sum_i Q_i}$$

where T_i is the number of days since the beginning of the water year; and Q_i is the daily mean discharge on the i^{th} day. Both metrics indicate that the spring snowmelt runoff is coming earlier in the year across western North America over the period 1948–2002 (Stewart et al. 2005). The largest advances in the onset and center of mass of spring snowmelt runoff, from 10 to more than 20 days, have occurred in the Northern Rockies, the Pacific Northwest, and the northern Sierra Nevada. For both metrics there is a well-defined spatial trend to smaller advances in the timing of snowmelt runoff through the middle to southern Sierra Nevada. Stewart et al. (2005) reported that the onset of snowmelt runoff has typically advanced by 5–10 days, while the runoff center of mass has advanced by <5 to 5–10 days in and around the SIEN. Most of the trends were not statistically significant at the 10 percent confidence level; however, they were consistent with the trends observed elsewhere across western North America.

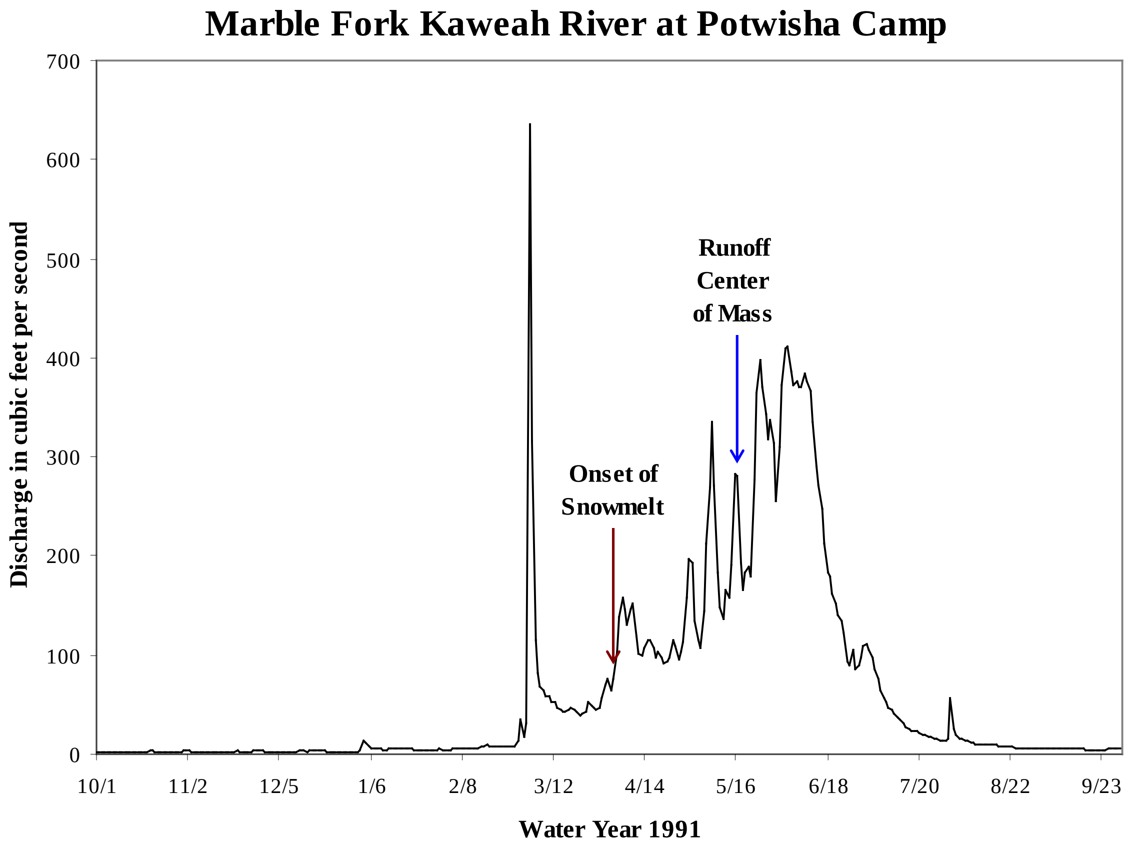


Figure 3. Hydrograph of the Marble Fork Kaweah River near Potwisha Camp for the 1991 water year. Mean daily discharge data from the USGS National Water Information System (NWIS) – station # 1120800. Onset of snowmelt and runoff center of mass calculated in the MatLab program.

Annual variation in temperature and precipitation influence the onset of snowmelt runoff and the runoff center of mass (Stewart et al. 2005). Higher late winter and spring temperatures tend to advance the snowmelt onset and center mass. An increase in precipitation tends to delay the snowmelt onset and center of mass, offsetting the effect of warmer temperature. El Niños, the warm phase of the El Niño-Southern Oscillation (ENSO), and warm phase of the Pacific Decadal Oscillation (PDO) (Mantua et al. 1997) are associated with anomalously high temperatures and precipitation during the winter and spring seasons in the southern Sierra Nevada (Ropelewski and Halport 1986 and Cayan et al. 1999). Several strong El Niños occurred during the period of warm PDO from 1978 to 1999. Stewart et al. (2005) determined that number of days to the runoff center of mass was positively correlated with ENSO and the warm phase of the PDO over the period 1948-2002. Thus, it appears that the increased precipitation typically associated with the El Niño phase is sufficient to offset the accompanying warming and extend or delay the CM until later in the spring. Accordingly, the relative abundance of well-developed El Niños from the 1978 to 1999, during the second half of the streamflow period of record considered (1948-2002), compared to the first half, diminished somewhat the response one would have otherwise expected. Stewart et al. (2005) estimates that the combined effect of more frequent well-developed El Niños and a warm PDO obscures about half of the advance in the runoff center of mass as one would have otherwise expected from the regional and global warming trend alone.

2.3. Mountain Snowpack

Throughout the 20th century, the maximum water content of the snowpack or snow water equivalent (SWE) has occurred in the late winter to early spring. For consistency, April 1 has been chosen as the reference date to measure SWE at snow courses established throughout the Sierra Nevada. Although the actual date of maximum SWE varies from year-to-year, the April 1 SWE has great practical value, and has been applied successfully to predict snowmelt runoff and manage water resources in river basins with appreciable snowpack. Newer technologies from real-time snow sensors and remote sensing increasingly provide the information required for operational hydrology. Measurements of April 1 SWE at snow courses, many of which have been maintained since the 1920s and 1930s, have proven to be the best source of information with which to investigate long-term trends in snowpack across the southern Sierra Nevada. While April 1 SWE has been a standard for operational hydrology for decades, its value to climatology was not appreciated until Mote (2003) showed that April 1 SWE had declined substantially across the Pacific Northwest. Subsequently, Mote et al. (2005) evaluated trends in April 1 SWE across western North America, including the area within and around the SIEN. They determined linear trends in the April 1 SWE over the period 1950-1997 by fitting a least squares regression to the time series of SWE values. In general, the linear trend (the regression slope) was not statistically significant; however, there was strong coherence (consistency) both regionally and with elevation. The changes in April 1 SWE from 1950–1997 represented by the linear trend were expressed in two ways: 1) as a difference between the last value (1997) and the first value (1950) determined from the best fit line and 2) as a percent change between the 1997 SWE and 1950 SWE from the best fit line divided by the 1950 SWE. Mote et al. (2005) showed that April 1 SWE has decreased by as much as 80 percent at the vast majority of snow courses across western North America, except for the southern Sierra Nevada where April 1 SWE appears to have increased at nearly all snow courses. The figure in Mote et al. (2005) may be misleading, however, due to the large scale and plotting technique employed (Mote personal communication). Mote et al. (2005) determined that trends in April 1 SWE are well-correlated with mean December through February (DJF) temperatures. The largest decreases in April 1 SWE have occurred where the mean DJF temperature is near +5°C. Trends in April 1 SWE become less negative and turn positive as the mean DJF decreases. On average, trends in April 1 SWE over the period 1950-1997 are positive at snow courses where mean DJF temperatures are less than -3°C. As shown below, a re-analysis of snow courses located within and around the SIEN parks using the approach of Mote et al. (2005) through the 2008 water year, found decreasing trends in April 1 SWE at snow courses below about 8500 feet with the largest decreases at the lowest elevation, and increasing trends in April 1 SWE at elevation above 8500 feet with the largest increases at the highest elevations.

Knowles and Cayan (2002) used results from a global climate system model to drive a watershed hydrology model of the San Joaquin River basin through 2090 assuming the business-as-usual accumulation of atmospheric GHG. The projected temperature increases were 0.6°C by 2030, 1.6°C by 2060, and 2.1°C by 2090. The analysis focused on the effects of increasing temperature, while total precipitation is unchanged. Daily precipitation for the water years 1965-1987 were used as model inputs. A significant result of their analysis is the estimated change in April 1 SWE across the Sierra Nevada, including the SIEN parks through 2090. The region-wide average decrease in April 1 SWE is more than 30 percent in 2060 and approximately 50 percent in 2090 (the figure from Knowles and Cayan (2002) showing predicted changes in April 1 SWE through 2090 is reproduced in this report in Chapter 6 with a discussion of some considerations for a SIEN hydrologic monitoring plan). The decrease in April 1 SWE, however, varies substantially with elevation and is far from uniformly distributed. The April 1 SWE decrease is greatest at elevations between approximately 6000 and 9000 feet along the west slope of the Sierra Nevada, where the predicted change exceeds 70 percent by 2060 and 85 percent by 2090. The Knowles and Cayan (2002) results are fully consistent with the observed trends in April 1 SWE described by Mote (2006). The magnitude of changes in late season snowpack predicted by Knowles and Cayan (2002) would dramatically alter the hydrology of SIEN catchments within the zone of 6000 to 9000 feet elevations.

2.4. Fluvial Sediment

Kattelman (1996) compiled an extensive list of published sediment yields for drainage basins throughout the Sierra Nevada. Sediment yields were determined by a variety of methods, primarily by the resurvey of reservoir bathymetry, and sampling of suspended sediment concentrations in streamflow. He reported basin sediment yields vary from less than 10 to more than 430 tons/mi^2-yr. Natural sediment yields are affected by a number of factors including precipitation, vegetation, topography, and soil development. Helley (1966) and Janda (1966) concluded that the largest sediment yields, >600 tons/mi^2-yr, in the Sierra Nevada come from the zone between 1000-3000 feet elevation, typically a woodland-grassland community and relatively steep topography. Glaciated parts of the Sierra Nevada commonly have very low sediment yields. The quantity of material in those particle sizes that can be moved by fluvial action is limited and lakes formed in glacially scoured basins trap what sediment becomes entrained by streamflow. Anderson (1979) estimated the sediment yield from the drainage basin above the Merced River at Happy Isles Bridge is approximately 13 tons/mi^2-yr.

2.5 Detection and Attribution of Hydrologic Trends within the SIEN Parks Areas

Observed trends in various components of the hydrologic cycle within and adjacent to the SIEN, including April 1 SWE, annual distribution of runoff, and the magnitude and frequency of streamflows, reflect decadal to multidecadal variations in temperature and precipitation associated with shifting patterns of atmospheric circulation, such as the ENSO and PDO, as well as general warming across western North America since the early 1980s. Several investigations have attempted to evaluate the relative significance of several natural and anthropogenic contributing factors. Specifically, these studies have sought to quantify the extent to which the observed trends in temperature, precipitation, and April 1 SWE are consistent with the natural variability one would expect given the ENSO, PDO, volcanic emissions, solar radiation, etc. as they were during the 20th century or whether increasing atmospheric greenhouse gas (GHG) concentrations are required as well to explain observed trends. While various models and statistical approaches have been applied, the studies have reached consistent and similar conclusions. Barnett et al. (2008), Bonfils et al. (2008), Pierce et al. (2008), Hidalgo et al. (2009) and Das et al. (2009) describe the focused efforts of a dedicated team of scientists to understand the contribution of increasing atmospheric GHGs to regional warming across the western United States over and above the naturally driven variations. It is appropriate to consider these publications together as an integrated body of work. Eight scientists are co-authors on all five publications and an additional four are co-authors on three of the publications. The investigation employed two fully-coupled ocean-atmosphere climate models, the National Center for

Atmospheric Research/Department of Energy Community Climate System Model (version 3), and the Department of Energy/National Center for Atmospheric Research Parallel Climate Model (Bonfils et al. 2008). These models capture the low-frequency oscillation of the global atmosphere-ocean circulation that produces the ENSO and PDO. The models were run with various combinations of natural climate forcings, such as volcanic aerosols and solar irradiance with and without increased atmospheric GHG concentrations, in order to isolate the effect of GHG. Bonfils et al. (2008) concluded that the observed warming since 1980 across California and the mountainous areas of the western United States cannot be explained solely by natural variability. The observed rise in temperatures requires an anthropogenic contribution and is consistent with model predicted temperatures given the recorded increase in GHG.

Pierce et al. (2008) extended the analysis of Bonfils et al. (2008) to the observed trend of the ratio April 1 SWE / water year to date precipitation (P_d) across the western United States. The SWE/P_d ratio was used to reduce the effect of year-to-year difference in precipitation and isolate the effect of temperature. The observed decreases in the SWE/P_d ratio, as well as the spatial patterns, were determined to be consistent only with model results that include the build-up of atmospheric GHG. Natural variability alone did not explain the observed changes in the April 1 SWE/P_d ratios. Furthermore, the climate model results, when the anthropogenic forcing was included, predicted that the largest decreases in the April 1 SWE/P_d ratio will occur at lower elevations and that the slope of the decreasing trends will decline with increasing elevations.

Hildago et al. (2009) used spatially downscaled precipitation, minimum and maximum temperature from the Community Climate System Model which represented natural variability with and without additional anthropogenic GHG forcing as input to the Variable Infiltration Capacity (VIC) hydrology model, (Liang et al. 1994). Runoff was calculated for three river drainages in the SIEN area, the Tuolumne, Merced, and San Joaquin. Subsequently however, the results were aggregated with Sacramento River flows. Hidalgo et al. (2009) considered trends in the observed and modeled streamflows by comparing the day of the water year when the accumulative runoff equals 50 percent of the annual runoff (CD50). This is the same streamflow metric evaluated by Maurer et al. (2007), which is somewhat different from the runoff center of mass investigated by Cayan et al. (2001) and Stewart et al. (2005). The investigation determined that both models with anthropogenic GHG forcings predicted river flows and the observed Sacramento-San Joaquin river flows lacked a significant trend in the CD50. Furthermore, modeled trends in the CD50 for the Sacramento-San Joaquin Rivers fall within the domain of natural variability and could not be confidently attributed to warmer climate associated with anthropogenic GHG emission. A statistically significant trend in the CD50, however, was determined for the Colorado River Basin.

Das et al. (2009) used spatially downscaled results from the Community Climate System Model, which represented natural variability with and without additional anthropogenic GHG forcings, as input to the VIC hydrology model. They evaluated trends in several hydrologic metrics, including the ratios of January through March runoff to accumulated water year runoff and April 1 SWE to accumulated water year precipitation. Consistent with the studies described above, the hydrologic effects of warmer winter temperatures, especially minimum temperatures, were most significant in the Pacific Northwest, including the Columbia River Basin. Conversely, trends in January through March runoff and the April 1 SWE/P_d ratio in the southern Sierra Nevada could not be distinguished from natural variability with confidence (Das et al. 2009).

3. Hydrologic Records for the Southern Sierra Nevada

A primary purpose of this study was to identify streamflow and snowpack records that can be evaluated to describe the hydrology of the SIEN Parks. The records must be of sufficient length to approximate the range of hydrological conditions which have occurred over the past century and the streamflows should not be appreciably affected by diversion, artificial storage, or regulation. That is, the streamflow records should represent essentially natural, unimpaired flow. The initial objective was to identify all records of unimpaired streamflow and snowpack, at least 10 or more years in length and within 10 kilometers of the SIEN park boundaries.

3.1. Streamflow Gaging Stations

Hydrologic records in the SIEN area are collected principally by the U.S. Geological Survey (USGS), National Park Service (NPS), California Department of Water Research (CDWR), City of San Francisco, City of Los Angeles, as well as two public utilities: Pacific Gas and Electric (PG&E) and Southern California Edison (SCE). Representatives for each of these organizations were contacted to discuss the gaging stations they operate and to identify the appropriate records.

The primary source of streamflow records is the National Water Information System (NWIS) maintained by the U.S. Geological Survey (USGS). Streamflow records for California were accessed at http://waterdata.usgs.gov/ca/nwis/dv. The NWIS database contains streamflow records collected at gaging stations operated by PG&E and SCE as well as the USGS. All of the streamflow records in the NWIS database are reviewed to ensure that they are collected and analyzed in a consistent manner. Both PG&E and SCE also operate gaging stations whose records are not stored in the NWIS database. PG&E and SCE declined to provide any of these additional records. So far as can be determined, none of the unavailable information concerned long-term records of unimpaired streamflow. Most, if not all of the unavailable records, describe releases from reservoirs, diversions, and the flow through hydroelectric power plants.

The California NWIS database was searched by county to identify all available streamflow gaging stations located within or receiving runoff from drainage basins bordering the SIEN. The locations and period(s) of record of several hundred active and discontinued gaging stations were reviewed to identify those suitable for detailed evaluation. Complete information describing the extent of streamflow diversions, reservoir storage and/or regulation is frequently unavailable in the NWIS database, especially for those gaging stations discontinued a decade or more ago. Various information resources, including the USGS Water Supply Paper Series issued prior to 1963, USGS Water Data Reports for California published annually since 1963, topographic maps and California Department of Water Resources reports were consulted to identify the gaging station records that represent essentially unimpaired streamflow. The term “essentially” has been applied because only a few gaging stations in the southern Sierra Nevada area represent streamflows totally free from any human manipulations. For example, as much as 1.5 ft^3/s was diverted from the Merced River in Yosemite Valley upstream of the Happy Isles Bridge gage prior to 1983. While the diverted flow is very small compared to the annual mean discharge, it is an appreciable portion of summer low flows, especially during the driest years.

A degree of judgment was required to evaluate the extent to which streamflows at a particular gage have been impaired and, thus, were unsuitable for the objectives of this study. The magnitudes and timing of flow diversions and regulation typically vary year-to-year depending upon many factors, including the priority of water rights, accessibility of the diversion site, and capacity of the headgate and diversion canal. (Note: For the purpose of this study, only complete water years of record, October 1 to September 30, are considered. In those instances, which are common, when a gage began operation during the middle of a water year, the partial year of record has been deleted.) When in doubt, my bias was to exclude a suspect streamflow record.

Twenty streamflow gaging station records from the NWIS database were determined to be essentially unimpaired and suitable for all of the proposed analyses. An additional two gaging stations listed in the NWIS database and five gaging stations not listed in the NWIS database, as described below, were suitable or available for only partial analysis. The locations of the 27 gaging stations are shown in Table 1 and Figure 4. The first 20 stations listed in Table 1 are those suitable for all analyses. The last seven stations are those for which only partial analyses were performed. As noted previously, the mean land surface elevation broadly increases from north to south across the SIEN. Ten of the 27 gages are at an elevation of 2800 feet or less and all of them are located south of the North Fork Kings River. Accordingly, drainage basin relief in the southern portion of the study area is considerably greater than in the northern portion. Contributing drainage areas of the selected gaging stations range from 22.9 sq. mi. to 952 sq. mi. Half of the drainage areas are less than 100 sq. mi. The gage elevations range from 807 ft. to 8,144 ft.

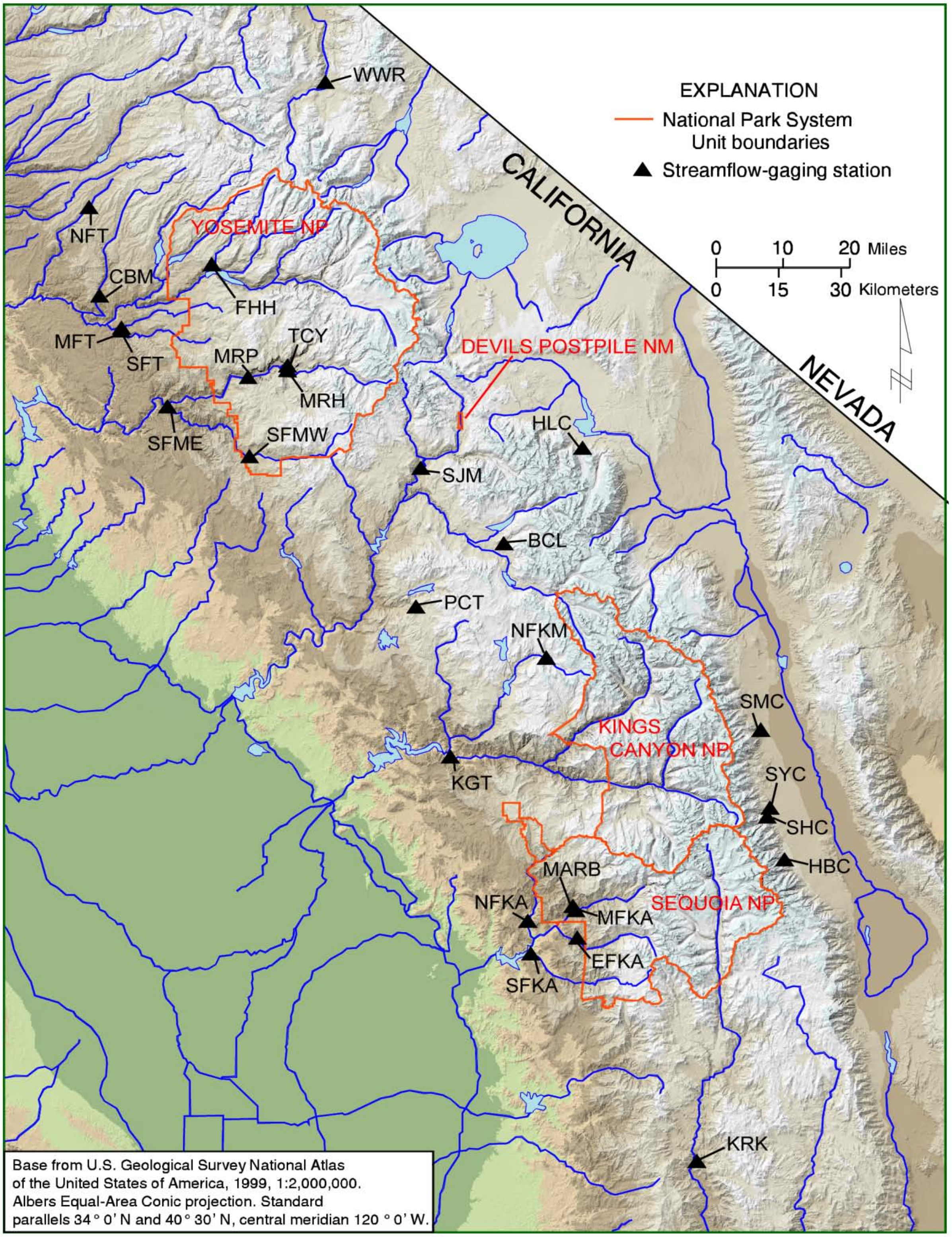


Figure 4. Map of the southern Sierra Nevada showing the 27 streamflow gaging stations selected for this study

Table 1. Streamflow gaging stations within ad adjacent to the SIEN including a summary of characteristics.

Streamflow Station	Station No.	Abbrev.	Period of Record Used for Analyses	Water Years of Record	Area $(mi)^2$	Elevation (feet)	Mean Annual Discharge $(ft.^3/sec)$
Merced River at Happy Isles Bridge near Yosemite	11264500	MRH	1916–2009[1]	94	181	4017	354
Merced River at Pohono Bridge near Yosemite	11266500	MRP	1917–2009[1]	93	321	3862	625
Bear Creek near Lake Thomas A. Edison	11230500	BCL	1922–2009[1]	87	52.5	7367	93.3
Pitman Creek below Tamarack Creek	11237500	PCT	1928–2009[1]	80	22.9	7020	42.7
Kern river near Kernville	11186000	KRK	1913–2009[1]	96	846	3620	757
West Walker River below Little Walker River near Coleville	10296000	WWR	1939–2009[1]	71	180	6590	267
MiddleTuolumne River near Oakland Recreation Camp	11282000	MFT	1917–2002	85	73.5	2800	78.5
South Fork Tuolumne River near Oakland Recreation Camp	11281000	SFT	1924–2002	78	87.0	2800	96.7
Middle Fork Kaweah river near Potwisha Camp	11206500	MFKA	1950–2002[1]	53	102	2100	179
Marble Fork Kaweah River at Potwisha Camp	11208000	MARB	1951–2002	52	51.4	2210	102
East Fork Kaweah River near Three Rivers	11208730	EFKA	1953–2002[1]	32	85.8	2700	104
North Fork Kings River below Meadow Brook	11214000	NFKM	1922–2009[1]	48	37.7	8144	74.2
North Fork Kaweah River at Kaweah	11209500	NFKA	1911–1982	50	129	1027	100
Falls Creek near Hetch Hetchy	11275000	FHH	1916–1982	66	46.	5350	143
Kings River above North Fork near Trimmer	11213500	KGT	1927–1982	53	952	1002	1460
Tenaya Creek near Yosemite Village	11265000	TCY	1916–1958	53	46.9	4000	106
South Fork Kaweah River at Three Rivers	11210100	SFKA	1958–1990	32	86.7	807	76.8
San Joaquin River Miller Crossing	11226500	SJM	1922–1991	47	249	4570	600
Clavey River near Buck Meadows	11283500	CBM	1960–1983	24	144	2374	286
North Fork Tuolumne River Long Barn	11284700	NFT	1963–1986	24	23.1	4650	32.5

Table 1. Streamflow gaging stations within and adjacent to the SIEN including a summary of characteristics. (continued).

Streamflow Station	Station No.	Abbrev.	Period of Record Used for Analyses	Water Years of Record	Area $(mi)^2$	Elevation (feet)	Mean Annual Discharge $(ft.^3/sec)$
South Fork Merced River at Wawona	11267300	SFMW	1958–1968	10	100	3955	174
South Fork Merced River near El Portal	11268000	SFME	1952–1975	24	241	1490	350
Owens River Tributaries							
Hogback Creek		HBC	1959–2009	51	N/A	6590	2.15
Shepherd Creek		SHC	1959–2009	51	N/A	6100	5.84
Symmes Creek		SYC	1959–2009	51	N/A	5700	1.95
Sawmill Creek		SMC	1959–2009	51	N/A	4760	3.89
Hilton Creek		HLC	1959–2009	51	N/A	7480	6.94

[1]Streamgage operated during 2010 water year. The USGS records of the combined flows at MFKA and EFKA end in 2002, but the gages continue to be operated by SCE; partial records remain available through NWIS and SCE provides the full records to SEKI.

Two types of streamflow records, one included and one excluded, need additional explanation. Three of the streamflow records listed in Table 1, the Kern River at Kernville, the Marble Fork Kaweah River at Potwisha Camp, and the Middle Fork Kaweah River near Potwisha Camp are calculated by summing the flow of a diversion canal and the flow remaining in the river channel below the diversion. That is, the streamflow is reconstructed as if the diversion did not exist. Under most conditions, the reconstructed streamflows are nearly identical, if not indistinguishable, to the unimpaired flows upstream of the diversion. (Notes: The period of record for the Marble Fork Kaweah River at Potwisha Camp ends in Sept. 2002 and for the Middle Fork Kaweah River near Potwisha Camp ends in Sept. 2003. The river channel gage on the Middle Fork continues to be operated, though the Marble Fork station has been removed. Southern California Edison continues to provide records below 36 cubic feet per second (cfs) to the USGS for review and provides record of all flows, including reconstructed flows, to SEKI.) At the extremes of the range of flow, both high and low, it is possible that the reconstructed streamflows are not identical to the unimpaired flow immediately upstream of the diversion. Diversion dams and head gates typically leak as much as a few cubic feet per second, which would be an appreciable portion of the summer low flow. The 7-day summer annual minimum flow equaled or exceeded 95 percent of the time is about 10 ft^3/s at the Marble Fork Kaweah gage and about 400 ft^3/s at the Kern River near Kernville gage. In contrast, the annual peak flows are not reconstructed by adding in the diverted streamflow. Annual peak flows are reported for the gage only under the river channel gage number. In most years, the annual peak flow will be much larger than the maximum diverted flow; however, there are years, especially those with below average snowmelt runoff where an appreciable portion of the annual peak flow may be diverted.

For example, the capacity of the diversion from the Kern River near Kernville is 650 ft^3/s, while the mean annual peak flood, equaled or exceeded 45 percent of the time is about 3200 ft^3/s. Following a thorough review of the three reconstructed streamflow records, it was concluded that they are a reasonably accurate record of the unimpaired flows.

An additional seven gaging station records were determined to contain some worthwhile information, but were not suitable for all of the planned analysis. These gaging stations are listed at the bottom of Table 1. The U.S. Geological Survey previously operated two gaging stations on the South Fork Merced River; at Wawona within Yosemite National Park, discontinued in 1968, and near the El Portal gage, discontinued in 1975. Streamflows at both of these gages are depleted by diversions, primarily from late spring through the early fall. Only a few cubic feet per second are diverted at the Wawona gage, and although the total volume diverted is small compared to the annual runoff or annual maximum flows, it is a substantial fraction of summer low flows. Streamflows in the South Fork Merced River near El Portal are affected by a much larger diversion. Therefore, neither of these gages' records represents unimpaired low and perhaps even intermediate flow. The annual peak floods, however, are appreciably larger than the diversions. Furthermore, annual peak floods were determined at the South Fork Merced River at Wawona over a 17 year period from 1956-1975, whereas the record of daily mean flow is only 10 years. Accordingly, both of the South Fork Merced River gages, at Wawona and near El Portal, have been included in the analysis of flood frequency.

The City of Los Angeles Department of Water and Power (LADWP) operates an extensive network of streamflow gages along the east slope of the southern Sierra Nevada as part of their diversions from the Owens River. Based upon a description of the study objectives, the LADWP Hydrology Office in Bishop, CA selected and provided mean monthly flows recorded at five gaging stations for the period of 1959-2009. Daily mean discharges are calculated from the continuous stage record; however, daily mean discharges prior to the early 1990s have not been stored in a digital form. The five selected gages are located near the mountain front upstream from the reaches substantially affected by infiltration into alluvial aquifers. Streamflows recorded at the five east slope gaging stations will be included in (1) calculated Pearson Correlation Matrix for annual mean flows across the southern Sierra Nevada region and (2) the evaluation of trends in the annual mean flow and in the temporal distribution of snowmelt runoff as indicated by the ratio of April through July runoff/annual runoff.

There are a number of reservoirs in the southern Sierra Nevada where the reservoir outflow (releases) and the change in reservoir volume are both gaged. A record of unimpaired flows at the reservoir site can be calculated by adding the change in reservoir volume and estimate of evaporation from the lake surface to the gaged reservoir outflow. The principal uncertainty in such a reconstruction, assuming the reservoir outflow is accurately gaged, would be the estimated daily evaporation. Reasonably accurate estimates of daily evaporation can be calculated given a meteorological station is near with recorded air temperature, humidity, wind velocity and solar radiation. In general, the required daily meteorological information will only be available for the past 20-30 years, considerably less than the existing streamflow and storage volume records. For periods lacking daily meteorological observation, reservoir evaporation can only be estimated at monthly or annual intervals with sufficient accuracy. When and where the hydrological and meteorological records are essentially complete, one can expect that the reconstructed records are a reasonably accurate estimate of unimpaired daily streamflows at the outlet if the reservoir had not been in place. As of January 2010, the City of San Francisco was conducting such an analysis for the outflow from Hetch-Hetchy Reservoir (Bruce McGurk, personal communication). Southern California Edison has contracted for a similar analysis of Florence Lake and Lake Thomas A. Edison, which are major elements of their hydropower facilities in the San Joaquin River Basin (Brian

McGurty, personal communication). In both instances, the projects are at an early stage and the extent and details of the evaporation analysis remains to be determined. The SCE study is anticipated to be completed in about two years. There are a number of other reservoirs in the southern Sierra Nevada, where the daily outflow and change in storage have been gaged for several decades. Although the data compilation and analysis would be quite time consuming, it is conceivable that a dozen or more long time series of unimpaired monthly and annual flows could be reconstructed by such an effort. Some of the reconstructed unimpaired flow would represent contributing drainage basins above 8000 feet and in a few instances, greater than 10,000 feet elevation.

As shown in Table 1, there are currently no available long-term records of streamflow above 8200 ft. in the Sierra Nevada. As noted previously, and will be demonstrated in greater detail later with the analysis of snow course measurements, the evolving climate has affected, and is anticipated to affect drainage basins at higher elevation substantially differently than those at lower elevation. Accordingly, it could be quite informative to reconstruct unimpaired daily streamflows at high elevation reservoirs given a sufficient period of record. An added benefit of the higher elevation drainage basins is that evaporation is somewhat less significant relative to runoff. Hetch-Hetchy Reservoir within Yosemite National Park, Saddlebag and Tioga Lakes adjacent to the northeast border of Yosemite Park, South Lake (South Fork of Bishop Creek) adjacent to the northern border of Kings Canyon National Park and Lake Thomas A. Edison in the San Joaquin River Basin are examples of reservoirs with both hydrological and meteorological records that would be worth further investigation. Given the time required to compile and analyze the available records and complete the reconstruction of unimpaired streamflows, it was not feasible to include those records in this study.

3.2. Snow Courses

Snowpack survey records collected by several entities are stored in the California Data Exchange (CDEC) database, maintained by the California Department of Water Resources. Historical measurements of snow water equivalent (SWE) sampled on the first day of the month during the winter and early spring can be found in the CDEC database at http://cdec.water.ca.gov/staInfo.html. Various options are provided to search and identify the desired records. For this study, snow courses were searched by the nine major river basins, Tuolumne, Merced, San Joaquin, Kings, Kaweah, Kern, Owens, Mono, and Walker draining the southern Sierra Nevada. The CDEC database contains records for snow courses that have been operated in the nine river basins. Most of the snow courses were established prior to 1970 and very few, if any, have been established since 1990. Accordingly, snow courses that are still active or have been discontinued in the past 15 years typically have more than 25 years of record. Given the large number of snow courses well-dispersed throughout the SIEN, discontinued snow courses with less than 25 years of record were not considered. Sixty-eight snow courses located within or adjacent (~10 miles) to the SIEN with 25 years or more of record were selected for analysis. Eighteen of the snow courses selected for this study have been discontinued and were not operated in 2008. Most of the discontinued snow courses were eliminated 1990 through 2000.

This study is focused almost exclusively on observations made at streamflow gaging stations and snow courses because they are the only long-term spatially distributed hydrologic records available for the SIEN with which means, exceedance probabilities, and trends can be examined. The existing network of gaging stations and snow courses was devised primarily to determine the volume of runoff that would be available for irrigation, hydroelectric power generation, and water supply for municipal and industrial uses. The SIEN Vital Signs Monitoring Plan identifies some different and broader range of hydrologic attributes than the daily, monthly, and annual runoff. Many of the ecologically relevant questions concerning the temporal and spatial distribution of water across the SIEN can be evaluated and answered using cost-effective and wilderness appropriate methods and techniques other than gaging stations and snow courses. Gaging stations and snow courses will, no doubt, continue to be an important and most likely, essential component of a hydrologic monitoring program for the SIEN. They are not, however, the only available hydrologic monitoring tools. Frequently, the ecologically relevant questions concern the water surface elevation at a given place and time, rather than the water discharge (Michael Dettinger, written communication). Chapter 6 of this report considers this formulation of a hydrologic monitoring plan for the SIEN. A number of alternative approaches and observations, such as crest stage gages, evaporation pans, soil moisture probes, and remote sensing of snow cover, will be presented.

4. Methods for the Analysis of Gaging Station and Snow Course Records

The first purpose of this study as defined by the NPS scope of work is to describe and characterize streamflows within and adjacent to the SIEN, including: (1) the magnitude, frequency, and timing of low flows and high flows, (2) the duration of streamflows, i.e. the probability that a given flow magnitude will be equaled or exceeded, and (3) the magnitude, frequency and timing of annual peak floods. A second broad purpose of the streamflow analysis is to identify and investigate trends in the magnitude, frequency, and timing of the streamflow regimes of the southern Sierra Nevada, including any spatial pattern. These objectives might seem somewhat inconsistent in that the statistical analysis to accomplish the first purpose depends on the assumption that the observed streamflows are stationary, i.e. there is no trend. As described above, numerous studies published over the past decade or so have considered and demonstrated trends in various aspects of the snowpack and streamflows. Weak trends are apparent in many hydrologic parameters, as will be developed in considerable detail in the following analyses. These apparent trends could be, in part, entirely due to chance. Where the trend of a given streamflow characteristic follows a consistent pattern across the region and/or with elevation, then the evidence becomes much more compelling. More broadly, the dilemma is how one should do hydrology in a non-stationary world, where the anticipated climate change becomes a reality. For example, what would be the scientifically justifiable and socially acceptable way to do floodplain zoning, if the estimated 100 year flood at some location today is significantly different from what it might be in 20-30 years? Pragmatically, there is and will continue to be a need to estimate the magnitude of various streamflows in order to design the capacity of a culvert or bridge, determine the location of a structure approximate to a watercourse or calculate the ecologically safe size of a diversion. What is the prudent approach? There may, in fact, be very limited alternatives to that of relying on the historical record and adding a generous margin of safety. Accordingly, my approach was to analyze streamflows as if the records are stationary as well as analyze trends and report the results together with the appropriate confidence limits and probabilities.

4.1. Streamflow Magnitude and Frequency

The analyses of streamflow magnitude and frequency for this study followed well-established, conventional methods and practice. Riggs (1985) describes the widely applied methods for characterizing low and high flows, as well as the analysis of flow duration. A flow duration curve represents the cumulative frequency distribution of daily mean discharge (or some other time interval) over the period of record (Riggs 1985). Low flows are typically calculated on an annual, seasonal or monthly basis depending on the particular issues of interest. For this study, I chose to focus on winter and summer low flows. The lowest streamflows over consecutive 3-, 7-, 10-, and 14-day periods and the dates on which they occurred were determined for the winter and summer seasons for each year of record using the sequence of daily mean discharge for the first 20 NWIS gaging stations listed in Table 1. Summer low flows are of particular interest and concern because they coincide with relatively high water temperatures and low dissolved oxygen; these conditions are a time of substantial stress for the aquatic ecosystem. Summer low flows were calculated over the July-August-September period. Although October streamflows are lower than September streamflow in some years, lower temperatures are sufficient to relieve stress on aquatic organisms.

Initially, the “winter season” low flows were calculated for the period January-February-March. However, it became apparent that the lowest flows frequently occurred in early January and rarely, if ever, in March. Furthermore, streamflows in December were commonly the lowest throughout the water year. The analysis has focused specifically on the winter season low flows because of the observed shift to more rain and less snow in the Sierra Nevada during the winter (Knowles et al. 2006). Accordingly, the winter season low flows were calculated for the December-January-February period. The exceedance probabilities, the amount of time a give flow is equaled or exceeded, for the winter and summer low flows were calculated from each series of annual values. The annual series and the dates on which the values occurred were then analyzed for any trend through the period of record.

The highest streamflows averaged over consecutive 3-, 7-, 10-, and 14-day periods and the dates on which they occurred were determined for each water year from the series of daily mean discharges for each of the 20 NWIS gaging stations listed in Table 1. Due to the prominence of the snowmelt runoff, typically 70-85 percent of the total annual runoff occurs during the April to July period, thus high flows calculated by season or month are not particularly relevant except where there are site-specific issues.

A flow duration curve shows the percent of time a given flow has been equaled or exceeded from the largest to the smallest flow. As such, it is a concise way to represent the long-term variability in streamflow. For example, the flow duration curve for a stream affected by relatively frequent rainfall on an existing snowpack would be markedly steeper over the range of higher flows than the duration curves for a basin dominated by snowmelt runoff. Likewise, the flow duration curve for a stream that receives a relatively small contribution of groundwater would be steeper over the range of smaller flows than a stream that receives a relatively large contribution of groundwater. For streams unaffected by diversion and/or regulation, the slope of the flow duration curve reflects and integrates the broad range of runoff processes. As described above, considerable effort has been devoted in recent years to analyzing temporal changes in the snowmelt runoff pulse of Sierra Nevada streams. Three calculated metrics, namely the percent of annual runoff which occurs during April, May, June, and July (AMJJ), flow center of mass (CM), and onset of snowmelt runoff, have been developed and applied to temporal changes in snowmelt runoff. The three approaches give somewhat different though complementary results, and all have been applied as described by Stewart et al. (2005), as adapted from Roos (1987, 1991) and Cayan (1996).

Most of the calculations for the study were performed with algorithms written in the MATLAB platform. In addition, statistical routines available within the Microsoft Excel and MINITAB software package were utilized.

Flood frequencies were calculated using software developed by the U.S. Geological Survey Office of Surface Water, following guidelines established by the U.S. Water Resources Council, Bulletin 17-B (1981). The software, PEAKFQ, can be retrieved from http://water.usgs.gov/software. The software fits the log Pearson Type 3 distribution to the observed record annual peak floods. The most challenging and controversial aspect of the WRC Bulletin 17-B procedure is the choice of an appropriate and representative skew. Calculated flood frequencies are most sensitive to the estimated skew when the gaging station record is relatively short (less than 20 years), and the objective is to estimate the magnitude of flood equaled or exceeded less than 1 percent of the time, i.e. flood with a recurrence interval of 100 years and greater. Conversely, the uncertainty in an estimated flood magnitude decreases when the gaging station record is relatively long; i.e. approaching the recurrence interval(s) of interest. Sixteen of the 22 gaging station records analyzed for flood frequency have 50 or more years of record.

The proper and best method to determine the distribution skew for WRC flood frequency analysis has been and continues to be an area of active research and innovation (National Research Council 1999). Currently, the California Water Science Center - USGS, is in the midst of a statewide update and refinement of their approaches for flood frequency analysis (anticipated to be published in late 2011). This effort includes the development of a revised relation for calculating generalized (re: regional) skews using the Generalized Least Squares (GLS) developed by Stedinger and Tasker (1986a, b). Regional skews calculated for the southern Sierra Nevada by alternative methods, however, relied upon the same long-term gaging station records of unimpaired streamflows that were selected for and analyzed in the study. Consequently, the estimated skew values and the resulting flood magnitudes do not differ greatly. Chuck Parrett (personal communication), Chief, USGS California Flood Frequency Project, estimates that the difference between the Bulletin 17-B flood magnitudes reported in the study and the flood magnitudes they expect to report within the next 2 years for the southern Sierra Nevada area will probably be within the range of ± 2-8 percent for the 1 percent exceedance floods, i.e. a recurrence interval of 100 years.

4.2. Analysis of Trends in Streamflow and Snowpack

The second primary purpose of this study as defined by the NPS scope of work was to identify and evaluate trends in streamflows and snowpacks. As described above, streamflow records collected at the 20 gaging stations selected for this study were analyzed to describe and define various portions of the annual hydrograph from the lowest discharge over three consecutive days up to the instantaneous annual peak flood as well as when the respective flow occurred each water year. Twenty-three time series describing a streamflow characteristic and/or the date when it occurred during a year were calculated for each of the 20 NWIS gaging stations. In addition, the snow water equivalent recorded annually on April 1 at 68 snow courses was analyzed to identify and evaluate trends in the snowpack near the end of the accumulation seasons. In total, more than 500 time series representing the year-to-year variation of some part of the hydrological cycle in the southern Sierra Nevada were examined.

The methods and techniques of trend analysis are numerous, and extensive literature has developed. A casual scan of one library shelf revealed 12 textbooks on the general topic of trend analysis that have been published in the past 15 years. An algorithm developed to investigate whether a given series of observation tends to increase, stay the same or decrease involves making assumptions about the observations, e.g. the population distribution from which the sample was drawn and whether the sample is, in fact, the entire population and whether the observations are independent. Evaluation of the significance of an apparent trend involves additional assumptions. Hydrologic observations rarely fit neatly within the prescribed assumptions for which a statistical method was developed. The risk is that, as a given set of observations deviates from the assumed characteristics, the results one obtains will be misleading.

A number of alternative statistical methods for trend analysis including variants were evaluated by applying them to three of the longest records, Merced River at Happy Isles Bridge, Bear Creek at Lake Thomas A. Edison, and the Kern River at Kernville. The gages were selected to represent any north-to-south and/or elevation differences. In the end, it was decided to rely upon the two mostly commonly applied approaches, regression analysis and the Kendall's Tau rank correlation.

The assumptions and limitations of regression analysis are almost always noted in the general textbook development, namely that the observations are independent, and deviations from the trendline are normally distributed. Several hydrologic characteristics considered in this study differ from the ideal condition to various degrees. Four streamflow characteristics recorded at the Merced River at Happy Isles Bridge are examined in Figure 5, including annual peak floods, annual mean discharge, 3-day winter low flow, and ratio of April-May-June-July (AMJJ) runoff to annual total runoff as a percent. The confidence bands show the 95 percent confidence limits for a normally distributed variable (i.e. there is a 5 percent chance that a randomly chosen sample would deviate to such an extent). Annual peak floods and annual mean discharges deviate substantially from the assumed normal distribution. The results summarized in Figure 5 are fairly typical of hydrologic variables. In many instances, the year-to-year variability is too large (i.e. the extreme values on either tail of the distribution are more common than would be indicated by a normal distribution). Only the ratio of AMJJ runoff to annual total runoff, which varies within a relatively narrow range, is well represented by a normal distribution. It is common to improve the correspondence of a given hydrologic characteristic to the assumed conditions by transforming the observations in some way to reduce the variability, e.g. taking the logarithm or smoothing. Although widely practiced, these methods introduce additional complications. Transforming a given sample of observations in the log-space, performing a set of calculations, and then taking the anti-log returns sample statistics that are different from the original sample. Alternatively, smoothing the sequence of observations by calculating the moving averages reduces the variability, but greatly increases the auto-correlation (i.e. dependence of successive values).

The statistical significance of an apparent trend is typically evaluated by determining the p-value, which is the probability expressed as a decimal fraction that the trend would occur by chance in a randomly selected sample from a given population. Reporting the statistical significance by the method of null hypothesis significances testing (NHST), though commonly practiced and, considered essential by many, has, been criticized for a variety of reasons (e.g. see Nicholls 2000). The topic is especially germane to this study, because as will be shown, the vast majority of the trends, both positive and negative, determined for various aspects of the hydrologic regimes of the southern Sierra Nevada over the past 100 years are not statistically significant at the 95 percent, $p<0.05$, or even 90 percent, $p<0.10$, confidence level. P-values are strongly affected by extreme observations, those well above or below the trend line. Just one or two extreme observations in a streamflow record of 70 years or more can have substantial effect on the resulting p-value for the statistical significance of a trend. It should be noted as well that the 95 percent confidence limit means that there is a 5 percent chance, 1 in 20 that an apparent trend would appear solely by chance.

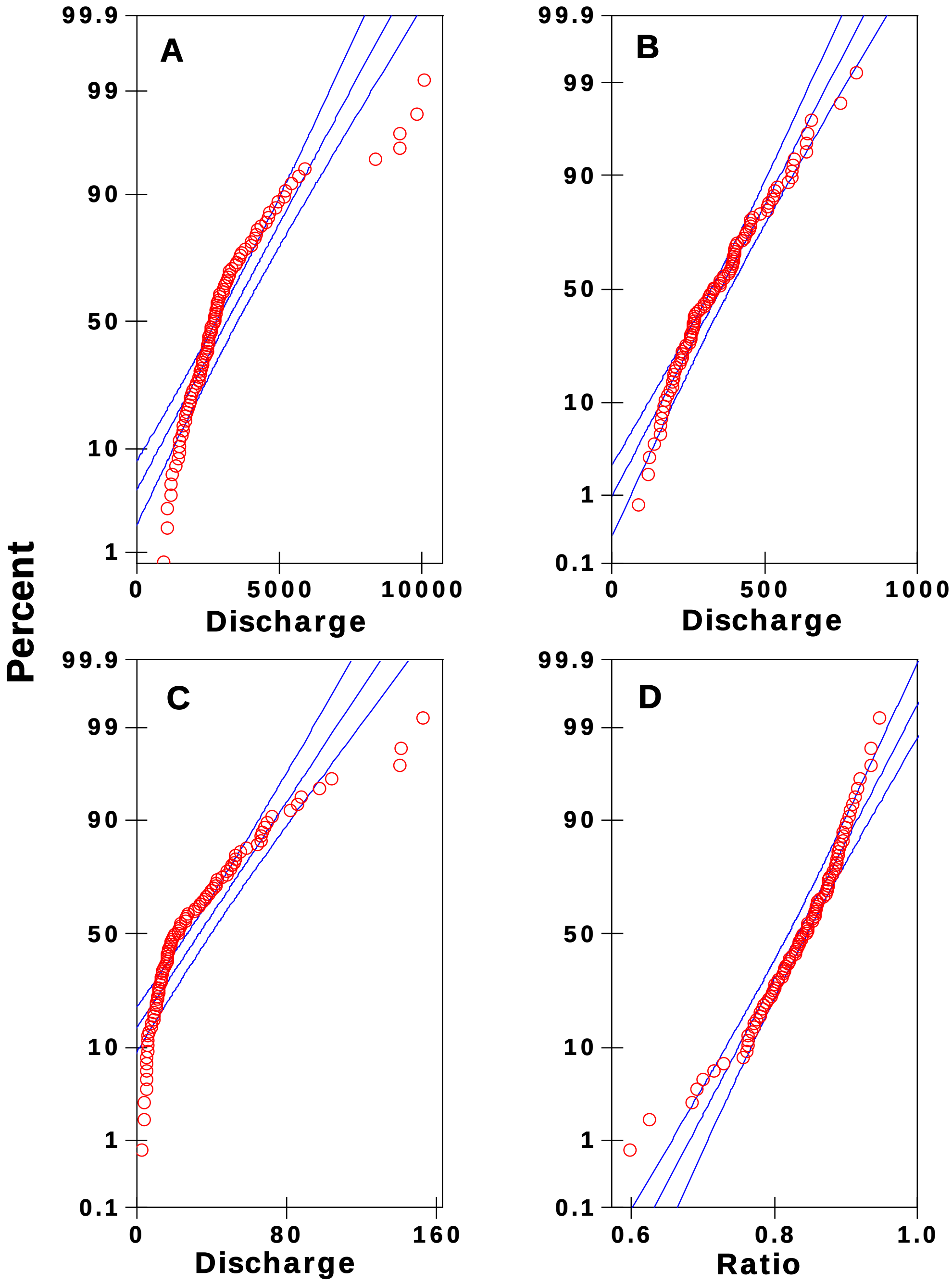


Figure 5. Normal distribution graphs for selected streamflow characteristics recorded at the Merced River near Happy Isles Bridge gage: annual peak flood (a), annual mean discharge (b), annual 3-day winter low flow (c), and ratio of April through July runoff to mean runoff (d). Blue lines represent the confidence limits. Mean daily discharge data from NWIS and streamflow characteristics calculated in MatLab.

As noted earlier, more than 500 records describing streamflows and snowpack in the southern Sierra Nevada were analyzed for this study. Therefore, one would expect to find more than 25 "statistically significant" trends that are, in fact, just random occurrences. In fact, less than 50 statistically significant trends at the 95 percent confidence limit were identified in the analysis. Finally, NHST is an either or test, e.g. $p \leq 0.05$ implies a significant trend, where $p>0.05$ implies no significant trend. In terms of understanding and evaluating a record of streamflows or snow water equivalents, and making a resource management decision, there is no practical difference between $p = 0.049$ or $p=0.040$ versus $p=0.051$ or $p = 0.06$. Accordingly, it was decided to simply report the p-value for each trend analysis and readers can make their own judgments.

5. Hydrology of the Sierra Nevada Network National Parks

The 20 NWIS streamflow and 68 snow course records were analyzed fully and by the same methods. While there are important differences, primarily related to elevation, there are substantial similarities between the individual records, especially temporal trends and distribution of flow during a given year. Flood frequency, flow duration, time of snowmelt runoff, magnitude and occurrence of high and low streamflows, and snow water equivalent on April 1 are described and evaluated in the following sections.

Discussion of each of the records within each of the following sections would be quite repetitive, and not particularly informative. Therefore, the discussion of results will focus on six gaging stations, the Merced River at Happy Isles Bridge (MRH), the Merced River at Pohono Bridge (MRP), Bear Creek near Lake Thomas A. Edison (BCL), Marble Fork Kaweah River at Potwisha Camp (MARB), Kern River near Kernville (KRK), and the West Walker River below Little Walker River near Coleville (WWR). (Note: There is a streamgage designated West Walker River near Coleville (not included here), which is located downstream from the West Walker River below Little Walker River (LWR) near Coleville gage analyzed in this study. In order to avoid confusion and repetition, the gage studied here will be referred to as West Walker River below LWR near Coleville. The records for this study were selected based upon the length of record, whether the contributing drainage area represents a significant portion of the SIEN and/or southern Sierra Nevada watershed, and their distribution – must be within and around the SIEN. The selected streamflow records also represent a range of drainage basin elevations and contributing areas. The hydrologic characteristics and trends evident in each of the six streamflow records will be considered in detail. In some instances, pertinent information from other gaging stations will be included to emphasize a particular observation or conclusion. Complete results obtained for all gaging stations considered for each analysis are listed in a table within each section. In addition, figures showing the flood frequency and temporal characteristics of the snowmelt runoff for those gaging stations not specifically considered in the text have been placed in the appendices.

5.1. Correlation of Annual Mean Flows

The hydrology within and around the SIEN is considered in the following sections through an examination of streamflow gaging station and snow course records. Various aspects of the hydrological regime, flood frequency, high and low flow statistics, flow duration, and temporal distribution of runoff throughout the year are examined in detail. Table 2 presents the correlation of annual mean discharge, i.e. annual runoff, recorded at the 11 gaged stations that have a complete continuous record from 1959 to 2008. The analysis requires a concurrent period of record, and there is a trade-off between the number of gages, their geographical distribution within and around the SIEN parks, and obtaining the longest possible periods of record. The gaging stations are arranged in Table 2 from north-to-south along the west slope and from south-to-north along the east slope. The Pearson Rank correlation coefficient, or simply Pearson correlation, quantifies the linear dependence between two random variables. The Pearson coefficient is +1.0 where there exists a perfect positive relation, whereas the coefficient is -1.0 when the relation is perfect and negative. When the coefficient is zero, the two random variables are totally independent.

Given the similarities in geology, topography, and climate, one would anticipate that temporal distribution of annual runoff between stations across the SIEN area would be well-correlated. Indeed, the correlation between streamgages separated by a substantial distance and located on opposite slopes of the Sierra Nevada are still high. All of the gaging stations listed are part of a well-defined hydrologic region.

Within the generally strong correlations, there are consistent patterns and trends. The highest correlations are between nearby gages on the same slope of the Sierra Nevada. Annual mean flow recorded at the two Merced River gages are almost perfectly correlated, 0.998. Annual runoff from Bear Creek near Lake Thomas A. Edison and Pitman Creek near Tamarack, both tributaries to the San Joaquin and located within a straight line distance of about 16 miles, are highly correlated at 0.981. The correlation of annual runoff observed at the Merced River at Pohono Bridge, the most northerly gage on the west slope, with the Kern River near Kernville, the most southerly gage on the west slope, is 0.921. In general, correlations of annual mean streamflows between east slope gaging stations are somewhat less than between west slope gages. As one might expect, the smallest correlation, although still relatively strong, >0.828, is between gages on opposite slopes of the Sierra Nevada. Even so, the correlations of annual mean flow between some pairs of gages located on opposite sides of the Sierra Nevada crest, such as Bear Creek and Hilton Creek (0.921), or between West Walker River and Merced River at Pohono Bridge (0.979), are quite strong.

Table 2. Pearson correlation matrix of annual mean discharges recorded at 11 streamflow gaging stations within and adjacent to the SIEN national parks for water years 1959–2008. Merced-HI is the Happy Isles gage, and Merced-PB is the Pohono Bridge gage.

	Merced-HI	*Merced-PB*	*Bear*	*Pitman*	*Kern*	*Hogback*	*Shepards*	*Symmes*	*Sawmill*	*Hilton*	*WWalker*
Merced-HI	1.000										
Merced-PB	0.998	1.000									
Bear	0.977	0.977	1.000								
Pitman	0.979	0.977	0.981	1.000							
Kern	0.914	0.921	0.940	0.933	1.000						
Hogback	0.863	0.865	0.903	0.884	0.952	1.000					
Shepards	0.874	0.875	0.909	0.892	0.942	0.981	1.000				
Symmes	0.897	0.901	0.906	0.887	0.936	0.964	0.955	1.000			
Sawmill	0.828	0.842	0.863	0.847	0.928	0.895	0.902	0.887	1.000		
Hilton	0.888	0.895	0.921	0.878	0.933	0.899	0.895	0.909	0.910	1.000	
WWalker	0.971	0.979	0.938	0.937	0.886	0.831	0.839	0.884	0.834	0.870	1.000

5.2. Flood Frequency

Determining the flood frequency and magnitude using long-term records and comparing these among different drainages helps us understand how watershed characteristics (such as size and topography) and weather patterns affect streamflow dynamics. Calculated flood magnitudes equaled or exceeded from 98 to 0.5 percent of the time for six gaging stations are shown by the solid curve in Figures 6 through 11. The flow duration curves and observed peak floods for the remaining stations are included in Appendix A. Dashed curves show the 95 percent confidence limits. Observed annual flood peaks are also shown. The season during which a flood occurred is identified by symbol type. The seasons were selected to distinguish the predominant runoff generating processes for the flood and, as such, are generalizations. Floods occurring during the November through February period are typically associated with intense rainfall and an existing snowfall at the higher elevations. The relative contribution to the total discharge of snow melted by rainfall depends on a number of factors - the existing snowpack, temperature of the snowpack, air temperature, etc., which vary greatly both spatially and temporally during a flood-producing storm, as well as from flood to flood. For example, melting snow would contribute little, if any, runoff to a given November flood. Floods occurring during the March to July 15 period are produced mainly by rising temperature and increasing solar radiation on an existing snowpack; rainfall may contribute to a given flood. Total rainfall during these months, however, is typically much less than what occurs during the November through February period. Floods occurring during the July 16 through September period are produced by intense localized rainfall. Such floods appear to occur only in the smaller drainage basins, where an appreciable portion of the basin area can be affected by the storm. These floods are unusual in the Sierra Nevada and have not received much attention in the hydrologic literature. They may be relatively important, however, in smaller basins which are represented poorly by the existing gaging stations network.

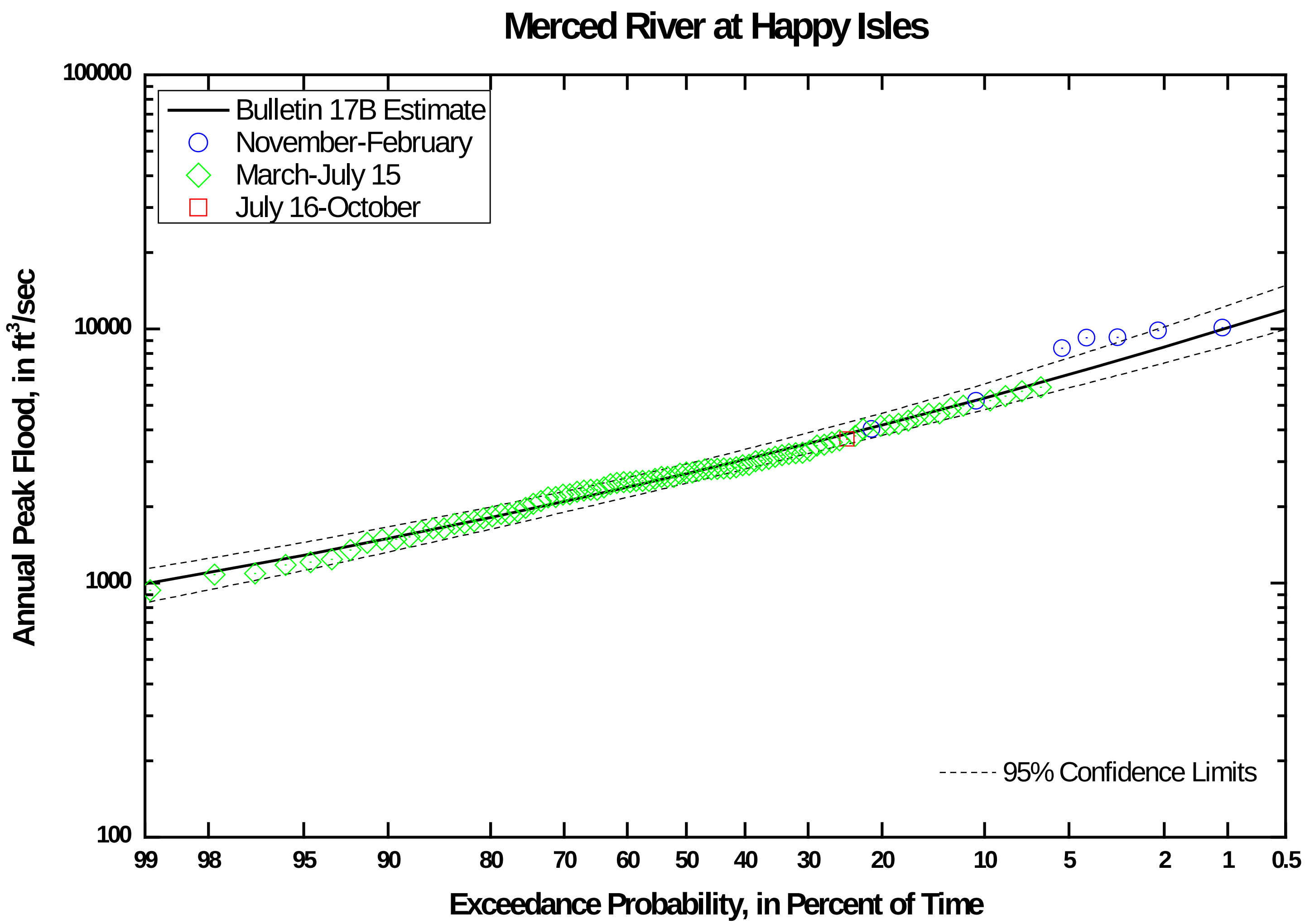


Figure 6. Calculated frequency of annual peak floods at the Merced River at Happy Isles Bridge gage and observed annual peak floods.

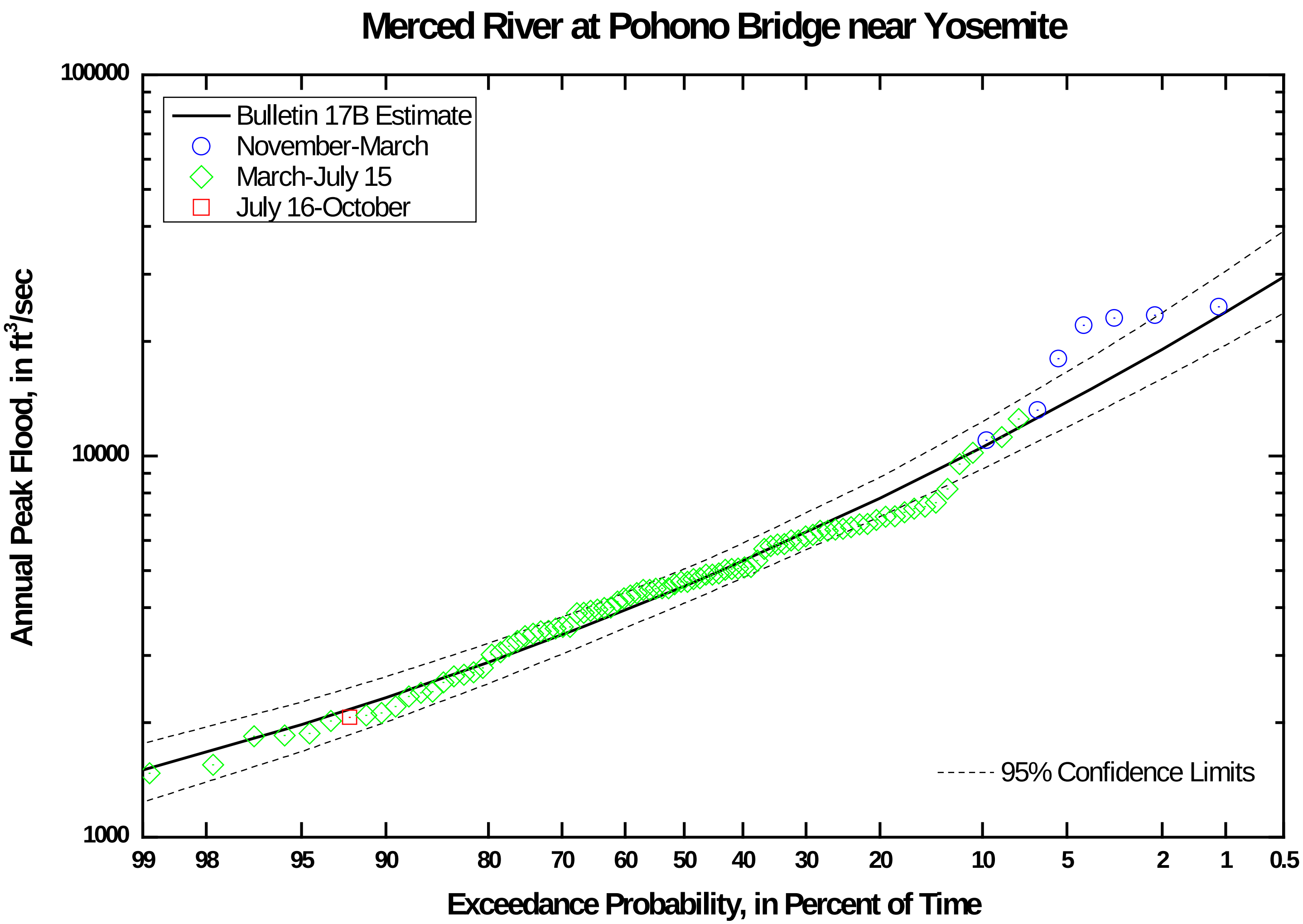


Figure 7. Calculated frequency of annual peak floods at the Merced River at Pohono Bridge near Yosemite gage and observed annual peak floods.

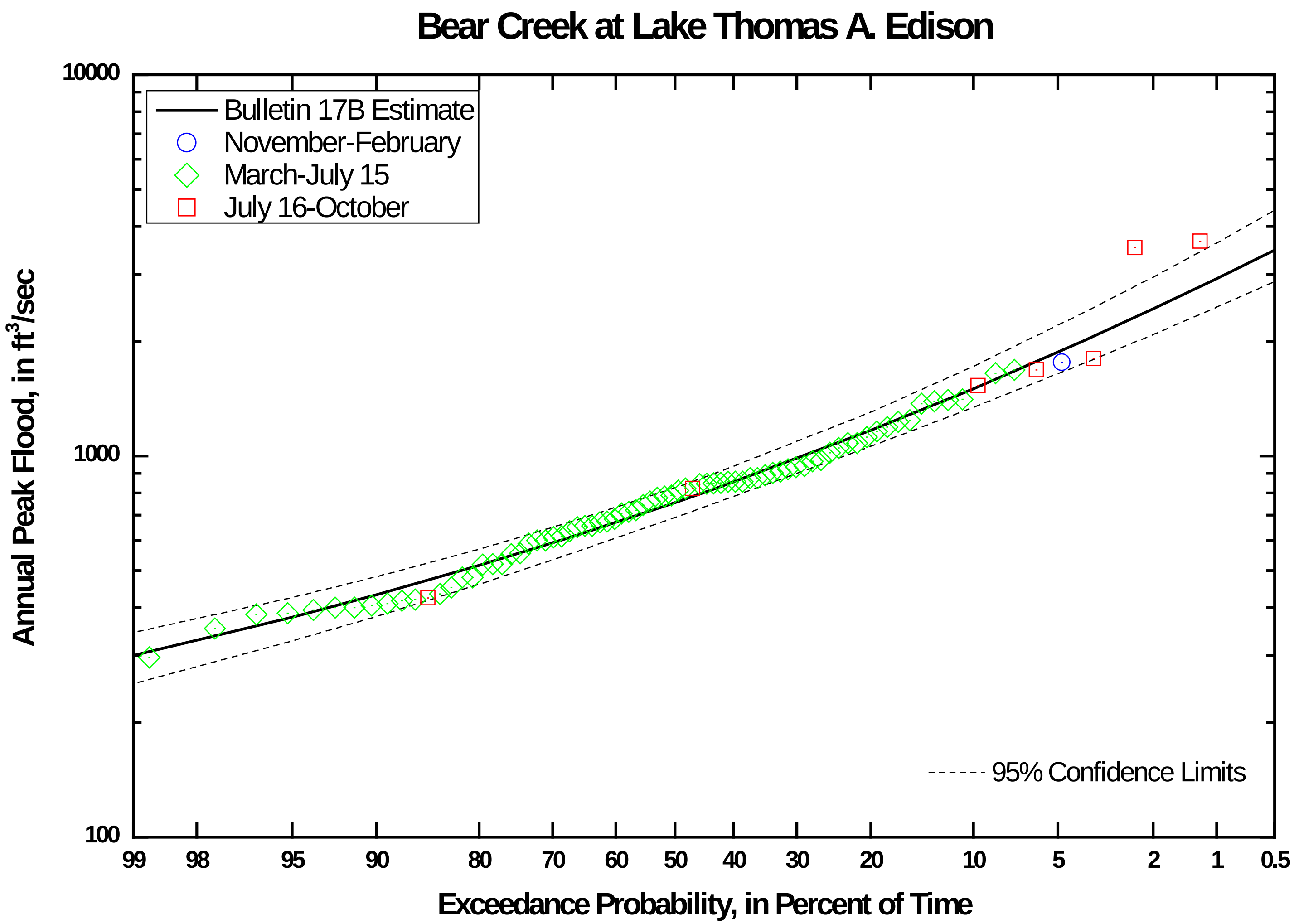


Figure 8. Calculated frequency of annual peak floods at the Bear Creek at Lake Thomas A. Edison gage and observed annual peak floods.

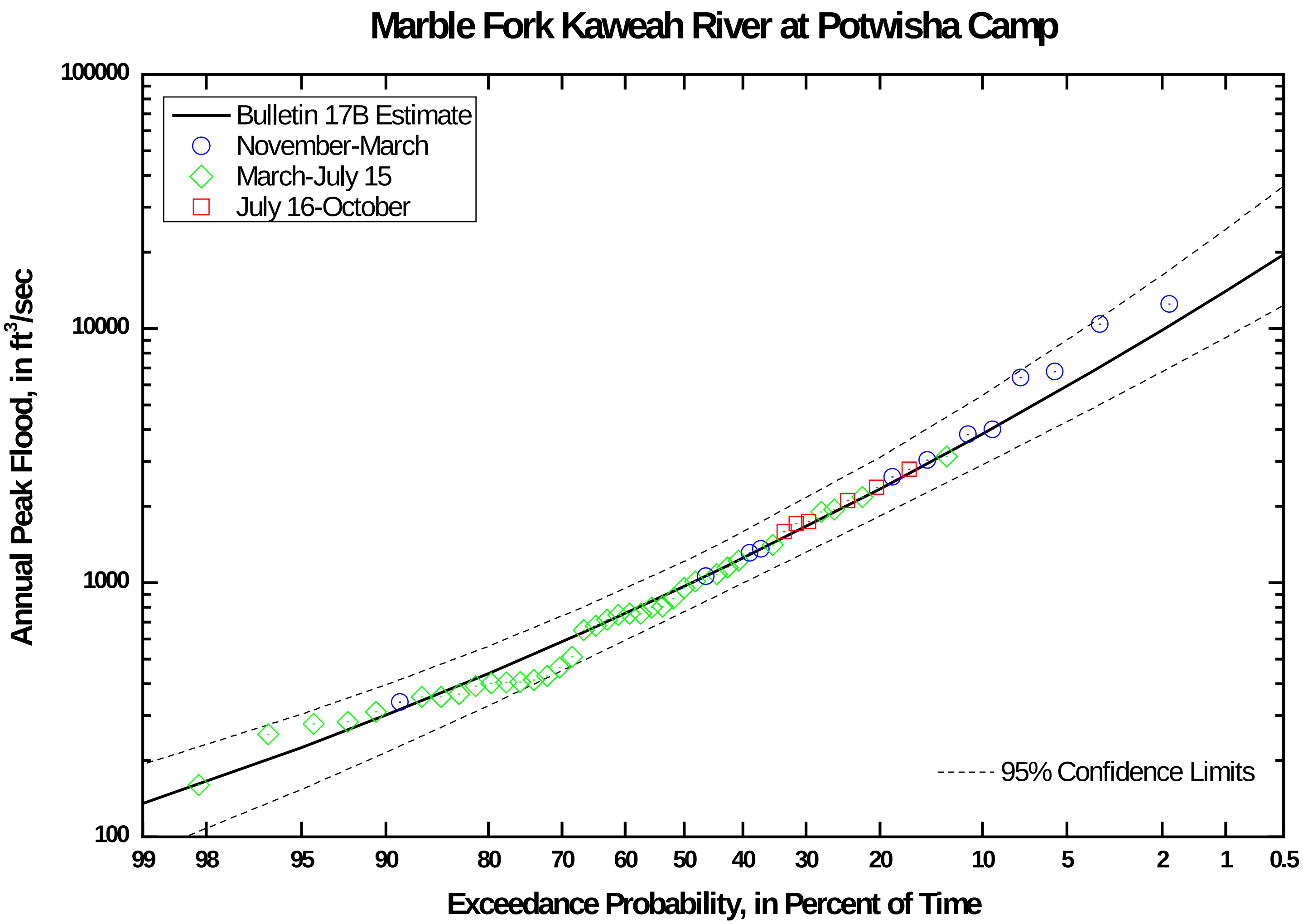


Figure 9. Calculated frequency of annual peak floods at the Marble Fork Kaweah River at Potwisha Camp gage and observed annual peak floods.

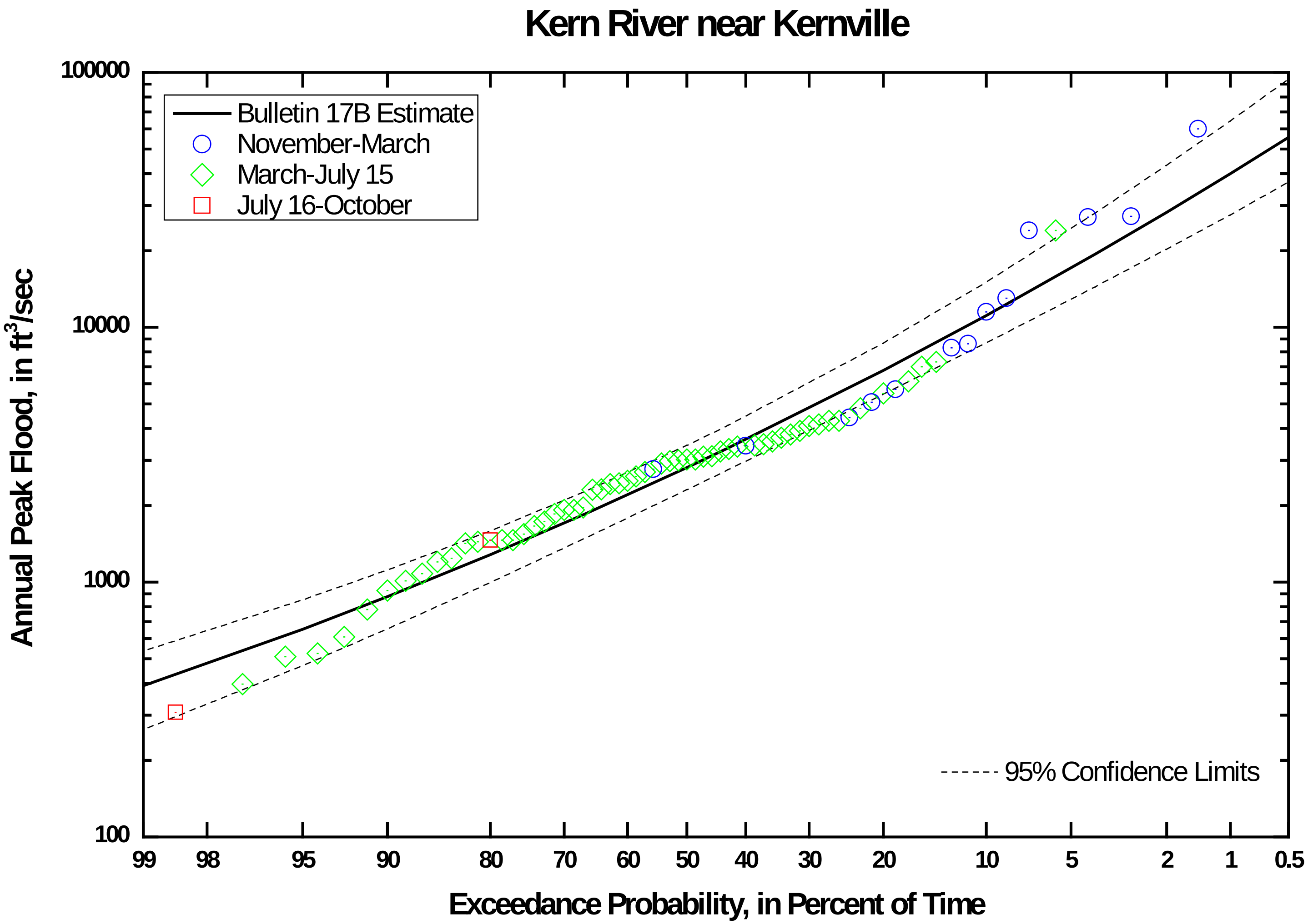


Figure 10. Calculated frequency of annual peak floods at the Kern River near Kernville gage and observed annual peak floods.

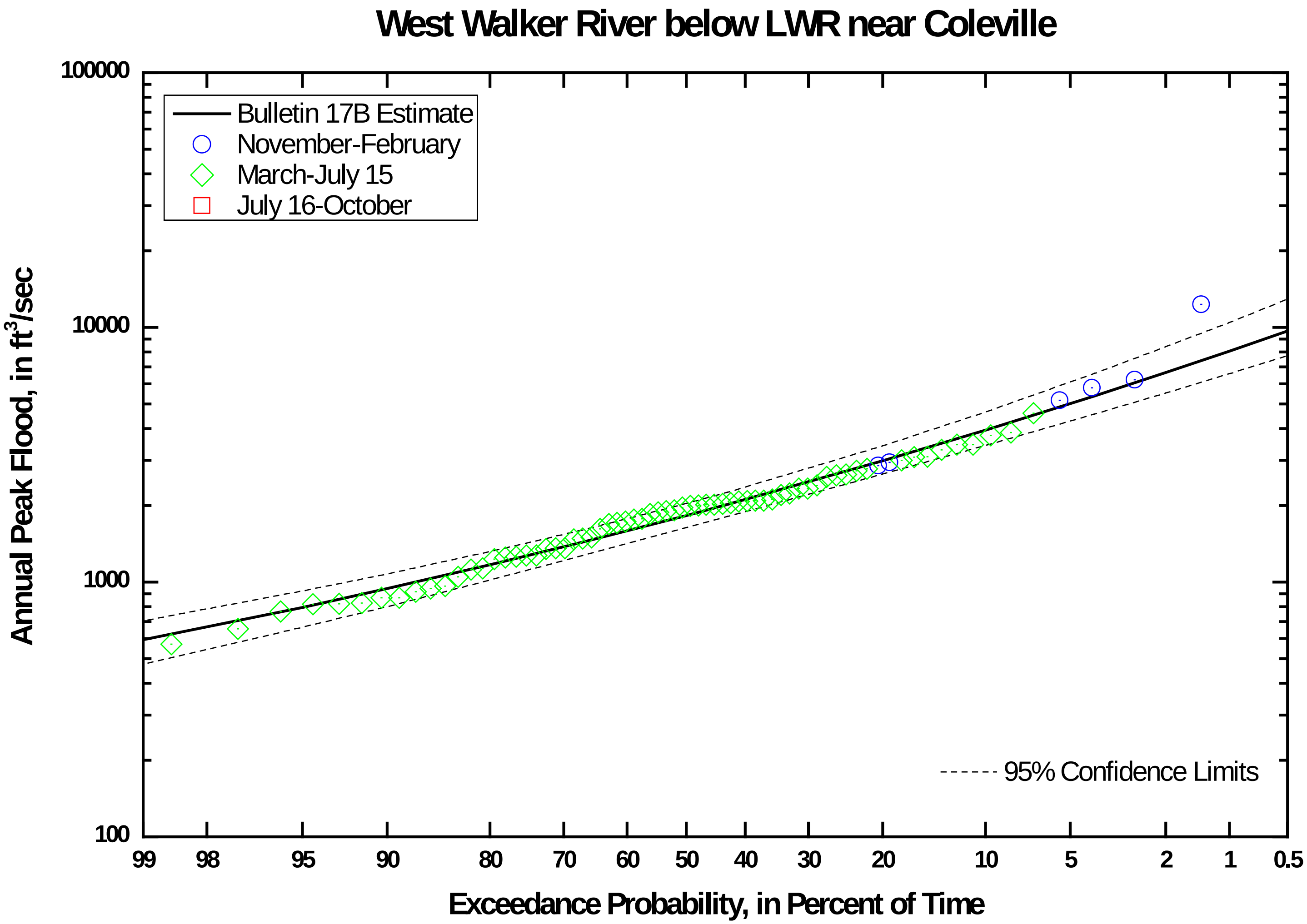


Figure 11. Calculated frequency of annual peak floods at the West Walker River below Little Walker River (LWR) near Coleville gage and observed annual peak floods.

The similarities and contrasts among the six gaging stations' flood frequencies provide a number of worthwhile insights. The comparison of flood frequency at the two Merced River gages is especially interesting. The largest floods recorded at both gages, five at Happy Isles and six at Pohono Bridge, have occurred during the November through February period. The largest November–February floods are almost twice the magnitude of the largest snow melt floods and are produced by unusually warm, very wet storms (Neiman et al. 2008). Over all, the flood frequency relation at Pohono Bridge is substantially steeper than at Happy Isles. That is, flood discharge increases more rapidly at Pohono Bridge than Happy Isles as the exceedance probability decreases. The contributing drainage basin at Happy Isles is 181 mi^2 and increases an additional 77 percent to 321 mi^2 at the Pohono Bridge gage. The ratio of floods equaled or exceeded 50 percent of the time, i.e. the two-year flood, is 1.69. Thus, the increase in the two-year flood is not quite proportional to the additional drainage. In contrast, the ratios of floods equaled or exceeded 1 percent of the time, i.e. the 100-year flood, is 2.36. On a per square mile basis, the drainage area upstream of the Happy Isles gage contributes on average 55.8 ft^3/s / mi^2 to the 100-year flood, whereas the drainage area between the two gages contributes on average 104 ft^3/s / mi^2. A substantial portion of the additional drainage area between the two gages is between 6000 and 9000 feet, within the zone that typically accumulates as significant snowpack, and also, infrequently receives very intense rainfall-- six or more inches in 24 hours, from November to February storms. Above 9000 feet, the portion of the precipitation falling as snow increases rapidly with increasing elevation and the contribution to storm runoff decreases.

Calculated annual peak floods equaled or exceeded from 98 to 0.5 percent of the time for all gaging stations are shown in Table 3. The ratio of the flood equaled or exceeded 1 percent of the time to the flood equaled or exceeded 50 percent of the time, $Q_{0.01}/Q_{0.5}$, is a useful metric with which to compare flood frequency at the selected stations. The $Q_{0.01}/Q_{0.5}$ ratio for all stations is shown in Table 3. In drainage basins where the annual peak flood is predominantly the result of snowmelt and the contribution of rainfall is generally small, such as in the Rocky Mountains, the $Q_{0.01}/Q_{0.5}$ is typically between 2.5 to 3.0 (Andrews 1994). As the rainfall contributions to flood increase, the $Q_{0.01}/Q_{0.5}$ ratio increases significantly. The $Q_{0.01}/Q_{0.5}$ ratio for the Merced River at Happy Isles is 3.74, somewhat larger than is typical of a pure snowmelt regime, and increases to 5.23 at the Merced River at Pohono Bridge. Flood frequencies in other gaged drainage basins throughout the southern Sierra Nevada follow a similar pattern. In general, as the contributing drainage area in the zone of 4000 to 9500 feet increases relative to drainage area above or below that zone, the $Q_{0.01}/Q_{0.5}$ ratio increases, in some instances, quite dramatically. The largest $Q_{0.01}/Q_{0.5}$ ratio observed in this study is 31.4 at the South Fork Kaweah River, followed by 29.0 at the Middle Fork Kaweah River near Potwisha.

Concurrently, with an increase in the $Q_{0.01}/Q_{0.5}$ ratio, there is an increase in the frequency of annual peak floods during the November through February period. Seven of the annual peak floods at the two Merced River gages over a period of 93 years at Happy Isles and 92 years at Pohono Bridge occurred during the November to February period. In comparison, 18 annual peak floods in 34 years of record at the South Fork Kaweah River at Three Rivers gage and 21 annual peak floods in 53 years of record at the Middle Fork Kaweah River have occurred during the November through February period. The relation is as one would expect - intense precipitation associated with storms during the November to February period is rainfall at lower elevation and snowfall at higher elevation. When the storm is relatively warm, the zone of rainfall expands upward to include higher portions of a drainage basin which may or may not have a pre-existing snowpack, which if melted, will augment the storm runoff and further enhance a flood.

Annual peak floods during the July 15 through September period after the snowmelt runoff has subsided are unexpected. Indeed, an annual peak flood has never been recorded between July 15 and September 30 at either of the Merced River gages, the South Fork Kaweah River, or the South Fork Tuolumne River. Annual peak floods during the July 15 to September 30 period have occurred at 7 of the 20 gages. In some drainage basins, annual peak floods within this period have been more frequent than just a rare occurrence. Annual peak floods during that time frame have occurred seven times in 82 years of record in Bear Creek, five times in 44 years of record in the San Joaquin at Millers Crossings and three times in 53 years of record in the Middle Fork Kaweah River.

The evidence needed to evaluate the importance of floods within July 15 to September 30 is quite limited and contradictory. There is no obvious pattern within the gaging stations considered herein. Intense, localized, and brief rainfalls do occur throughout the southern Sierra Nevada during July, August, and September. These storms can cause substantial runoff within the affected area. The occurrence of floods within the July 15 to September 30 period, however, does not seem to follow a simple relation to drainage area. Pitman Creek below Tamarack Creek, the smallest drainage area in this study of 22.9 miles, has recorded no annual peak floods within the summer months in 70 years of record, whereas the San Joaquin River at Miller Crossing, with a drainage area of 249 $mi^{2,}$ recorded five annual maximum floods in 44 years of record. The issue at hand is not limited to solely when the annual peak flood for a given year occurs. Appreciable floods during the summer months when visitation is highest deserve to be considered even if the discharge is not the annual peak flood.

Kendall’s Tau test was used to evaluate trends in the observed sequences of annual peak flood. The results of this analysis are summarized in the last column of Table 3. Statistically significant trends at the 95 percent confidence limit toward larger annual peak floods were identified for three streamflow records, Bear Creek near Lake Thomas A. Edison, Falls Creek near Hetch-Hetchy, and North Fork Kaweah near Three Rivers. The Bear Creek gage is still in operation whilethe other two were discontinued in 1982. Nineteen of the 22 annual peak flood series had a p-value of 0.10 or greater, indicating no trend and, thus, a stationary record.

Table 3. Calculated annual peak floods (ft^3/second) equaled or exceeded from 98 to 0.5 percent of the time for 22 gaging stations within and adjacent to the SIEN national parks. Note that the $Q_{0.01}/Q_{0.5}$ (the ratio of the flood equaled or exceeded 1 percent of the time to the flood equaled or exceeded 50 percent of the time) typically increases in conjunction with rainfall contribution to peak floods. Trend was calculated using the Kendall's Tau test.

	Gaging	Period of	Exceedance Probability														$Q_{0.01}/Q_{0.5}$	Trend
Site	**Station ID**	**Record**	**0.995**	**0.99**	**0.95**	**0.9**	**0.8**	**0.6667**	**0.5**	**0.4292**	**0.2**	**0.1**	**0.04**	**0.02**	**0.01**	**0.005**		
Merced River at Happy Isles Bridge	11264500	1916-2008	906.4	991.5	1288	1497	1812	2188	2695	2948	4181	5352	7057	8501	10100	11880	3.75	+ 0.243
Merced River at Pohono Bridge	11266500	1917-2008	1371	1501	1974	2323	2876	3569	4557	5070	7755	10550	14990	19050	23840	29500	5.23	none
Bear Creek nr. Lake Thomas A Edison	11230500	1922-2008	278	300	377.4	432.3	516.1	617	754.7	823.9	1168	1502	2000	2431	2918	3469	3.87	+ 0.023
Pitman Creek bl. Tamarack Creek	11237500	1928-2008	84.9	98	149.7	191.4	262.8	360.1	511.5	595.2	1081	1654	2672	3696	4998	6644	9.77	+ 0.255
Kern River nr. Kernville	11186000	1912-1980	328.7	391.4	653.2	877.1	1280	1860	2816	3367	6776	11130	19420	28280	40090	55670	14.24	none
W. Walker River nr. Coleville	10296000	1938-2009	536.1	593	795.9	941.9	1168	1444	1825	2019	2991	3948	5388	6643	8065	9677	4.42	+ 0.27
M. F. Tuolumne River nr. Oakland Rec. Camp	11282000	1917-2002	118.6	139.1	219.4	283.1	390.1	532.4	746.8	862.3	1501	2205	3374	4479	5812	7412	7.78	none
S.F. Tuolumne River nr. Oakland Rec. Camp	11281000	1923-2002	77.6	102.5	218.9	327.2	531.2	833.1	1333	1618	3314	5317	8777	12120	16180	21060	12.14	none
M. F. Kaweah River nr. Potwisha Camp	11206500	1950-2003	182.7	208.8	320.8	420.5	608.2	896.6	1412	1729	3970	7391	15280	25330	40900	64740	28.97	none
Marble Fork Kaweah River at Potwisha Camp	11208000	1950-2002	113.9	135.4	224.9	301.6	439.5	638.7	967.3	1157	2336	3848	6750	9866	14040	19570	14.51	none
E. F. Kaweah River nr. Three Rivers	11208730	1953-2008	161.3	182.6	268.8	340.4	467	647	941.5	1111	2171	3555	6288	9316	13490	19210	14.33	+ 0.29

Table 3. Calculated annual peak floods (ft^3/second) equaled or exceeded from 98 to 0.5 percent of the time for 22 gaging stations within and adjacent to the SIEN National Parks (continued).

Site	Gaging Station ID	Period of Record	Exceedance Probability 0.995	0.99	0.95	0.9	0.8	0.6667	0.5	0.4292	0.2	0.1	0.04	0.02	0.01	0.005	$Q_{0.01}/Q_{0.5}$	Trend
N. F. Kings River bl. Meadow Brook	11214000	1922–1981	259.1	287	383.3	450.2	550.5	668.3	824.3	901	1267	1602	2075	2463	2883	3337	3.50	+ 0.67
N. F. Kaweah River at Kaweah	11209500	1911–1981	91.1	120	256.9	386.9	637.5	1020	1676	2061	4472	7513	13120	18860	26180	35400	15.62	+ 0.037
Falls Creek nr. Hetch Hetchy	11275000	1916–1983	411.2	441.8	556	642.5	782.4	962.1	1225	1365	2122	2951	4338	5670	7308	9319	5.97	+ 0.025
Kings River ab. North Fork nr. Trimmer	11213500	1927–1982	2469	2724	3679	4405	5584	7107	9349	10540	17050	24180	36090	47480	61410	78410	6.57	none
Tenaya Creek nr. Yosemite Village	11265000	1912–1958	376.4	401.8	496.1	566.5	679.1	821.8	1027	1135	1708	2318	3314	4249	5379	6742	5.24	+ 0.13
S. F. Kaweah River at Three Rivers	11210100	1956–1997	39.9	51.8	109.4	166.5	282.9	474	832.5	1058	2675	5102	10440	16840	26160	39480	31.42	None
San Joaquin River at Miller Crossing	11226500	1922–1988	1348	1502	2041	2418	2986	3659	4555	4997	7120	9081	11860	14150	16640	19340	3.65	- 0.167
Clavey River nr. Buck Meadows	11283500	1960–1997	161	205.1	408.6	600.7	974	1556	2587	3211	7373	13110	24770	37820	55790	80190	21.57	+ 0.116
N. F. Tuolumne River nr. Long Barn	11284700	1956–1997	--	--	38.9	70.8	141.4	261.5	482.3	615.5	1452	2463	4177	5767	7614	9720	15.79	+ 0.152
S.F. Merced River at Wawona	11267300	1956–1975	480.1	548.7	806.8	1004	1323	1732	2328	2642	4312	6075	8896	11480	14540	18120	6.25	+ 0.129
S.F. Merced River nr. El Portal	11268000	1951–1975	634.8	733.6	1139	1482	2093	2971	4422	5262	10540	17450	31080	46110	66750	94830	15.09	None

5.3. Temporal Distribution and Volume of Snowmelt Runoff

The most noteworthy observed hydrologic trend associated with a gradually warming climate across the southern Sierra Nevada over the past 30-40 years has been a shift in the temporal distribution of snowmelt runoff. Roos (1987) recognized that the portion of the annual runoff from the Sierra Nevada received during the April through July period was decreasing at many gaging stations. The effect appeared to be greatest at lower elevations within the snow accumulation zone. Subsequently, Wahl (1992), Aguado et al. (1992), Dettinger and Cayan (1995), Cayan et al. (2001), Regonda et al. (2005) and Stewart et al. (2004, 2005) have examined and evaluated various temporal aspects of spring snowmelt runoff across the western United States and evaluated the relative significance of causal factors in considerable detail, as described in the review section above. In general, the observed trends have not been statistically significant. However, a regionally consistent pattern (coherence) as well as a well-defined relation with increasing elevation, make the findings much more compelling. Most of these studies have encompassed a broad geographical extent and have demonstrated regional patterns; however, exactly how the results of a given study relate to snowmelt in the southern Sierra Nevada has not always been clear.

Three metrics are used here to describe temporal aspects of the spring snowmelt runoff: 1) the percent of the annual runoff coming during the April through July (AMJJ) period, 2) the date to the runoff center of mass, and 3) the onset of snowmelt runoff. Results for six of the 20 gaging stations selected for this study are discussed in detail. In this study, methodologies consistent with those of previous analyses were applied to an additional five to 10 years of record and expanded to 20 stations (25 stations for the AMJJ/annual runoff ratio). Annual variations in these metrics for six stations over their periods of record are shown in Figures 12-17. These gages were selected based upon the length of record, their contributing drainage area within the SIEN and/or southern Sierra Nevada watershed, and their spatial distribution within and around the SIEN. Figures for the remaining stations are shown in Appendix B. The figures display a trend line that has been fit to the annual time series of each metric by the method of least-squares regression. The regression equation, coefficient of correlation, R^2, and p-value of the trend line slope area are also shown. Results for the trend analyses by the regression method for all stations are summarized in Table 4a. In addition to the regression analysis, the trends in the time series were analyzed by the method of Kendall's Tau (Table 4b). The available periods of record for the 25 gaging stations vary. Only six of the 20 NWIS gages were operated in 2009 and/or still represent unimpaired streamflows. Two gages were discontinued by 1960, while five were established after 1950. When comparing the trends, or lack thereof, amongst the several gages, one must consider the period of record. The periods of record over which the trends were calculated are listed in Table 4a. Some of the stations contain one or more years of missing record. No trend (none) is reported for each analysis where $p>0.30$, i.e. the probability that the apparent trend is due strictly to chance is greater than 30 percent. Where $p<0.30$ for the slope of a regression, the change in percent or number of days along the trendline over the period of record is shown. As shown in Table 4a, the percent of annual runoff received within the April through July period at the Merced River at Happy Isles Bridge has decreased by 6.1 percent from 1916 to 2009. Opposite trends in the AMJJ/annual runoff ratio are evident between the west slope (decreasing) and east slope (increasing) of the southern Sierra Nevada. Thus, trends at the 19 NWIS gaging stations located on the west slope and six (one NWIS and five LADWP) gaging stations located on the east slope will be discussed separately.

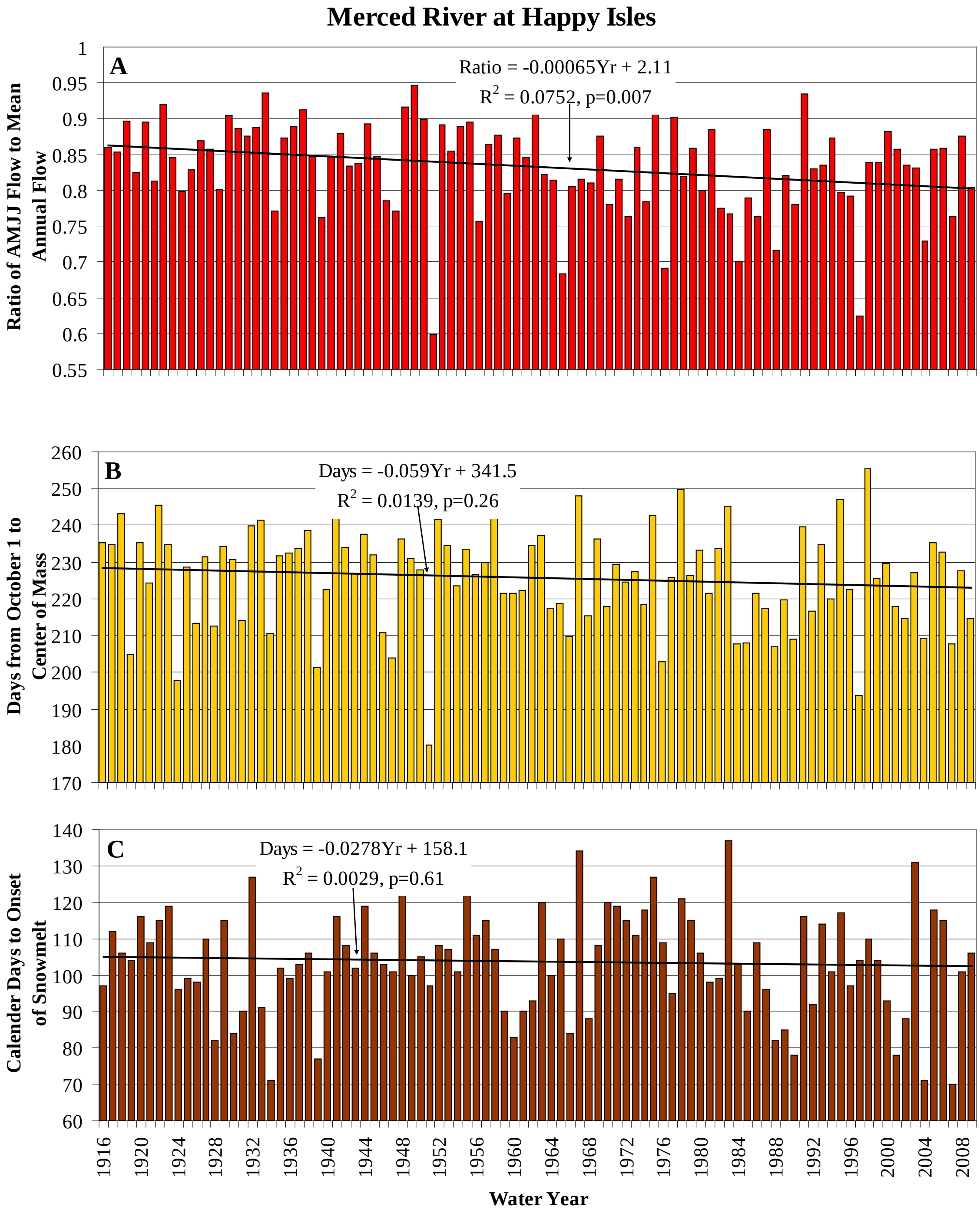


Figure 12. Graphs showing the observed sequence of (a) the ratio of AMJJ/annual runoff, (b) the number of days from Oct 1 to the runoff center of mass, and (c) number of days from Jan 1 to the onset of snowmelt runoff in the Merced River at Happy Isles Bridge.

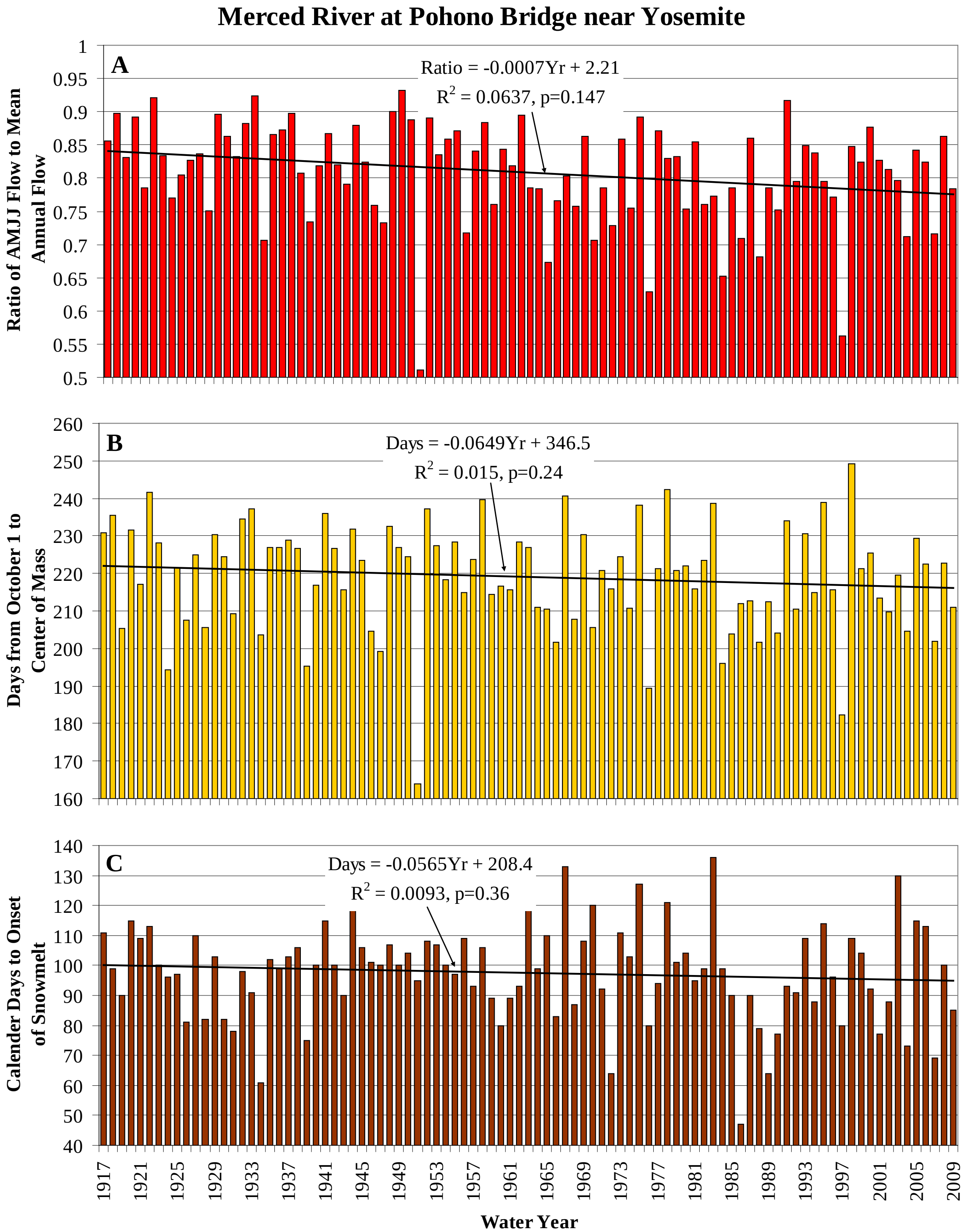


Figure 13. Graphs showing the observed sequence of (a) the ratio of AMJJ/annual runoff, (b) the number of days from Oct 1 to the runoff center of mass, and (c) number of days from Jan 1 to the onset of snowmelt runoff in the Merced River at Pohono Bridge.

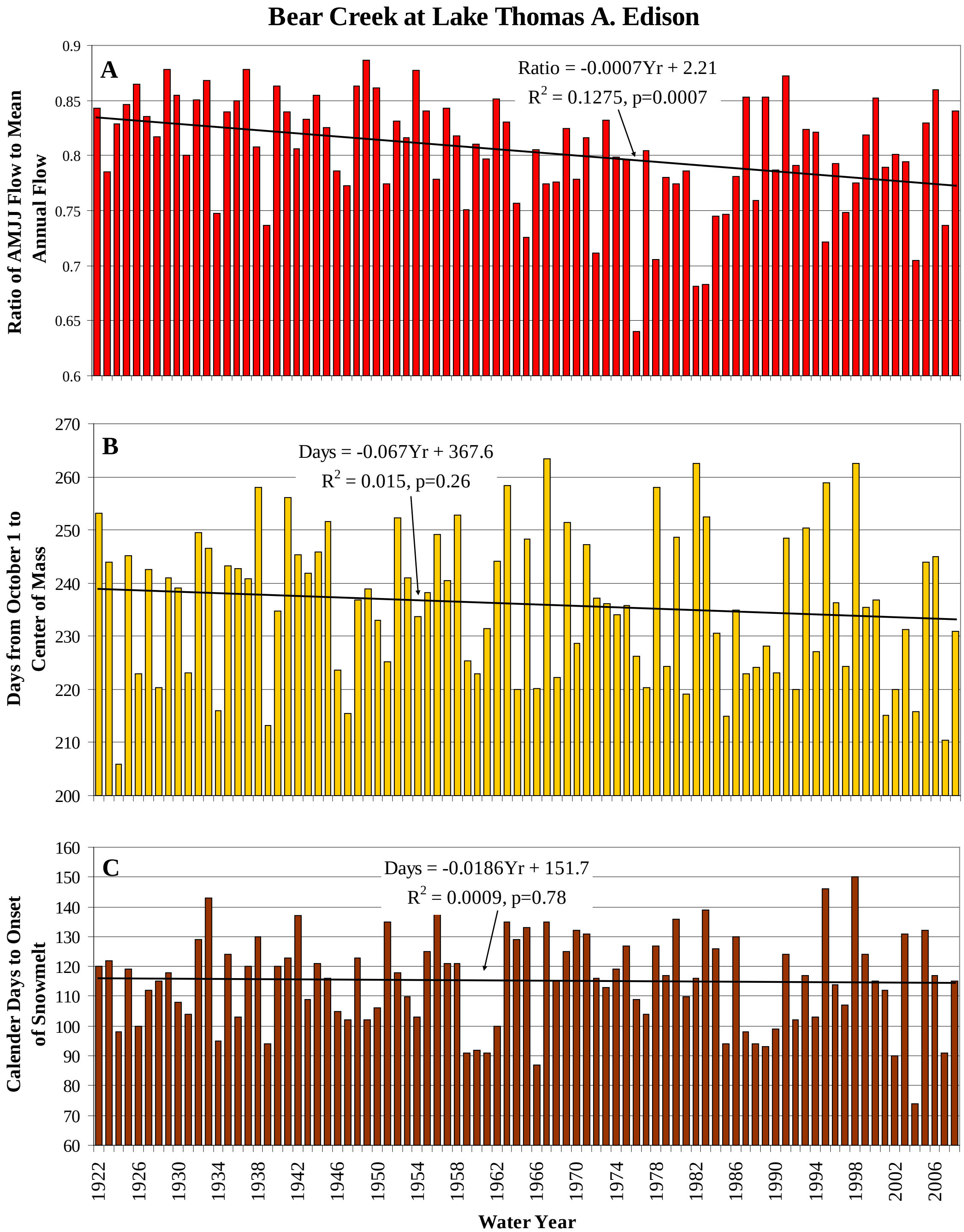


Figure 14. Graphs showing the observed sequence of (a) the ratio of AMJJ/annual runoff, (b) the number of days from Oct 1 to the runoff center of mass, and (c) number of days from Jan 1 to the onset of snowmelt runoff in Bear Creek near Lake Thomas A. Edison.

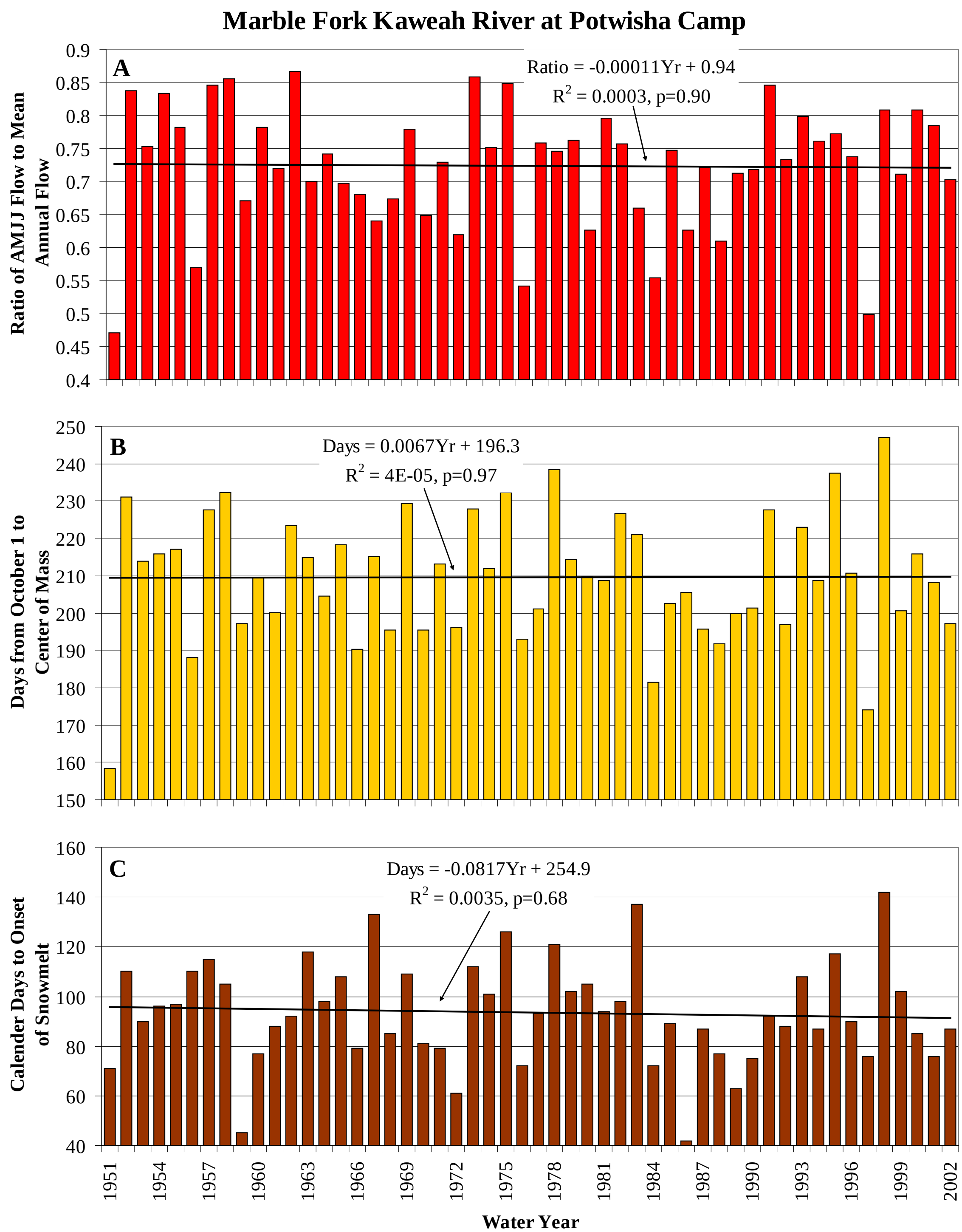


Figure 15. Graphs showing the observed sequence of (a) the ratio of AMJJ/annual runoff, (b) the number of days from Oct 1 to the runoff center of mass, and (c) number of days from Jan 1 to the onset of snowmelt runoff in the Marble Fork Kaweah at Potwisha Camp.

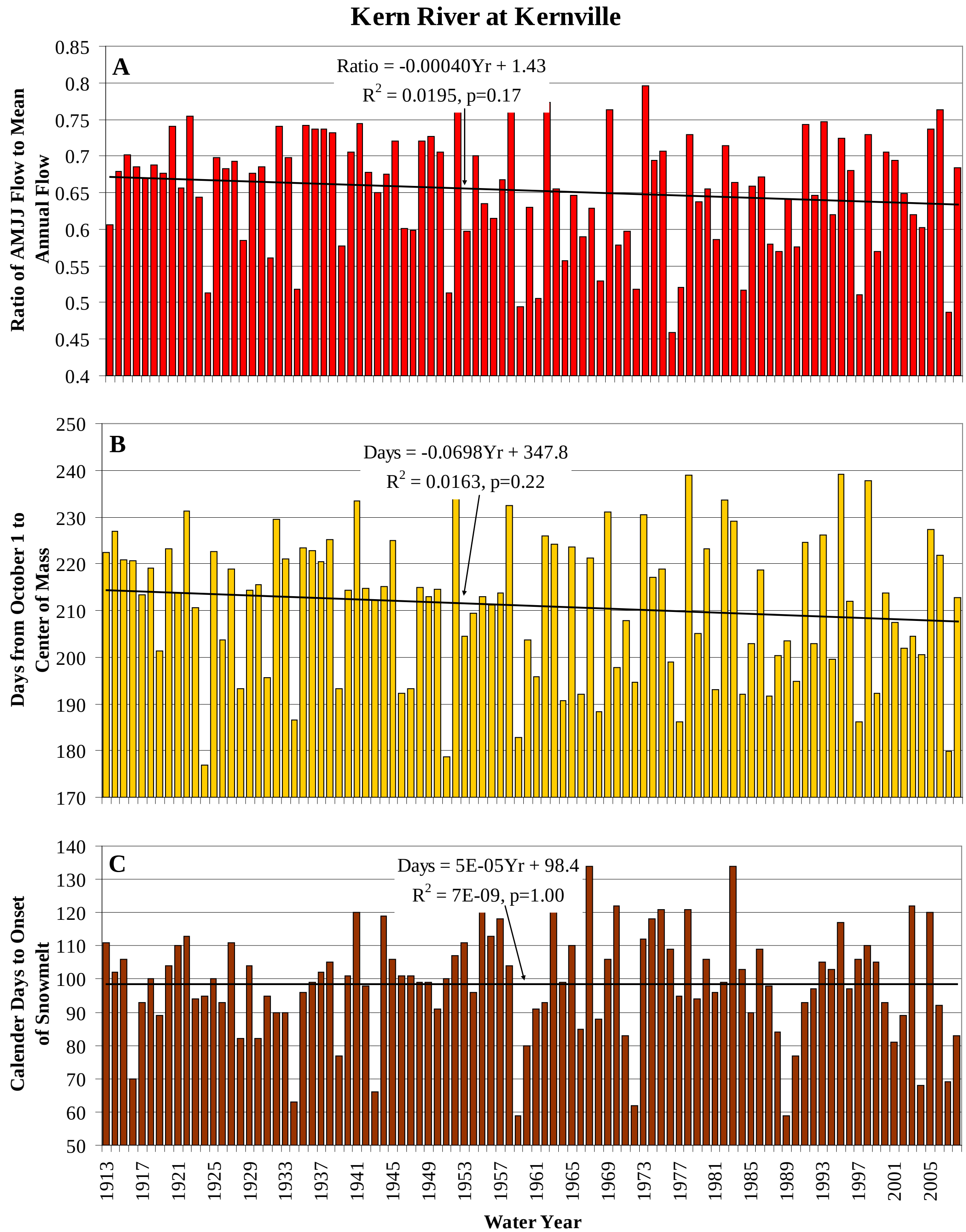


Figure 16. Graphs showing the observed sequence of (a) the ratio of AMJJ/annual runoff, (b) the number of days from Oct 1 to the runoff center of mass, and (c) number of days from Jan 1 to the onset of snowmelt runoff in the Kern River near Kernville.

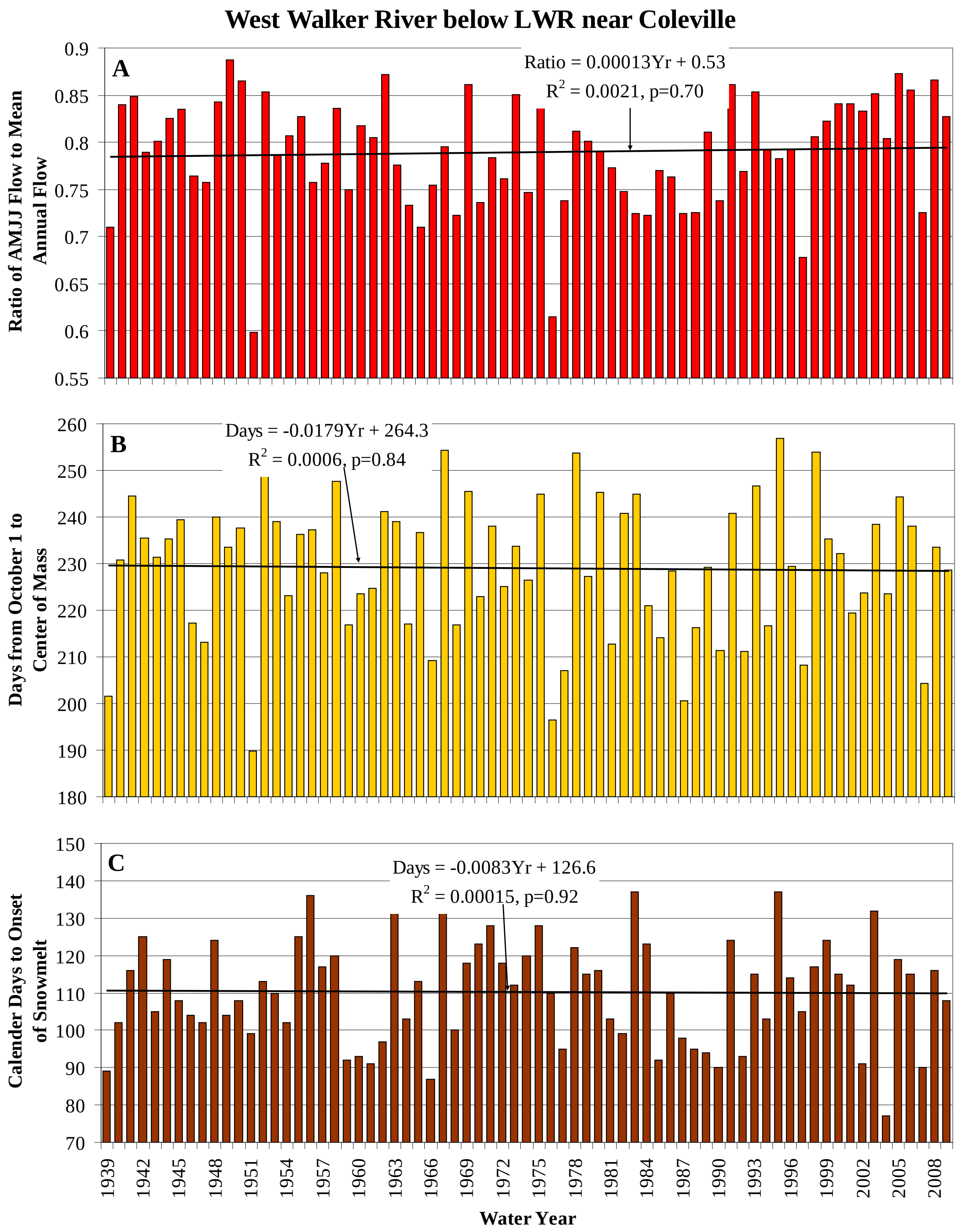


Figure 17. Graphs showing the observed sequence of (a) the ratio of AMJJ/annual runoff, (b) the number of days from Oct 1 to the runoff center of mass, and (c) number of days from Jan 1 to the onset of snowmelt runoff in the West Walker River below LWR (Little Walker River) near Coleville.

Table 4a. Evaluation of trends in relative volume and time of snowmelt runoff by the method of linear regression. AMJJ/MAQ is the ratio of the discharge during the April-July period to the mean annual discharge.

			Trend in Characteristics		
Streamflow station	**Station No.**	**Date of Record**	**AMJJ/MAQ (Percent)** *p*-Value	**Days to Runoff Center of Mass (Days)** *p*-Value	**Days to Onset of Snowmelt (Days)** *p*-Value
Merced River at Happy Isles Bridge near Yosemite	11264500	1916–2009[1]	-6.1 0.007	-5.5 0.26	None 0.61
Merced River at Pohono Bridge near Yosemite	11266500	1917–2009[1]	-6.5 0.147	-6.0 0.24	None 0.6
Bear Creek near Lake Thomas A. Edison	11230500	1922–2009[1]	-6.2 0.007	-5.4 0.26	None 0.78
Pitman Creek below Tamarack Creek	11237500	1929–2008[1]	-10.1 .052	-10.1 0.15	-9.5 0.14
Kern river near Kernville	11186000	1913–2008[1]	-3.8 0.17	-6.7 0.22	None 1.0
West Walker River below Little Walker River near Coleville	10296000	1939–2009[1]	None 0.70	None 0.84	None 0.92
Middle Fork Tuolumne River near Oakland Recreation Camp	11282000	1916–2002	-8.6 0.023	-8.4 0.17	None 0.38
Southern Fork Tuolumne River near Oakland Recreation Camp	11281000	1924–2003	-8.0 0.079	None 0.40	None 0.36
Middle Fork Kaweah river near Potwisha Camp	11206500	1950–2002	-None 0.83	None 0.94	-17.9 0.091
Marble Fork Kaweah River at Potwisha Camp	11208000	1951–2002	None 0.90	None 0.94	None 0.68
East Fork Kaweah River near Three Rivers	11208730	1953–2002	-13.0 0.01	-10.39 0.22	None 0.38
North Fork Kings River below Meadow Brook	11214000	1922–2009	None 0.90	None 0.82	None 0.88
North Fork Kaweah River at Kaweah	11209500	1911–1960	-8.5 0.20	-10.2 0.24	None 0.41
Falls Creek near Hetch Hetchy	11275000	1916–1982	-8.0 0.021	-7.9 0.25	None 0.65
Kings River above North Fork near Trimmer	11213500	1927–1982	-6.1 0.026	None 0.98	7.6 0.27

Table 4a. Evaluation of trends in relative volume and time of snowmelt runoff by the method of linear regression (continued).

			Trend in Characteristics		
Streamflow station	**Station No.**	**Date of Record**	**AMJJ MAQ (Percent)** ***p*-Value**	**Days to Runoff Center of Mass (Days)** ***p*-Value**	**Days to Onset of Snowmelt (Days)** ***p*-Value**
Tenaya Creek near Yosemite Village	11265000	1913–1958	None 0.46	None 0.32	None 0.70
South Fork Kaweah River at Three Rivers	11210100	1959–1990	-10.3 0.16	None 0.35	None 0.84
San Joaquin River Miller Crossing	11226500	1922–1992	-3.6 0.16	None 0.82	None 0.98
Clavey River near Buck Meadows	11283500	1960–1983	None 0.79	None 0.89	None 0.93
North Fork Tuolumne River Long Barn	11284700	1963–1986	-15.4 0.12	0.26	None 0.53
Owens River Tributaries					
Hogback Creek		1959–2009[1]	+16.5 .016		
Sheperds Creek		1959–2009[1]	21.8 .0007		
Symmes Creek		1959–2009[1]	12.8 .0058		
Sawmill Creek		1959–2009[1]	None .62		
Hilton Creek		1959–2009[1]	None .34		

[1]Stream gages operated during 2010 and 2011 water years.

Six of the 19 NWIS gaging stations located on the west slope show a statistically significant decrease in the ratio of AMJJ/annual runoff, from -6.1 to -13.0 percent, based upon regression analyses. (One of the NWIS gages, the West Walker River below Little Walker River near Coleville, is on the east slope.) Three of the six west slope streamgages operated through 2009 (complete records for two gages were only available through 2008) have a statistically significant trend towards decreasing AMJJ/annual runoff ratio. Furthermore, two of the five west slope streams where the gaging stations have been discontinued since 2000 have a statistically significant trend towards decreasing AMJJ/annual runoff ratio. Using the method of Kendall's Tau, a statistically significant decreasing trend of the AMJJ/annual runoff ratio was indicated at 10 of the 19 west slope gaging stations (Table 4b). As expected, the analysis of trend using Kendall's Tau provides more consistent results. For example, although similar decreases in the AMJJ/annual runoff ratio and days to runoff center of mass are indicated by the regression trend line for both of the Merced River gages, only the trend in the AMJJ/annual runoff ratio at the Happy Isles Bridge gage appears to be significant. Statistically significant trends in both the AMJJ/annual runoff ratio and days to the runoff center of mass are indicated by Kendall's Tau at both the Happy Isles Bridge and Pohona Bridge gages. Similarly, regression analysis indicates rather disparate trends for the South Fork and Middle Fork Tuolumne River gages. Using regression analysis, only the AMJJ/annual runoff ratio recorded at the Middle Fork Tuolumne gage is statistically significant, whereas the method of Kendall's Tau indicates statistically significant trends in the AMJJ/annual runoff ratio at both gages and in the Days to the Runoff Center of Mass at the Middle Fork Tuolumne gage.

Calculated trends and their significance towards a decrease in the AMJJ/annual runoff ratio as well as a decrease in the days to center of mass and days to onset for gaging stations located on the west slope of the Sierra Nevada are consistent with previously published results. No increasing trends in the AMJJ/annual runoff ratio, statistically significant or not, were found in west slope streams.

The trends summarized in Tables 4 a-b indicate that the relative portion of the annual discharge received as snowmelt runoff, i.e. AMJJ period, is generally increasing on the east slope, in contrast to the decreases evident on the west slope. For the six east slope gaging stations listed in Tables 4a-b, the ratio of AMJJ/Annual runoff is increasing in five of the six streams, three of which are statistically significant, and one shows no trend. In contrast to the west slope streams, no decreasing trends in the AMJJ/annual runoff ratio, statistically significant or not, were found in east slope streams. Increasing temperature does not appear likely to provide a simple explanation for this difference. Both annual and AMJJ runoff appear to be increasing in east slope streams with the AMJJ runoff showing the most appreciable increase.

Table 4b. Evaluation of trends in relative volume and time of snowmelt runoff by the method of Kendall's Tau.

			Trend in Characteristics		
Streamflow station	Station No.	Date of Record	AMJJ MAQ (Percent) *p*-Value	Days to Runoff Center of Mass (Days) *p*-Value	Days to Onset of Snowmelt (Days) *p*-Value
Merced River at Happy Isles Bridge near Yosemite	11264500	1916–2009[1]	- .005	- .036	None
Merced River at Pohono Bridge near Yosemite	11266500	1917–2009[1]	- .004	- .042	None
Bear Creek near Lake Thomas A. Edison	11230500	1922–2009[1]	- .003	- .070	None
Pitman Creek below Tamarack Creek	11237500	1929–2008[1]	- .002	- .002	- .046
Kern river near Kernville	11186000	1913–2008[1]	- .098	- .075	None
West Walker River below Little Walker River near Coleville	10296000	1939–2009[1]	None .350	None .360	None .458
Middle Fork Tuolumne River near Oakland Recreation Camp	11282000	1916–2002	- .002	- .035	- .053
Southern Fork Tuolumne River near Oakland Recreation Camp	11281000	1924–2003	- .028	- .145	- .083
Middle Fork Kaweah river near Potwisha Camp	11206500	1950-2002	- .349	- .262	- .041
Marble Fork Kaweah River at Potwisha Camp	11208000	1951-2002	None	None	- .185
East Fork Kaweah River near Three Rivers	11208730	1953-2002	- .006	- .073	None
North Fork Kings River below Meadow Brook	11214000	1922-2009	None	None	None
North Fork Kaweah River at Kaweah	11209500	1911-1960	- .091	- .205	- .288

Table 4b. Evaluation of trends in relative volume and time of snowmelt runoff by the method of Kendall's Tau (continued).

			Trend in Characteristics		
Streamflow station	**Station No.**	**Date of Record**	**AMJJ MAQ (Percent) *p*-Value**	**Days to Runoff Center of Mass (Days) *p*-Value**	**Days to Onset of Snowmelt (Days) *p*-Value**
Falls Creek near Hetch Hetchy	11275000	1916-1982	-- .015	- .067	None
Kings River above North Fork near Trimmer	11213500	1927-1982	- .010	None	+ .171
Tenaya Creek near Yosemite Village	11265000	1913-1958	None	- .143	+ .241
South Fork Kaweah River at Three Rivers	11210100	1959-1990	- .077	- .185	- .270
San Joaquin River Miller Crossing	11226500	1922-1992	- .039	None	None
Clavey River near Buck Meadows	11283500	1960-1983	None	None	None
North Fork Tuolumne River Long Barn	11284700	1963-1986	- .120	- .221	- .256
Owens River Tributaries					
Hogback Creed		1959-2009[1]	+ .0008		
Sheperds Creek		1959-2009[1]	+ .00001		
Symmes Creek		1959-2009[1]	+ .0019		
Sawmill Creek		1959-2009[1]	+ .789		
Hilton Creek		1959-2009[1]	+ .203		

[1]Stream gages operated during 2010 water years.

5.4. Three-, 7-, 10-, and 14-Day High Flows: Frequency and Trends

The 3-, 7-, 10-, and 14-day high flows are associated principally with the spring snowmelt runoff, except for some of the lower elevation drainage basins. As described above in the flood frequency section, floods which occur outside of the spring snowmelt runoff period, April through early July, are a result of intense rainfall with and without an existing snowpack. These floods are of relatively short duration and the elevated discharge typically recedes quickly unless the rainfall is sustained. Accordingly, it is expected that the 7-, 10-, and 14-day high flow at a given gage will occur during the spring snowmelt runoff, while the instantaneous peak flood for the year may occur outside of the spring runoff period. For these reasons, it is to be expected that the calculated trends in high flow magnitude and timing are quite similar to the trends in timing of snowmelt onset and center of mass, described in the previous section. The magnitude of annual 14-day high flow equaled or exceeded between 98 and 2 percent of the time together with the water year day on which the 14-day high flow occurred for six of the stations are shown in Figures 18 - 23. The magnitude of annual 3-, 7-, 10- and 14-day high flows equaled or exceeded between 98 and 2 percent of the time at all 20 gaging stations, which have a long-term record of unimpaired flows, are shown in Appendix C. Evaluation of trends in the magnitude and timing of the 3-, 7-, 10-, and 14-day high flows using the method of Kendall's Tau is shown in Table 5. In keeping with the practice applied elsewhere in this report, time series for which $p>0.30$ were judged to have no trend. Positive (increasing) trends in the magnitude of the 3-, 7-, 10-, and 14-day high flow, none of which were statistically significant, were found at about 30 percent of the gages studied. It must be noted that applying the $p<0.03$ to identify positive and negative trends, one would expect to find six positive or negative trends solely by chance among the 20 gaging stations. Thus, evidence for trends in the magnitude of the 3-, 7-, 10-, and 14-day high flows is quite weak.

This result is consistent with the analysis showing that only three of the 20 NWIS gages and only one of the six currently operated NWIS gages have a statistically significant trend toward increasing annual peak floods. No discernible trends in the magnitude of annual peak floods and mean annual runoff were seen. There is evidence of a trend, statistically insignificant, but regionally coherent across the southern Sierra Nevada for the 14-day high flow moving to earlier in the year.

5.5. Three-, 7- and 14-Day Winter and Summer Low-Flows

Three, 7- and 14-day summer and winter low flows were calculated for each of the 20 NWIS gaging stations. The calculated magnitudes of the 3-, 7-, and 14-day winter low flows equaled or exceeded from 98 to 2 percent of the time at all 20 gaging stations are shown in Appendix C. The analysis focused on seasonal rather than annual low flow in order to explore two specific aspects, one ecological and the other hydrometeorological, of the current hydrologic regime. Given the shift to an earlier snowmelt and the increasing portion of the cold season precipitation falling as rain (Knowles et al. 2006), one could reasonably expect that winter low flows would be increasing. Summer low flows coincide with higher water temperatures and reduced dissolved oxygen which is a time of elevated stress for many aquatic organisms. The shift to an earlier snowmelt runoff, even if the runoff volume is unchanged, leads to a longer recession and decreased summer low flow assuming that there is no appreciable increase in summer precipitation. Annual minimum 3-, 7-, 14-day flows, in fact, frequently occur in October and November throughout the southern Sierra Nevada. That is, streamflow continues to decrease until the first appreciable rain and/or snowfall. Thus, the analysis pursued herein may not capture the annual extreme in some years, though focusing only on the annual extreme would obscure significant aspects of a gradually warming climate over the southern Sierra Nevada.

The 3-, 7-, and 14-day winter low flows do not differ by very much from each other in a given year. The discussion will focus on the 7-day low-flow, which is the most commonly referenced low-flow statistic. As described above, the analysis of winter low flows initially considered the January 1 to March 31 period. After completing the analysis of about half of the gaging station records, it was observed that the winter low flow never occurred in March and, furthermore, streamflows in December were frequently less than at any time during the January through March period. Accordingly, the "winter" low flows were calculated over the December 1 through February 28(29) period.

The magnitude of the 7-day winter low flow equaled or exceeded from 98 to 2 percent of the time together with the day on which the flows occurred annually are shown for a subset of gages in Figures 24-29. A trend line has been fit by regression to the sequence of annual 7-day winter low flows recorded at each gage. The p-value for the slope of the trend line is shown in the respective figures. Identification and evaluation of trends in the magnitude and timing of the 3-, 7-, and 14-day winter low flow using the method of Kendall's Tau are shown in Table 5. In keeping with the practice applied elsewhere in the report, times series for which $p>0.30$ were judged to have no trend. The most consistently significant trends in streamflow magnitude among the 20 gaging stations studied were increasing winter low flows.

Table 5. Evaluation of trends in selected hydrologic characteristics representing the temporal distribution and magnitude of streamflows by the method of Kendall's Tau. Positive trends are identified by (+) and shown in green. Negative trends are identified by (-) and shown in orange. The significance of trends is expressed by the p-value, e.g. p = 0.05 indicates that a trend is significant at the 95 percent level.

		Low Flow Statistics								High Flow Statistics						
		Winter				Summer								Calendar Days to		
		3-Day	7-Day	14-Day	Calendar Days to 7-Day	3-Day	7-Day	14-Day	Calendar Days to 7-Day	3-Day	7-Day	10-Day	14-Day	3-Day	14-Day	Annual Mean Discharge
Merced River at Happy Isles Bridge near Yosemite	11264500	+ **.015**	+ **.015**	+ **.014**	None	+ .255	+ .286	None	None	None	None	None	None	- **.038**	- **.035**	None
Merced River at Pohono Bridge near Yosemite	11266500	+ **.037**	+ **.036**	+ **.047**	None	None	None	None	None	None	None	None	None	None	- .214	None
Bear Creek near Lake Thomas A. Edison	11230500	+ .071	+ **.043**	+ **.032**	+ **.009**	+ **.093**	+ .117	+ .106	None	+ .132	+ .125	+ .135	+ .143	- .138	- .085	+ .207
Pitman Creek below Tamarack Creek	11237500	+ **.048**	+ **.0148**	+ **.0041**	+ **.0072**	+ .0610	+ .062	+ 0.567	+ **.0037**	None	None	None	None	None	- 0.183	+ .234
Kern river near Kernville	11186000	+ .168	+ .181	+ .149	None	- .265	- .240	- .256	- .153	None	None	None	None	- .0128	- **.033**	None
West Walker River below Little Walker River near Coleville	10296000	None	None	None	None	- .159	- .177	- .168	- .236	+ .124	+ .092	+ .09	+ .091	- **.002**	- **.024**	None
Middle Fork Tuolumne River near Oakland Recreation Camp	11282000	+ .110	+ .110	+ .114	+ .073	+ .070	+ .070	+ .055	None	None	None	None	None	- .235	None	None
South Fork Tuolumne River near Oakland Recreation Camp	11281000	+ .162	+ .131	+ .118	+ .134	None	None	None	- **.047**	None	None	None	None	None	None	None
Middle Fork Kaweah river near Potwisha Camp	11206500	None	None	None	+ .285	None	None	None	+ **.049**	None	None	None	None	+ .262	None	None
Marble Fork Kaweah River at Potwisha Camp	11208000	None	None	None	None	None	None	None	None	None	None	None	None	+ .264	None	None
East Fork Kaweah River near Three Rivers	11208730	+ **<.0001**	+ **<.0001**	+ **<.0001**	None	+ **<.0001**	+ **<.0001**	+ **<.0001**	None	+ .233	+ .205	+ .171	+ .140	None	+ .179	+ .121
North Fork Kings River below Meadow Brook	11214000	None	None	None	- .275	- .087	- .079	- .078	- .083	+ .060	+ .088	+ .069	+ .054	None	None	None
North Fork Kaweah River at Kaweah	11209500	+ **.034**	+ **.039**	+ **.041**	+ .231	+ **.004**	+ **.003**	+ **.004**	+ .107	None	None	None	None	- .107	None	None
Falls Creek near Hetch Hetchy	11275000	+ **.006**	+ **.007**	+ **.006**	+ **.025**	None	None	+ .286	None	+ .210	None	None	None	- **.021**	- .244	None
Kings River above North Fork near Trimmer	11213500	+ .093	+ .056	+ **.039**	+ .175	+ .112	+ .101	+ .070	None	None	None	None	None	None	+ .280	None
Tenaya Creek near Yosemite Village	11265000	None	None	- .275	- .268	- **.022**	- **.004**	- **.003**	+ .173	None	None	None	None	- .122	- .269	None
South Fork Kaweah River at Three Rivers	11210100	+ .213	+ .223	+ .176	+ .269	None	None	None	None	None	None	None	None	- **.28**	None	None
San Joaquin River Miller Crossing	11226500	+ .193	+ .190	+ .164	+ .087	None	None	None	None	None	None	None	None	None	None	None
Clavey River near Buck Meadows	11283500	+ .136	+ .110	+ .088	- .199	+ .088	+ .092	+ .076	- .251	+ .153	+ .130	+ .110	+ .084	+ **.028**	+ **.056**	+ **.026**
North Fork Tuolumne River Long Barn	11284700	+ .159	+ .109	+ .130	+ .286	None	None	None	- **.050**	+ .207	+ .207	+ .153	+ .084	None	None	+ .101

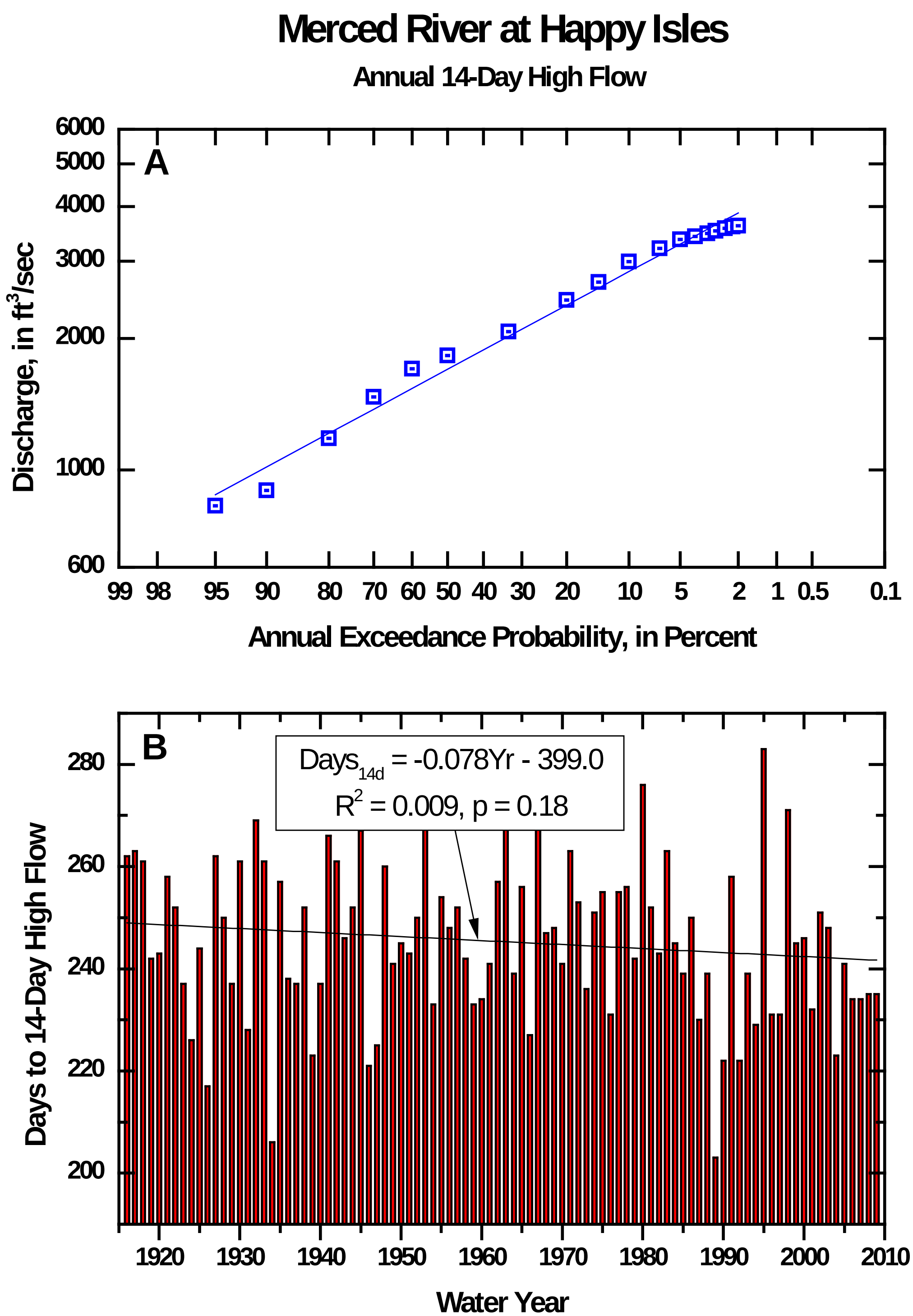


Figure 18. Magnitude of (a) annual 14-day high flow equaled or exceeded from 98 to 2 percent of the time, and (b) water year day the 14-day high flow occurred at the Merced River at Happy Isles Bridge.

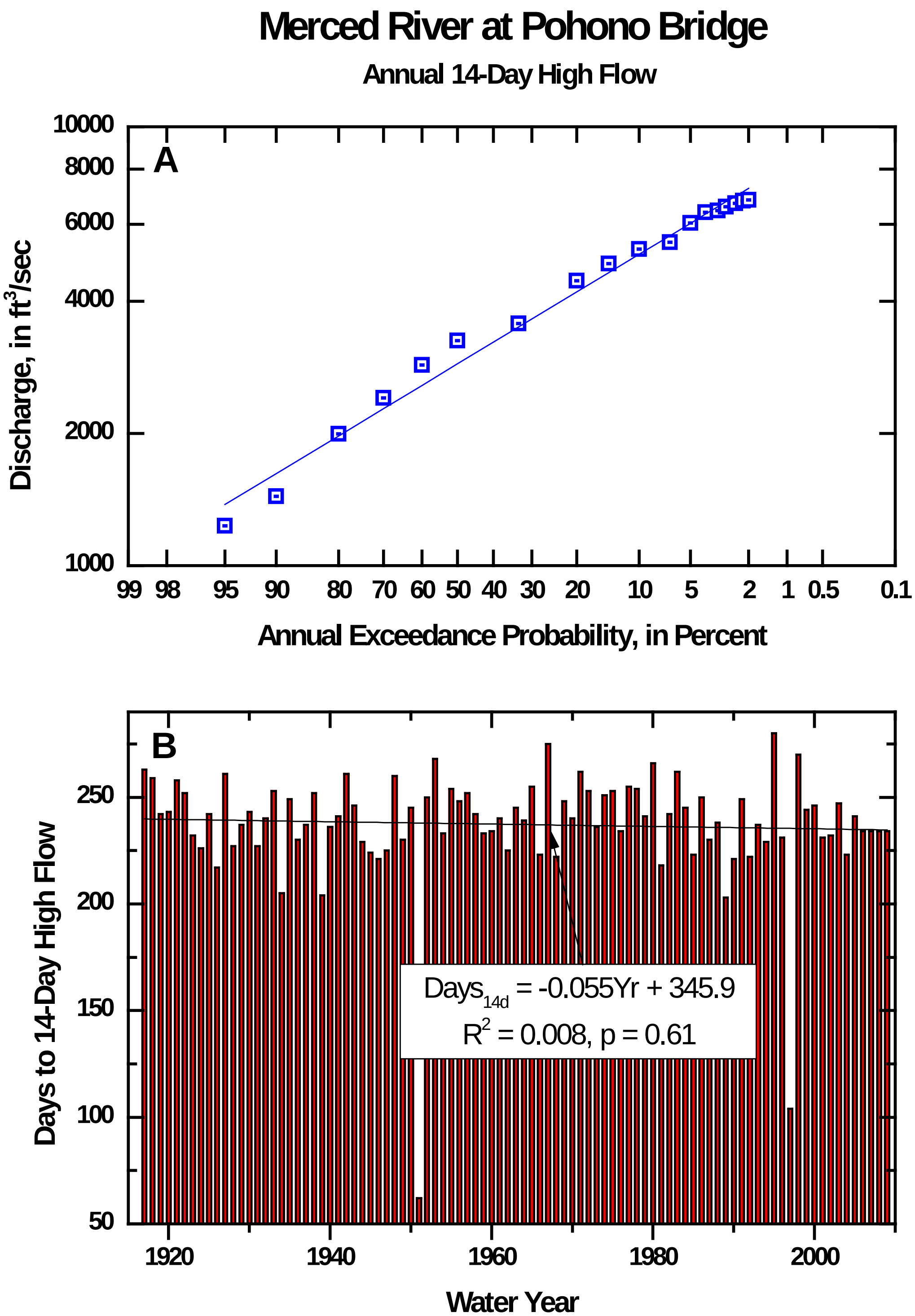


Figure 19. Magnitude of (a) annual 14-Day high flow equaled or exceeded from 98 to 2 percent of the time, and (b) water year day the 14-Day high flow occurred at the Merced River at Pohono Bridge.

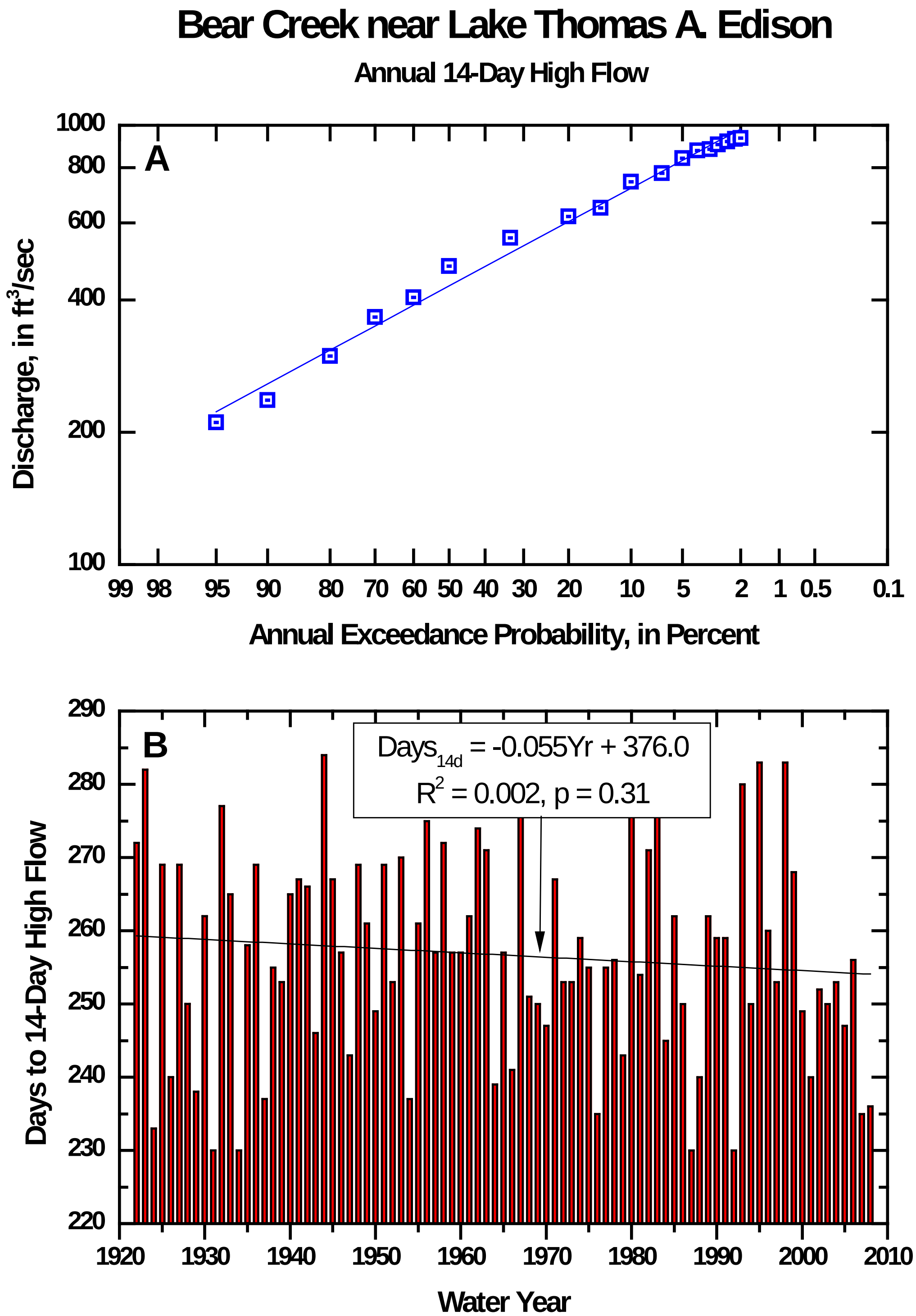


Figure 20. Magnitude of (a) annual 14-day high flow equaled or exceeded from 98 to 2 percent of the time, and (b) water year day the 14-day high flow occurred at Bear Creek near Lake Thomas A. Edison.

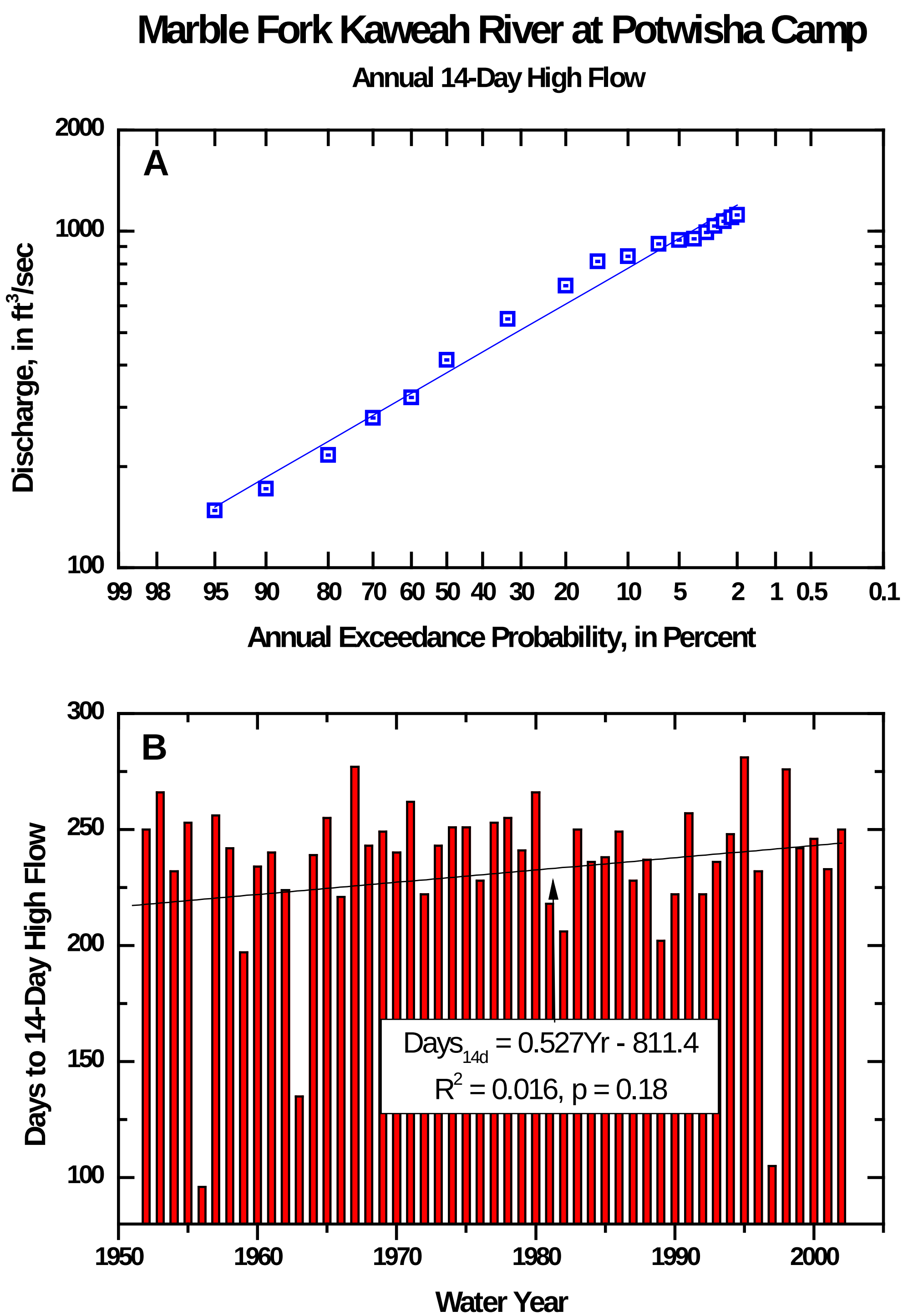


Figure 21. Magnitude of (a) annual 14-day high flow equaled or exceeded from 98 to 2 percent of the time, and (b) water year day the 14-day high flow occurred at the Marble Fork Kaweah River at Potwisha Camp.

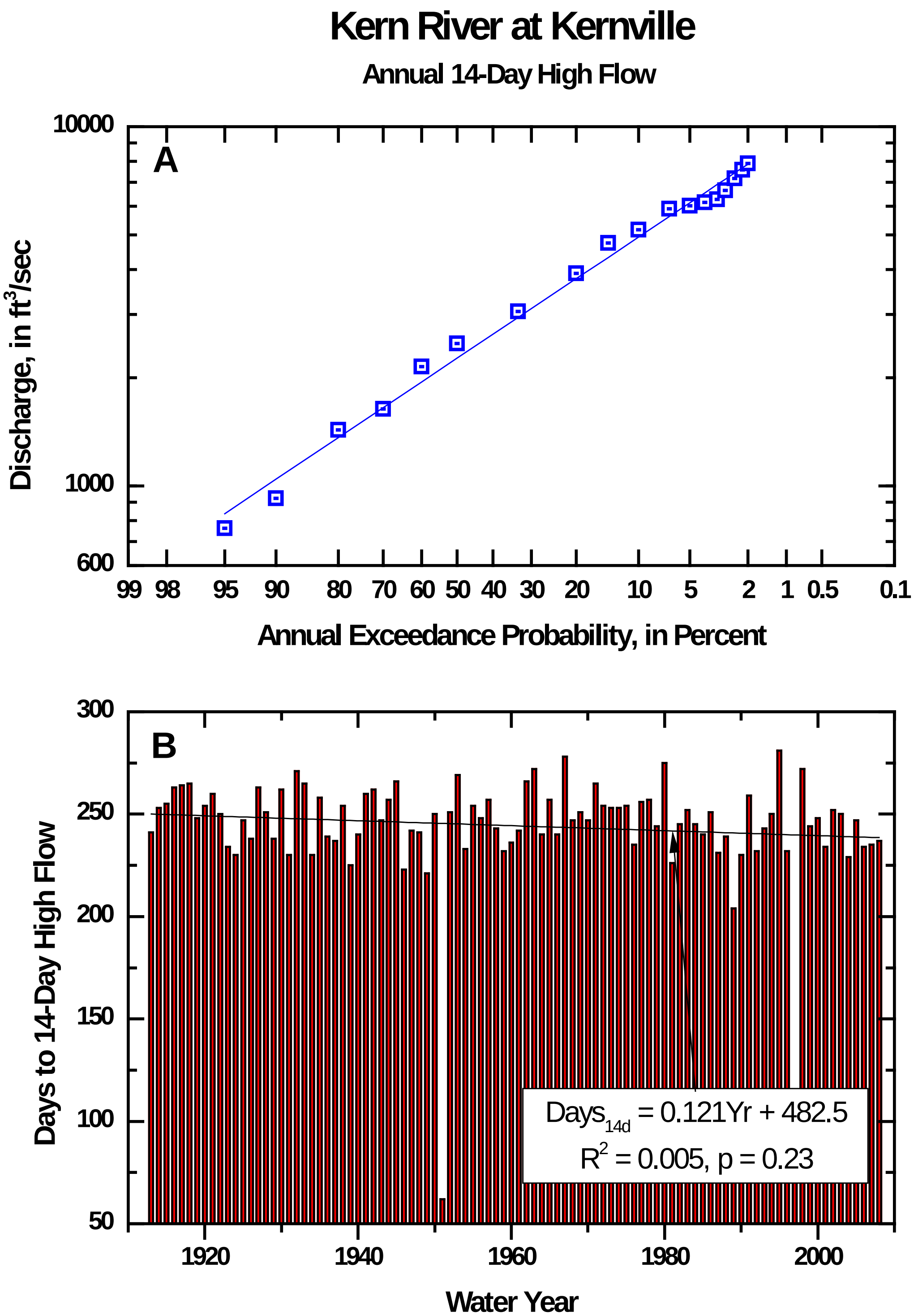


Figure 22. Magnitude of (a) annual 14-day high flow equaled or exceeded from 98 to 2 percent of the time, and (b) water year day the 14-day high flow occurred at the Kern River near Kernville.

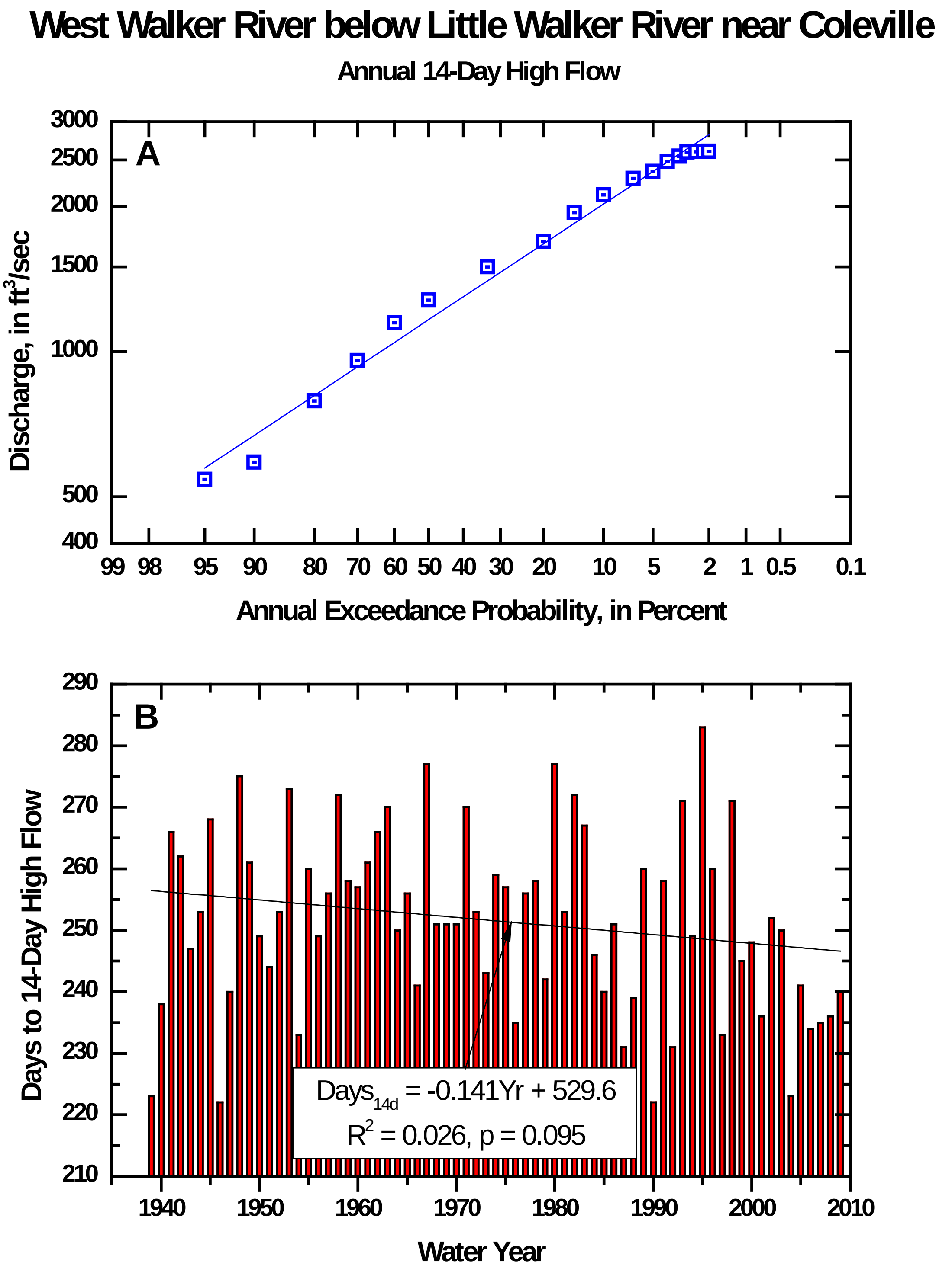


Figure 23. Magnitude of (a) annual 14-day high flow equaled or exceeded from 98 to 2 percent of the time, and (b) water year day the 14-day high flow occurred at the West Walker River below LWR near Coleville.

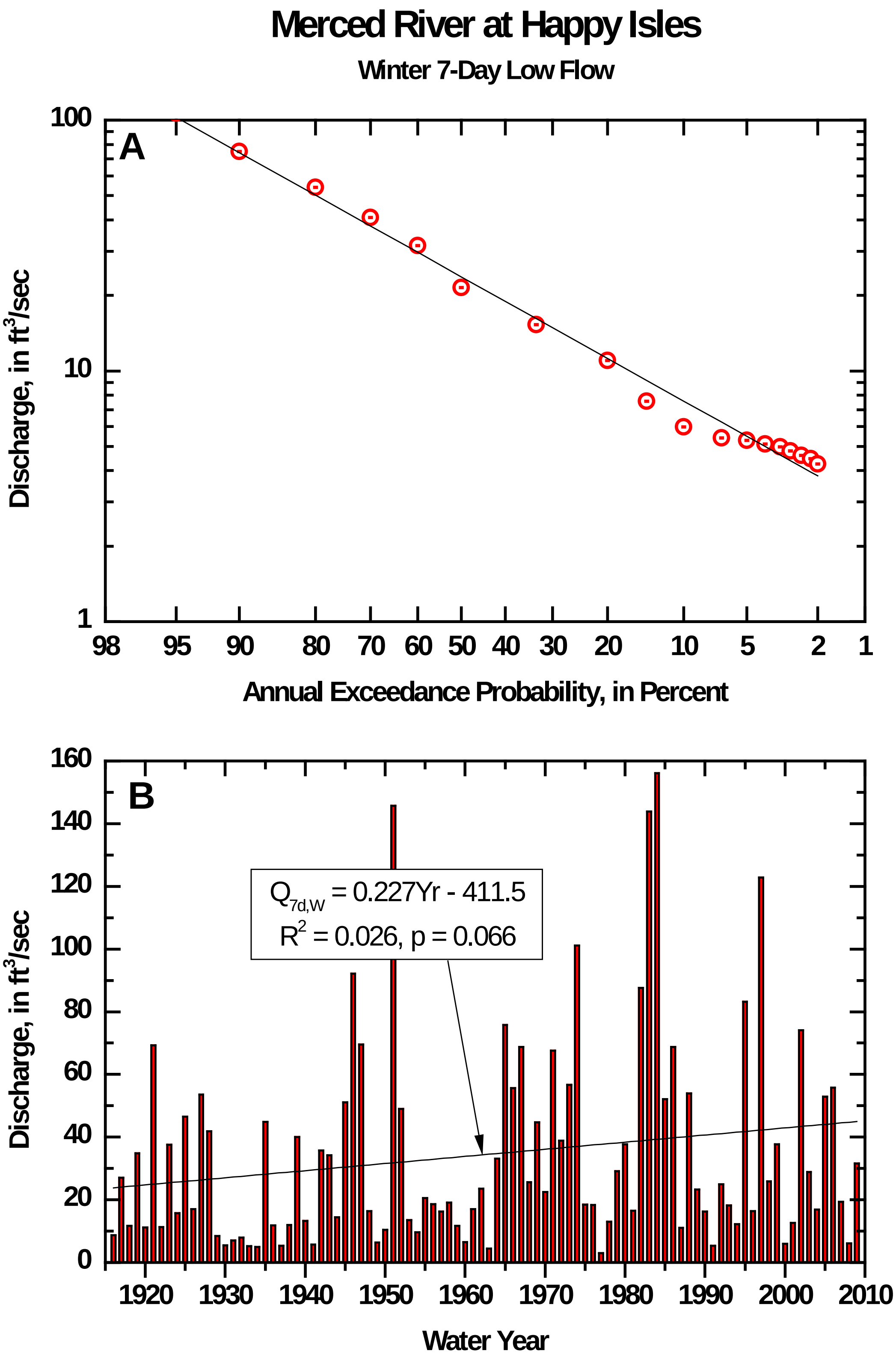


Figure 24. Magnitude of the (a) 7-day Winter low flows equaled or exceeded from 98 to 2 percent of the time, and sequence of (b) annual 7-day winter low flows for the period of record with fitted regression trend line at the Merced River at Happy Isles Bridge.

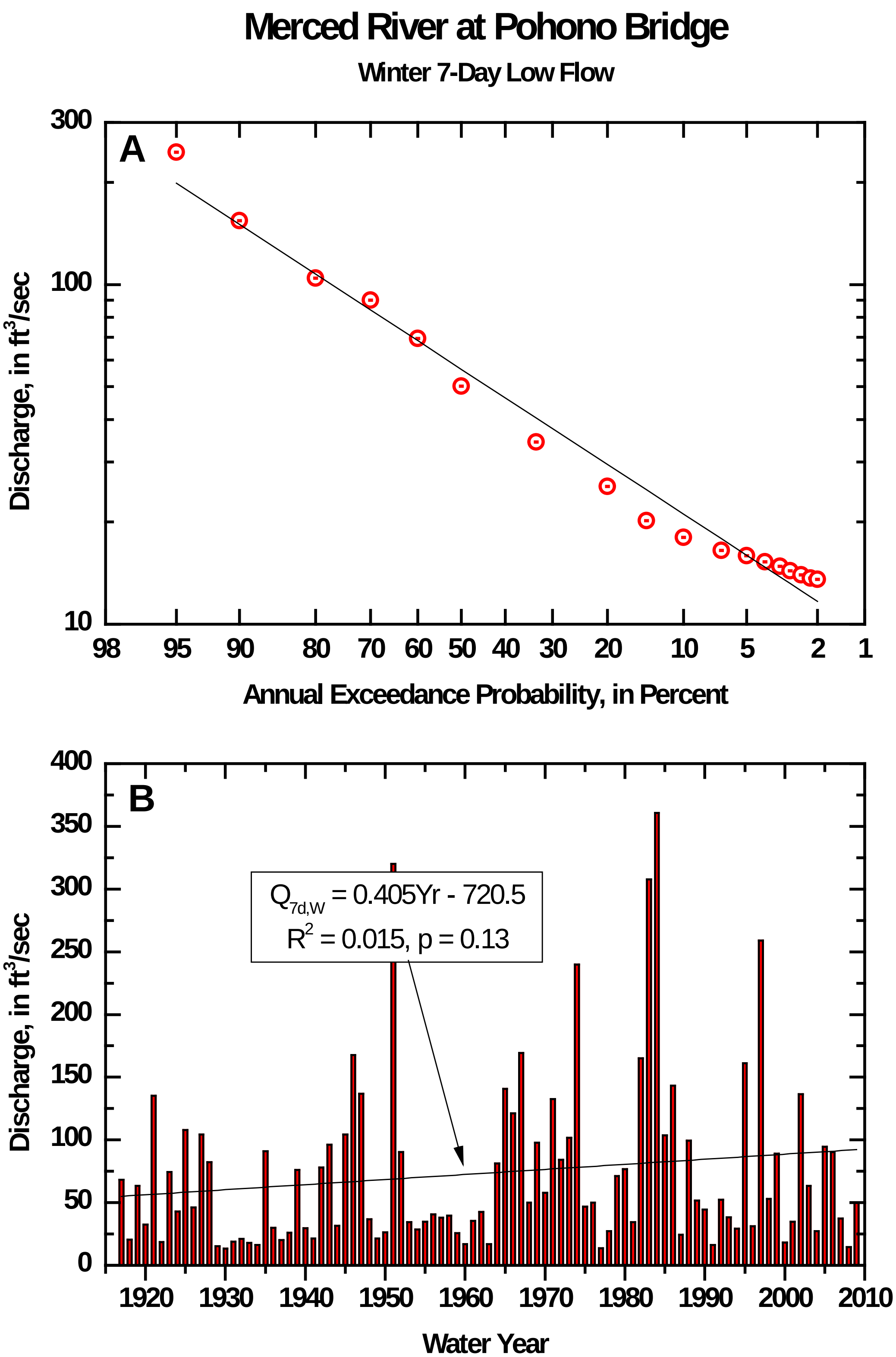


Figure 25. Magnitude of the (a) 7-day Winter low flows equaled or exceeded from 98 to 2 percent of the time, and (b) sequence of annual 7-day winter low flows for the period of record with fitted regression trend line at the Merced River at Pohono Bridge.

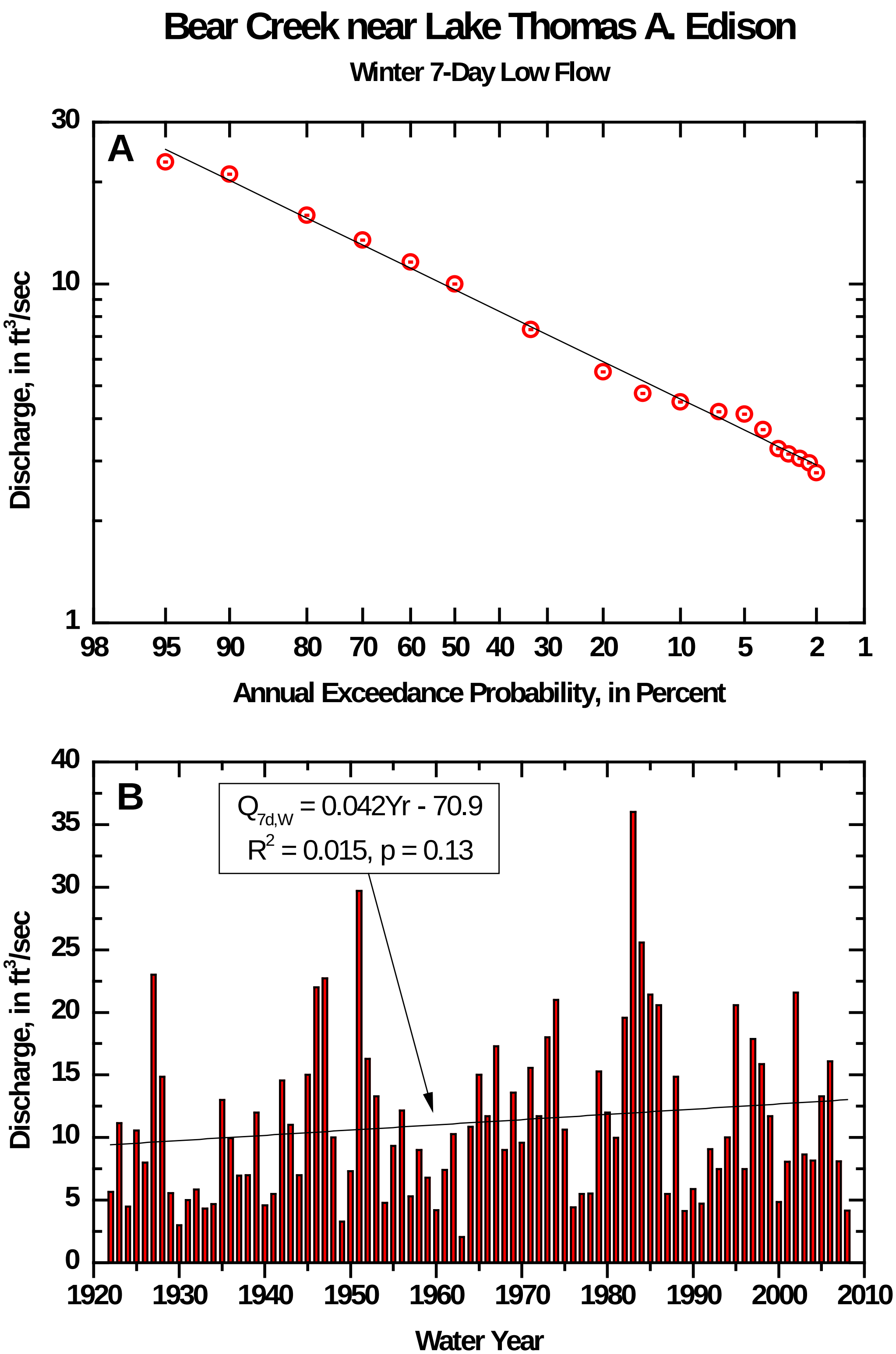


Figure 26. Magnitude of the (a) 7-day Winter low flows equaled or exceeded from 98 to 2 percent of the time, and (b) sequences of annual 7-day winter low flows for the period of record with fitted regression trend line at Bear Creek near Lake Thomas A. Edison.

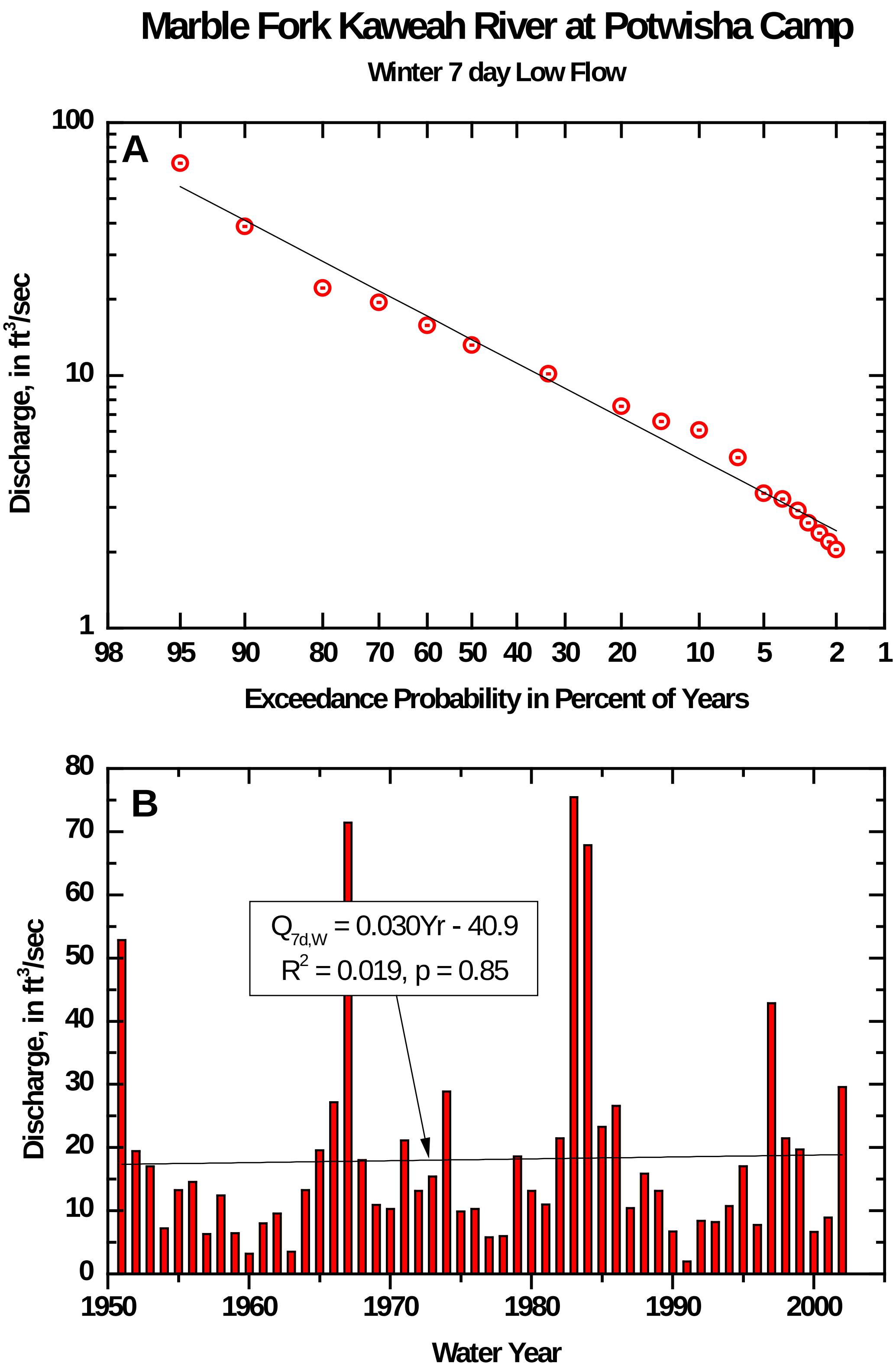


Figure 27. Magnitude of the (a) 7-day Winter low flows equaled or exceeded from 98 to 2 percent of the time, and (b) sequence of annual 7-day winter low flows for the period of record with fitted regression trend line at the Marble Fork Kaweah at Potwisha Camp.

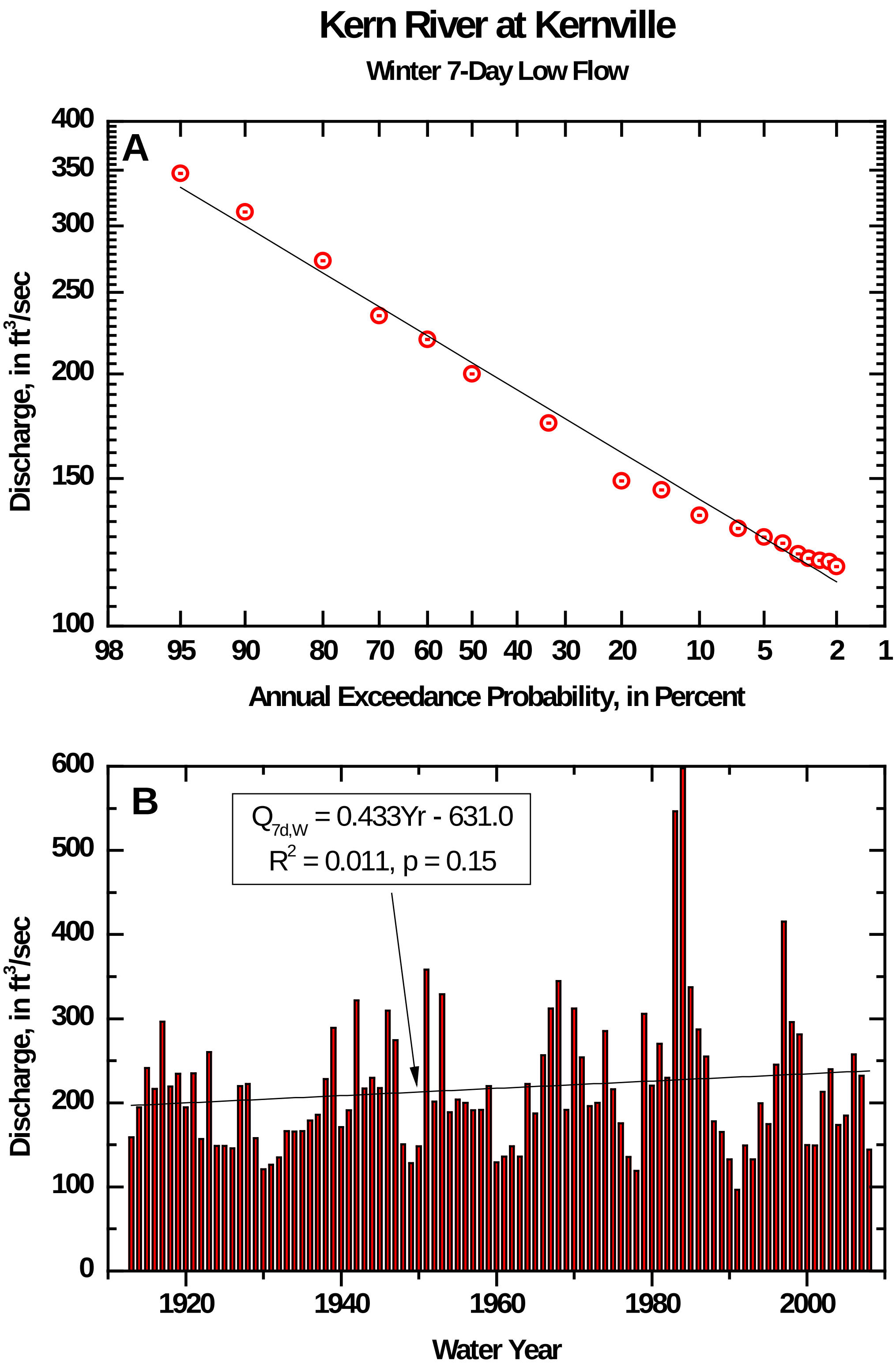


Figure 28. Magnitude of the (a) 7-day Winter low flows equaled or exceeded from 98 to 2 percent of the time, and (b) sequence of annual 7-day winter low flows for the period of record with fitted regression trend line at the Kern River near Kernville.

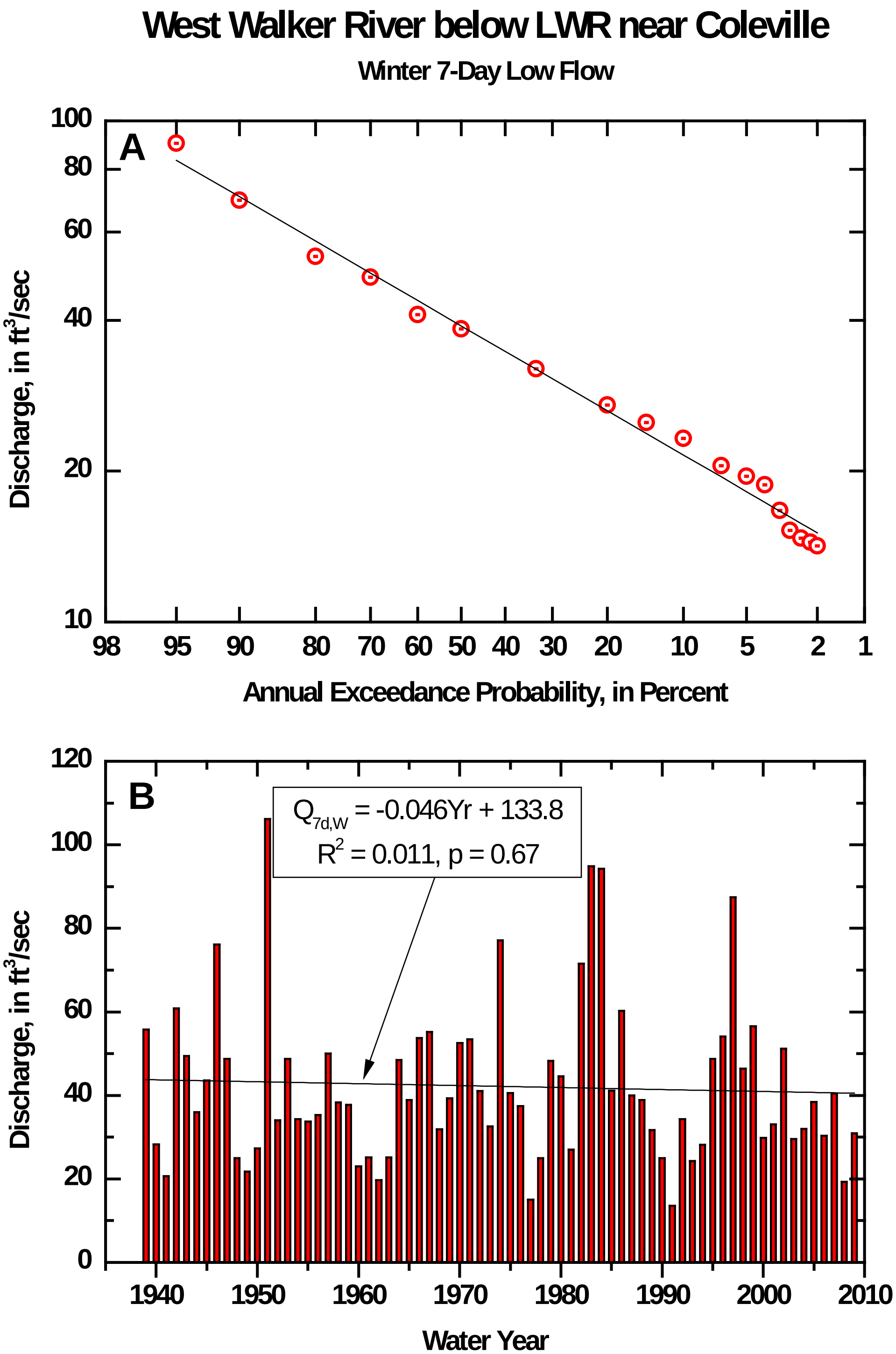


Figure 29. Magnitude of the (a) 7-day Winter low flows equaled or exceeded from 98 to 2 percent of the time, and (b) sequence of annual 7-day winter low flows for the period of record with fitted regression trend line at the West Walker River below LWR (Little Walker River) near Coleville.

A trend of increasing 7-day winter low flow was determined for 15 of the 20 streamflow records, and eight are statistically significant at the 95% confidence limit. Similarly, a trend of increasing 14-day winter low flow was determined for 16 of the 20 streamflow records, and eight are statistically significant. Statistically significant trends of increasing 3-, 7-, and 14-day winter low flow were identified at both the Merced River gages.

Among the gaging stations operated until at least 2000, the Marble Fork and Middle Fork Kaweah near Potwisha Camp showed no trend in the 3-, 7-, or 14-day winter low flows. The North, East, and South Fork Kaweah River, however, were determined to have trends toward increasing 3-, 7-, and 14-day winter low flows. Thirteen trends, three of which were statistically significant towards an earlier date for the 7-day winter low flow were found.

The magnitude of the 7-day summer low flow equaled or exceeded from 98 to 2 percent of the time and the sequence of 7-day summer low flows observed over the period of record are shown in Figures 30-35 for selected gages. A trend line has been fit by regression to the sequence of annual 7-day summer low flows. The equation of the fitted trend line and the p-value calculated for the slope are shown. None of these trends are statistically significant at the 90 percent confidence limit, and four of the six records for summer day low flows have no apparent trend. The calculated magnitudes of the 3-, 7-, and 14-day summer low flow equaled or exceeded from 98 to 2 percent of the time at all 20 gaging stations are shown in Appendix C. Identification and evaluation of trends in the magnitude and the timing of the 3-, 7-, and 14-day summer low flows using the method of Kendall’s Tau are presented in Table 5. There is little, if any, indication within the records analyzed for this study of a trend in summer low flows.

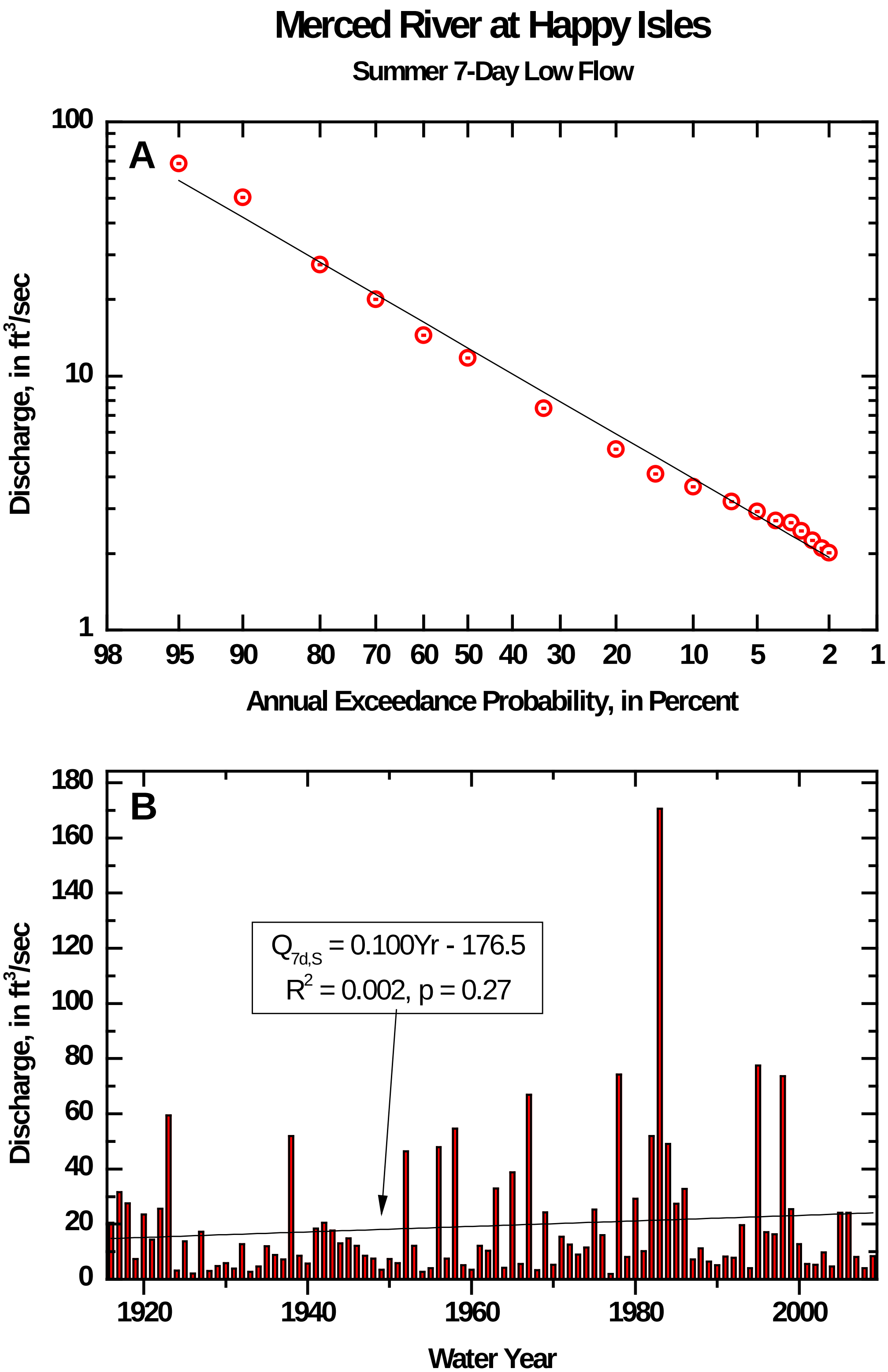


Figure 30. Magnitude of the (a) 7-day summer low flow equaled or exceeded from 98 to 2 percent of the time, and (b) sequence of annual 7-day summer low flows for the period of record with fitted regression trend line at the Merced River at Happy Isles Bridge.

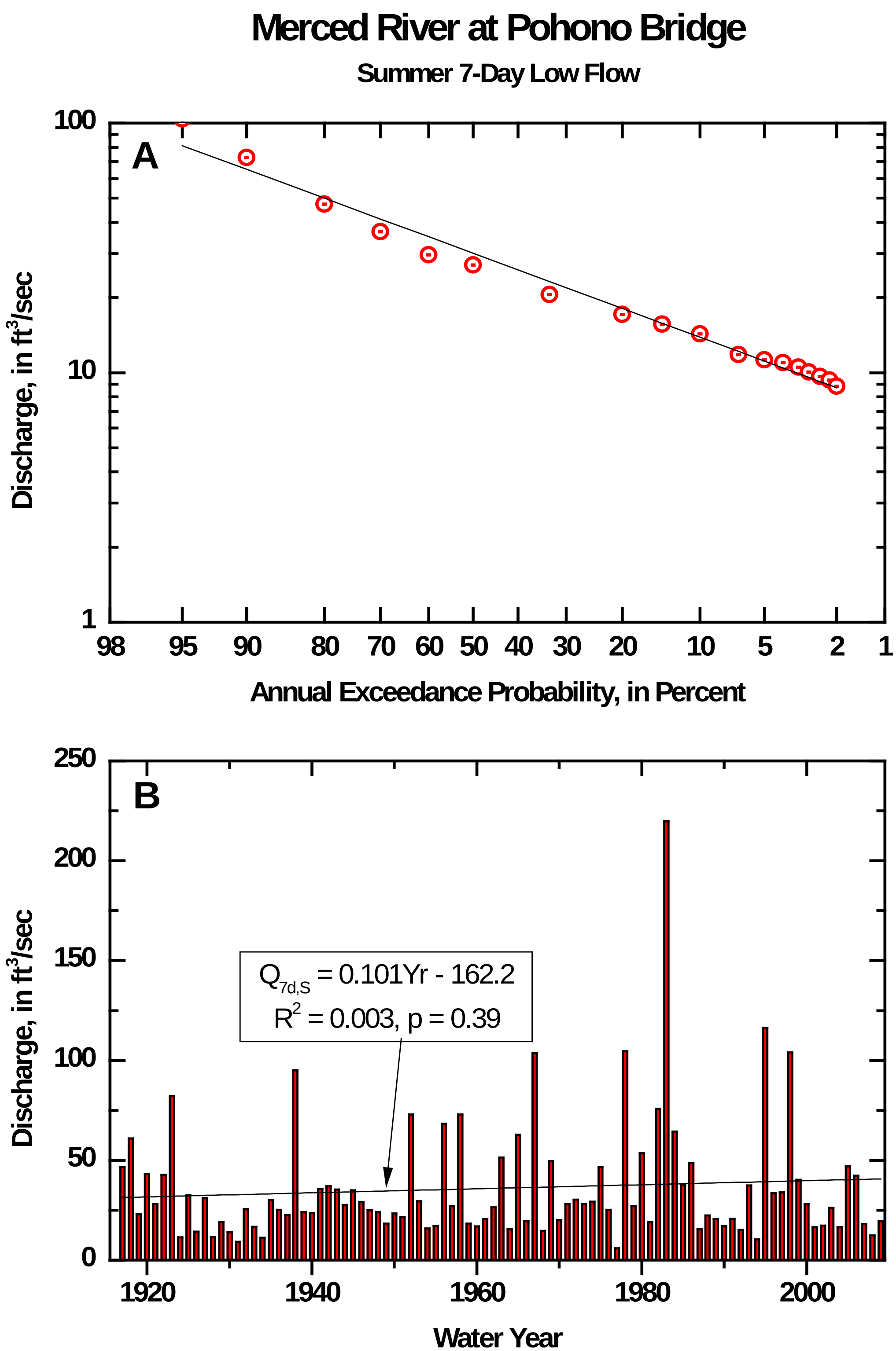
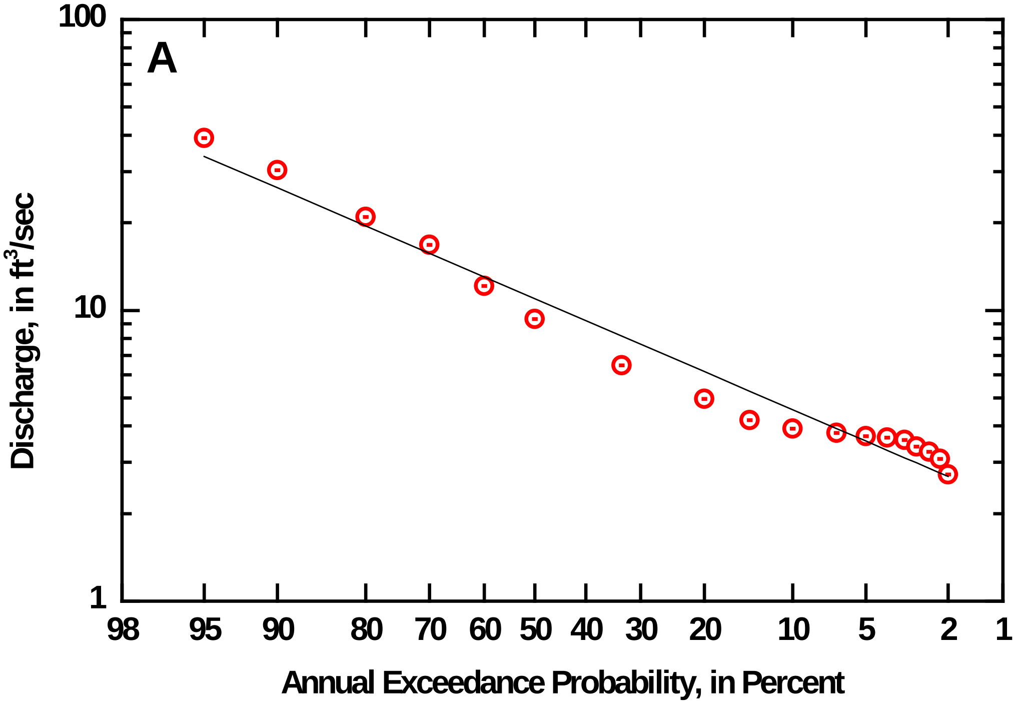


Figure 31. Magnitude of the (a) 7-day summer low flow equaled or exceeded from 98 to 2 percent of the time, and (b) sequence of annual 7-day summer low flows for the period of record with fitted regression trend line at the Merced River at Pohono Bridge.

Bear Creek near Lake Thomas A. Edison

Summer 7-Day Low Flow



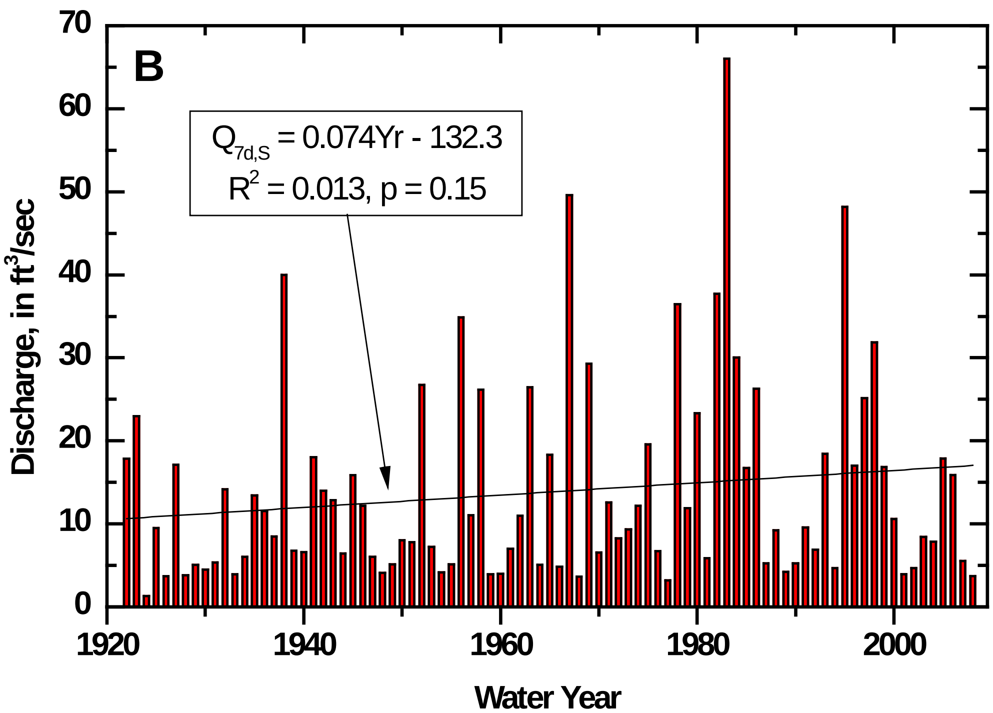


Figure 32. Magnitude of the (a) 7-day summer low flow equaled or exceeded from 98 to 2 percent of the time, and (b) sequence of annual 7-day summer low flows for the period of record with fitted regression trend line at Bear Creek near Lake Thomas A. Edison.

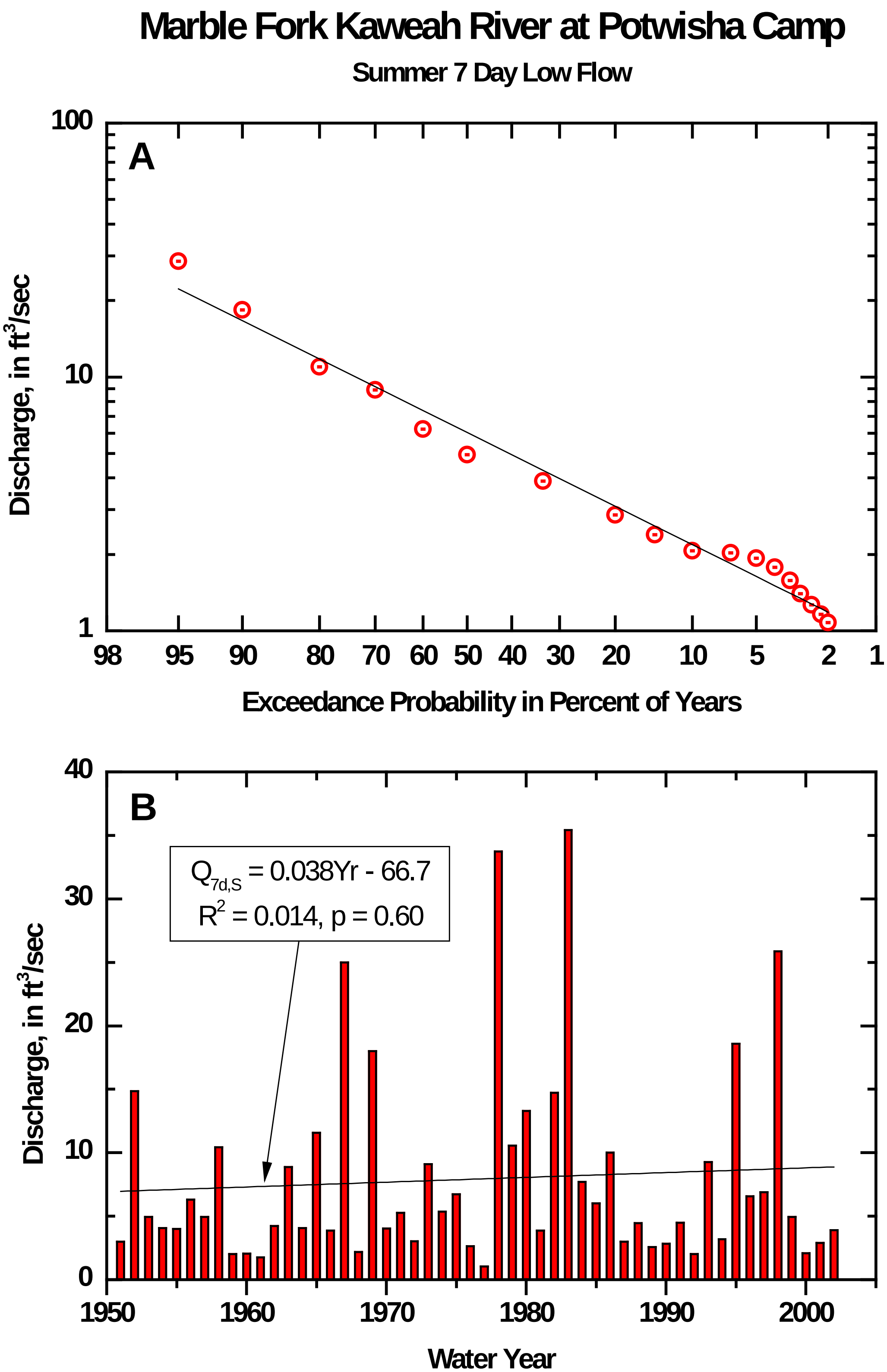


Figure 33. Magnitude of the (a) 7-day summer low flow equaled or exceeded from 98 to 2 percent of the time, and (b) sequence of annual 7-day summer low flows for the period of record with fitted regression trend line at the Marble Fork Kaweah at Potwisha Camp.

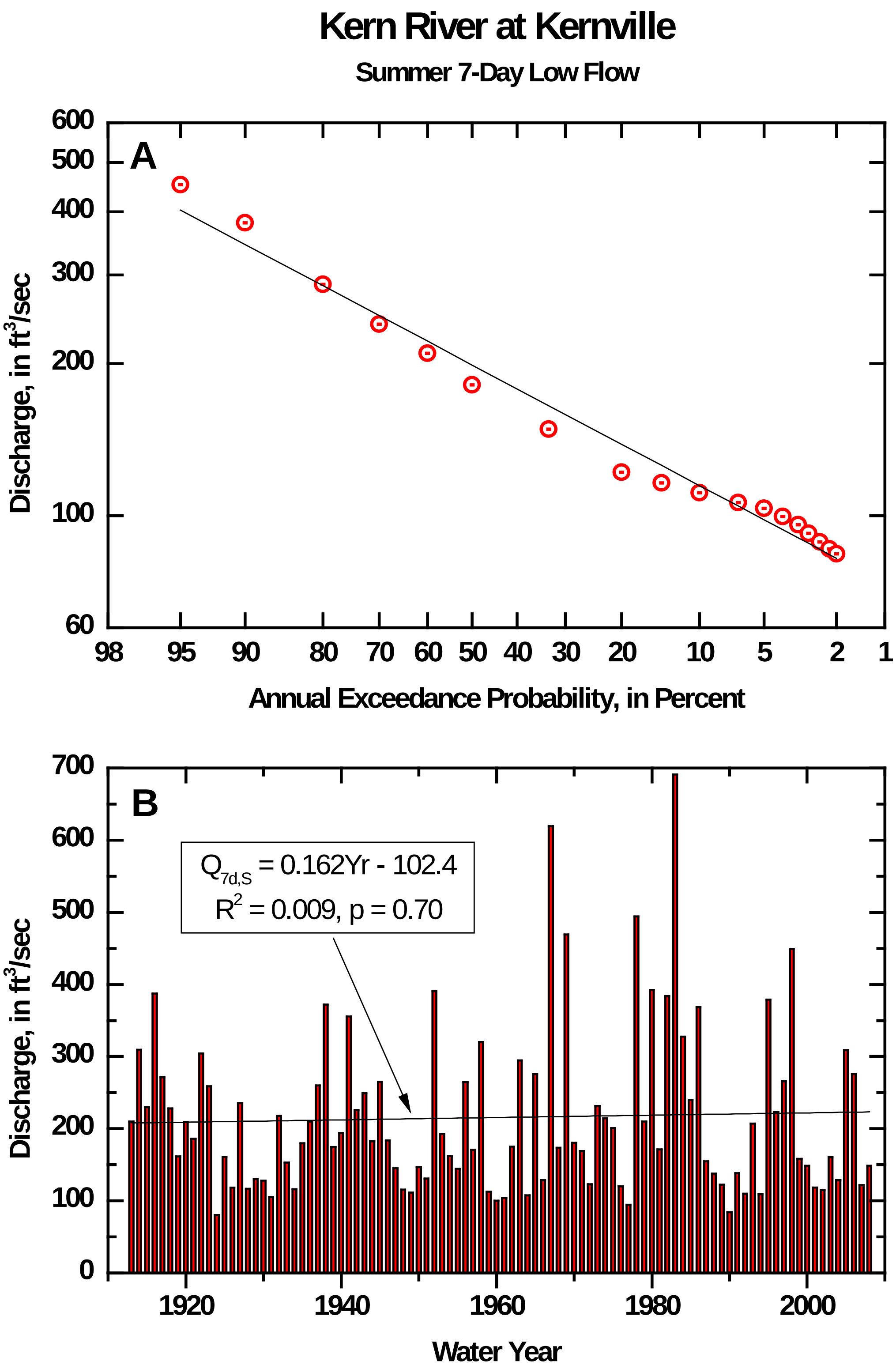


Figure 34. Magnitude of the (a) 7-day summer low flow equaled or exceeded from 98 to 2 percent of the time, and (b) sequence of annual 7-day summer low flows for the period of record with fitted regression trend line at the Kern River near Kernville.

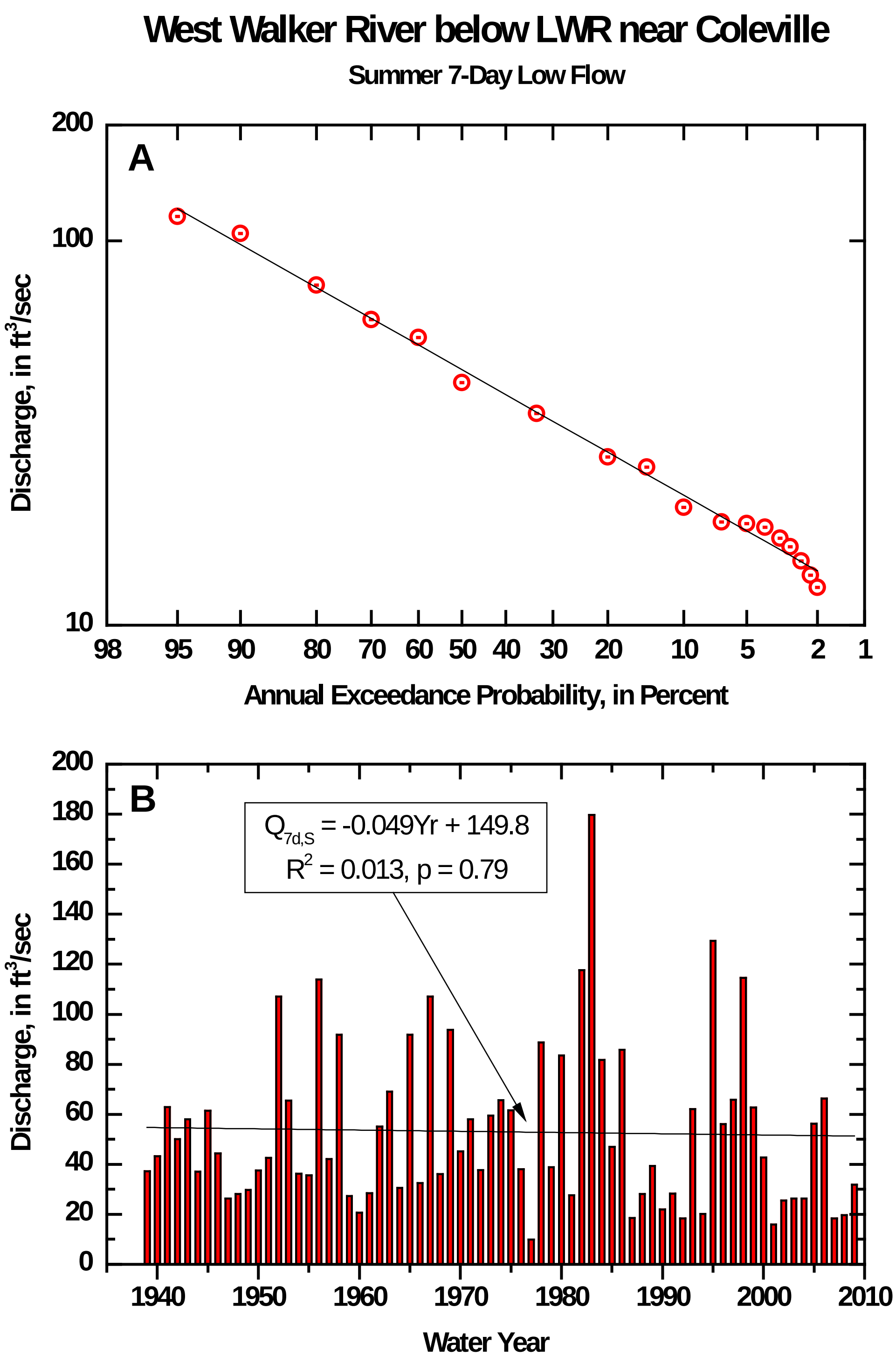


Figure 35. Magnitude of the (a) 7-day summer low flow equaled or exceeded from 98 to 2 percent of the time, and (b) sequence of annual 7-day summer low flows for the period of record with fitted regression trend line at the West Walker River below LWR near Coleville.

5.6. Streamflow Duration

The cumulative frequency distribution of streamflows, typically the daily mean, over a period of record is called duration of streamflows or flow duration (Riggs 1986). The flow duration curve indicates the percent of time a given flow has been equaled or exceeded during the period of record. It is a convenient way to summarize a great deal of information about the flow regime in a concise manner, and as such, has a number of practical applications. Furthermore, as will be shown below, a comparison of flow durations can be an efficient way to identify similarities and differences between multiple gages. The observed duration of streamflows over the available periods of record are shown in Figures 36–41. Flow duration statistics for all of the 20 NWIS gaging stations are listed in Table 6. The Kings River streamgage had the largest flow equaled or exceeded one percent of the time - 32,584 ft^3/s.

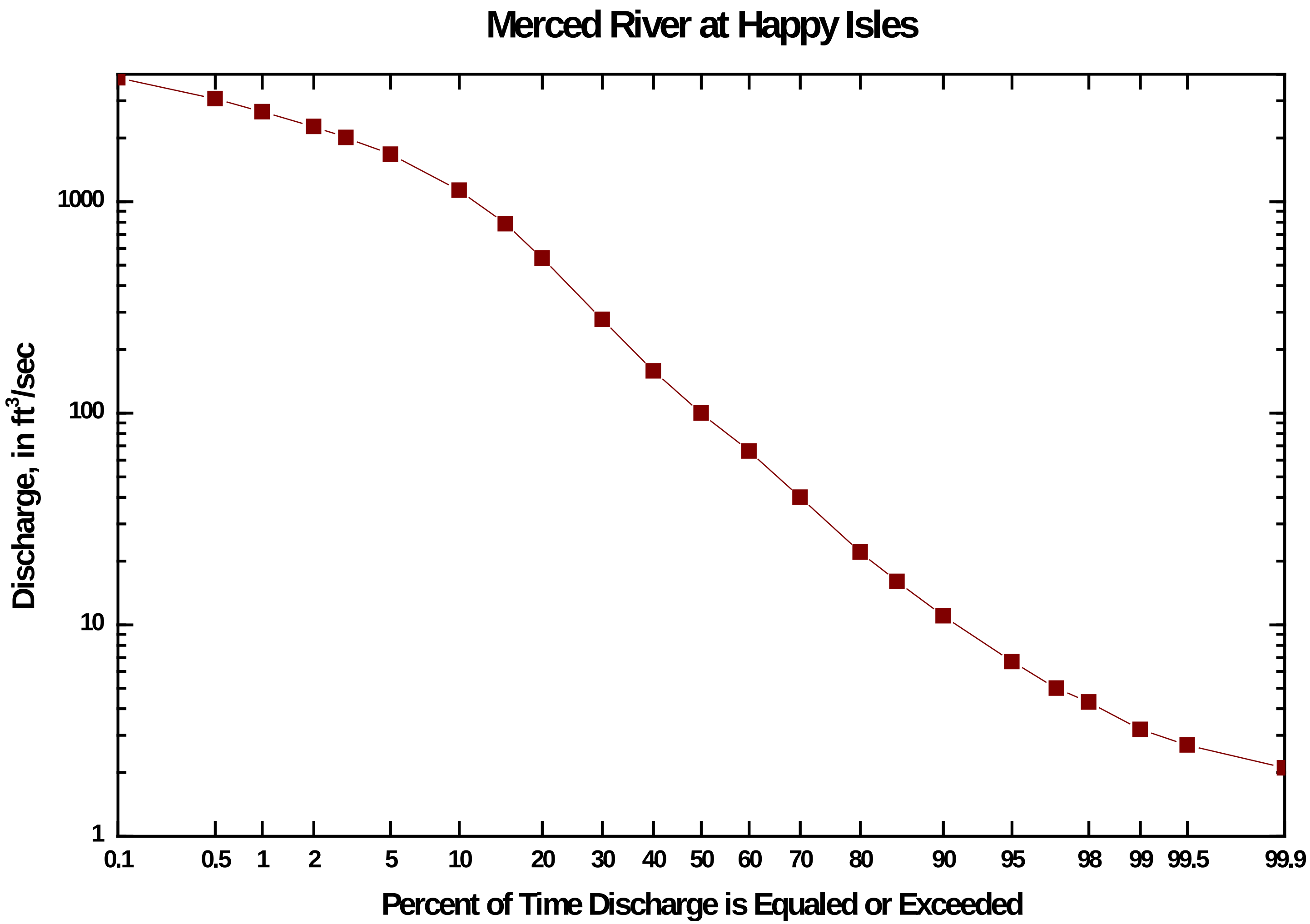


Figure 36. Duration of streamflows in the Merced River at Happy Isles Bridge.

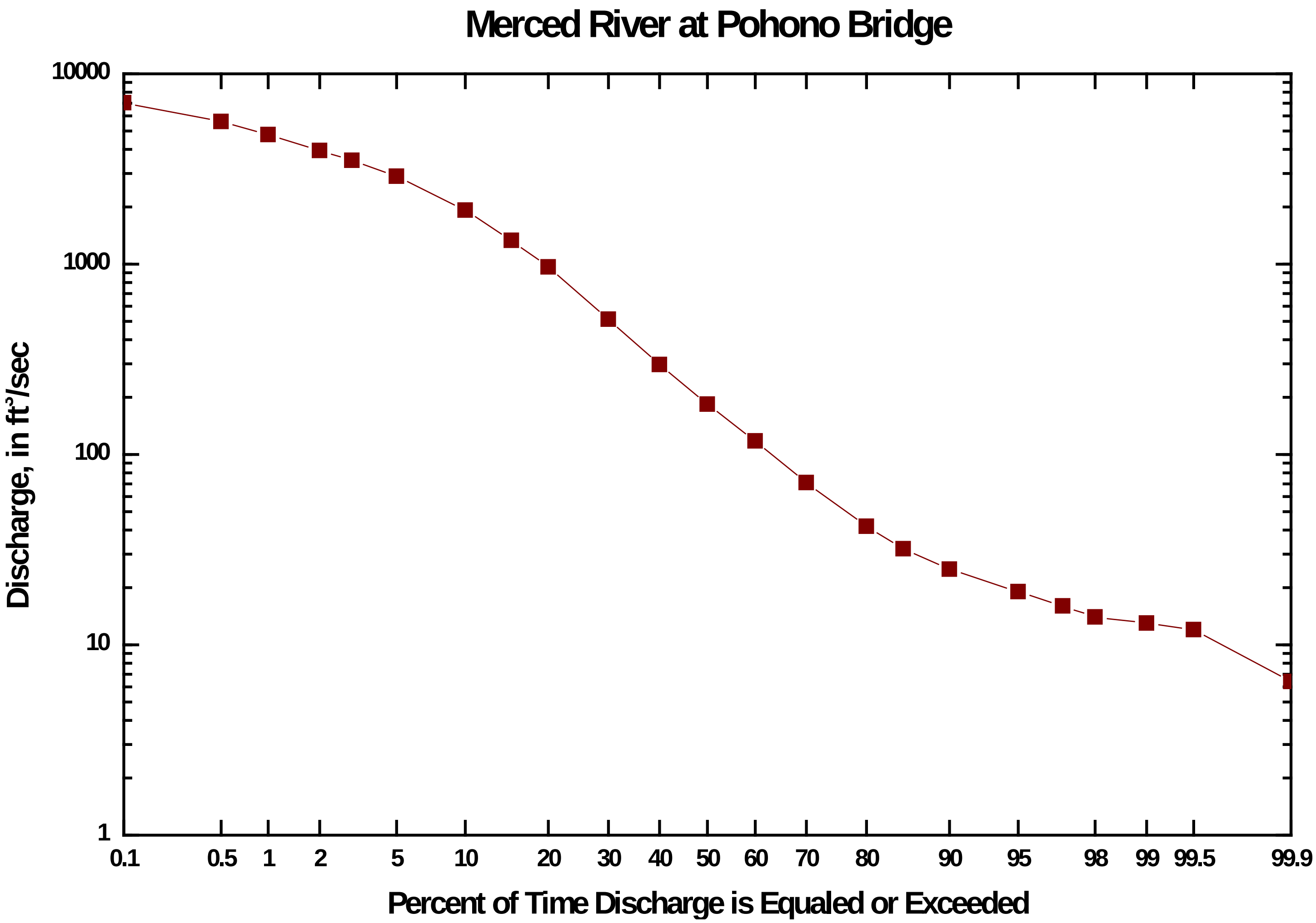


Figure 37. Duration of streamflows in the Merced River at Pohono Bridge.

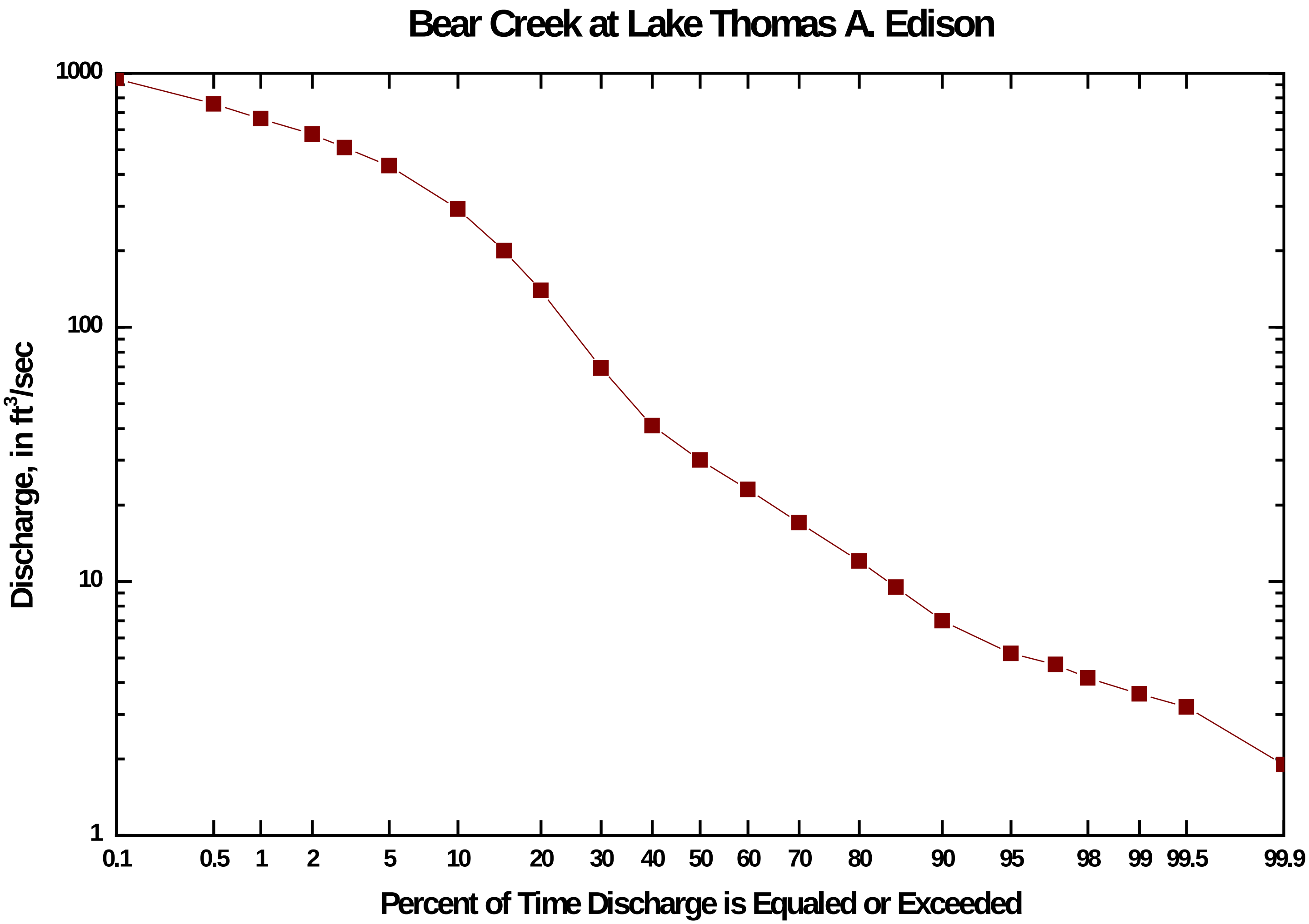


Figure 38. Duration of streamflows in Bear Creek near Lake Thomas A. Edison.

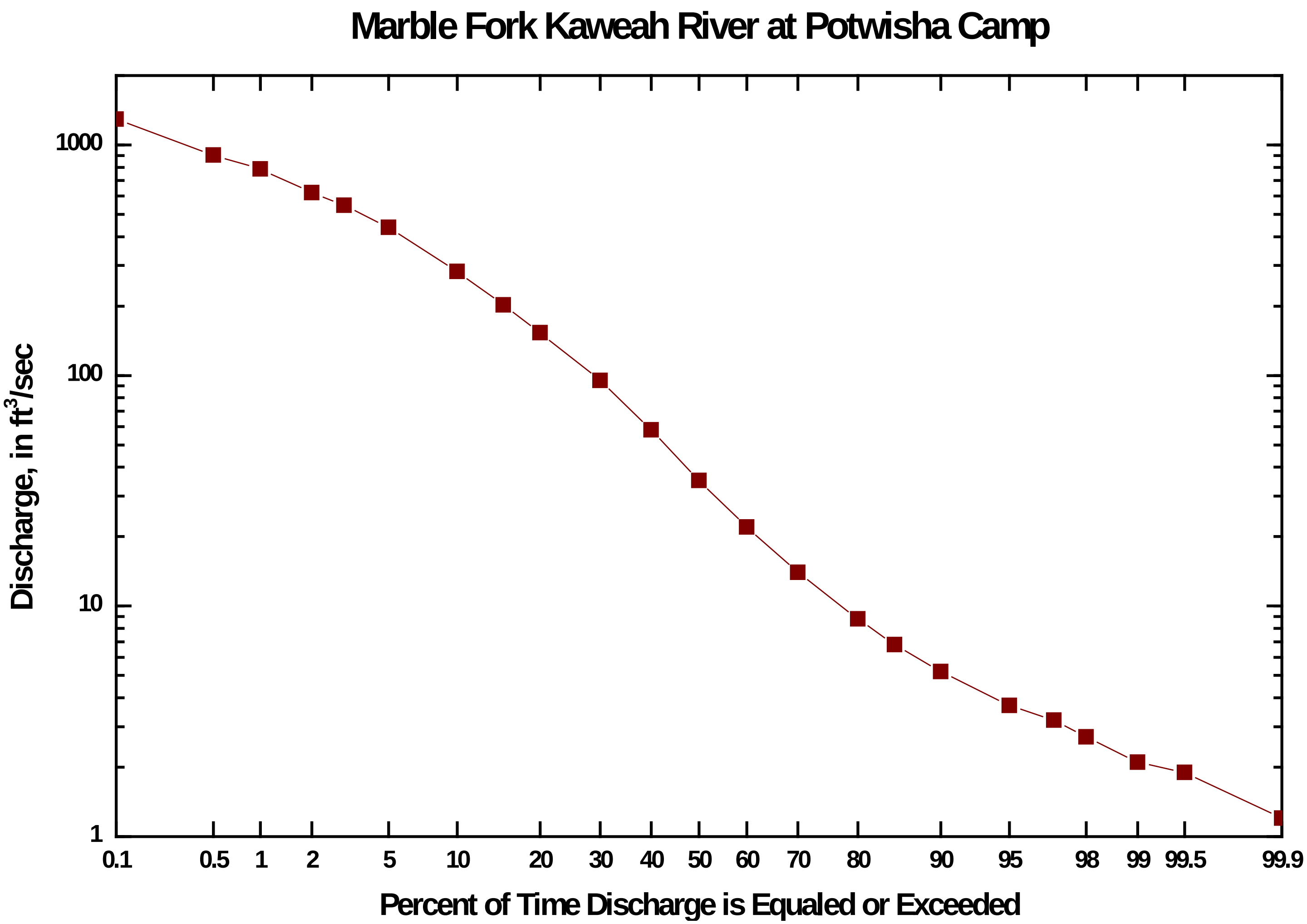


Figure 39. Duration of streamflows in the Marble Fork Kaweah River at Potwisha Camp.

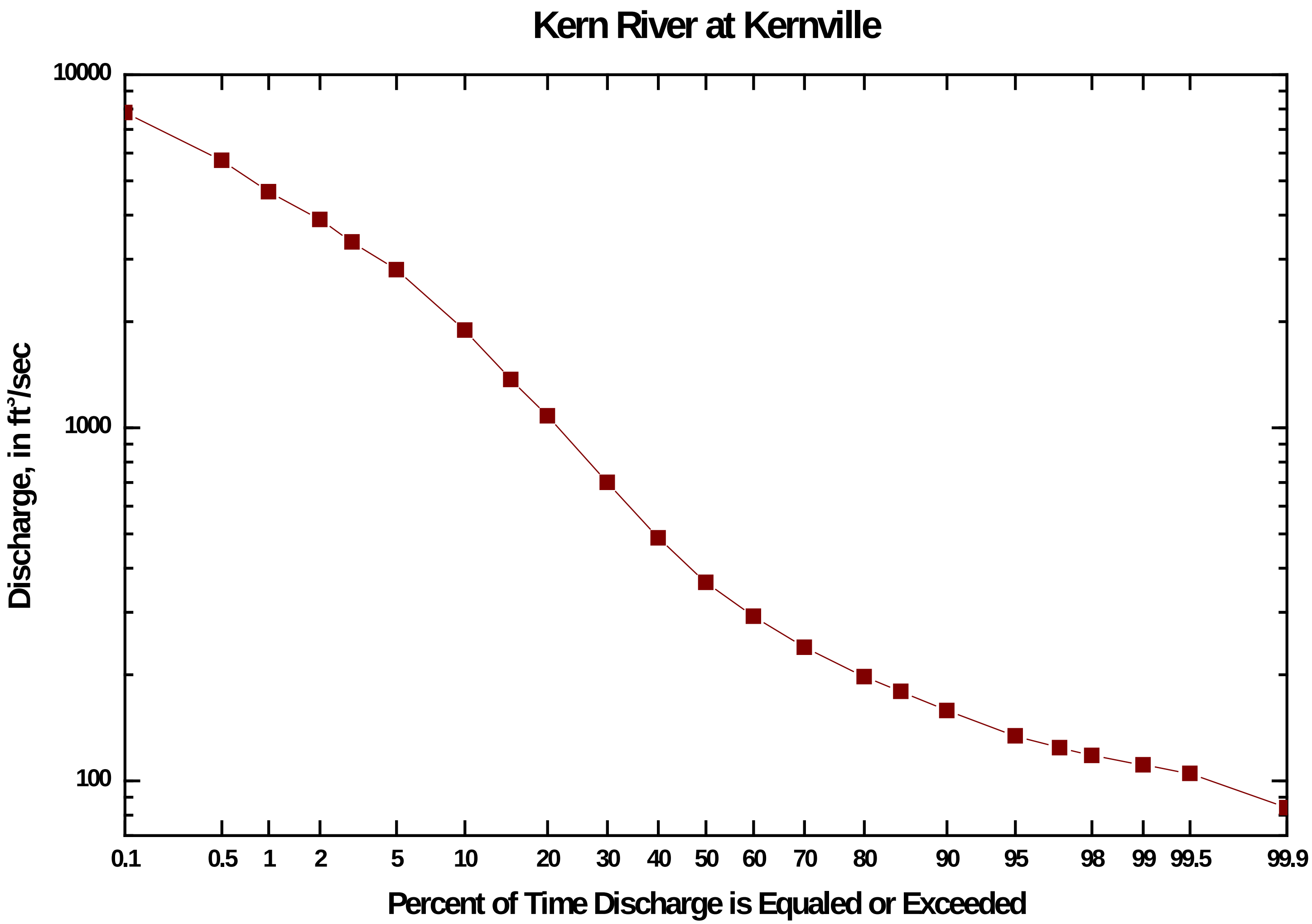


Figure 40. Duration of streamflows in the Kern River at Kernville.

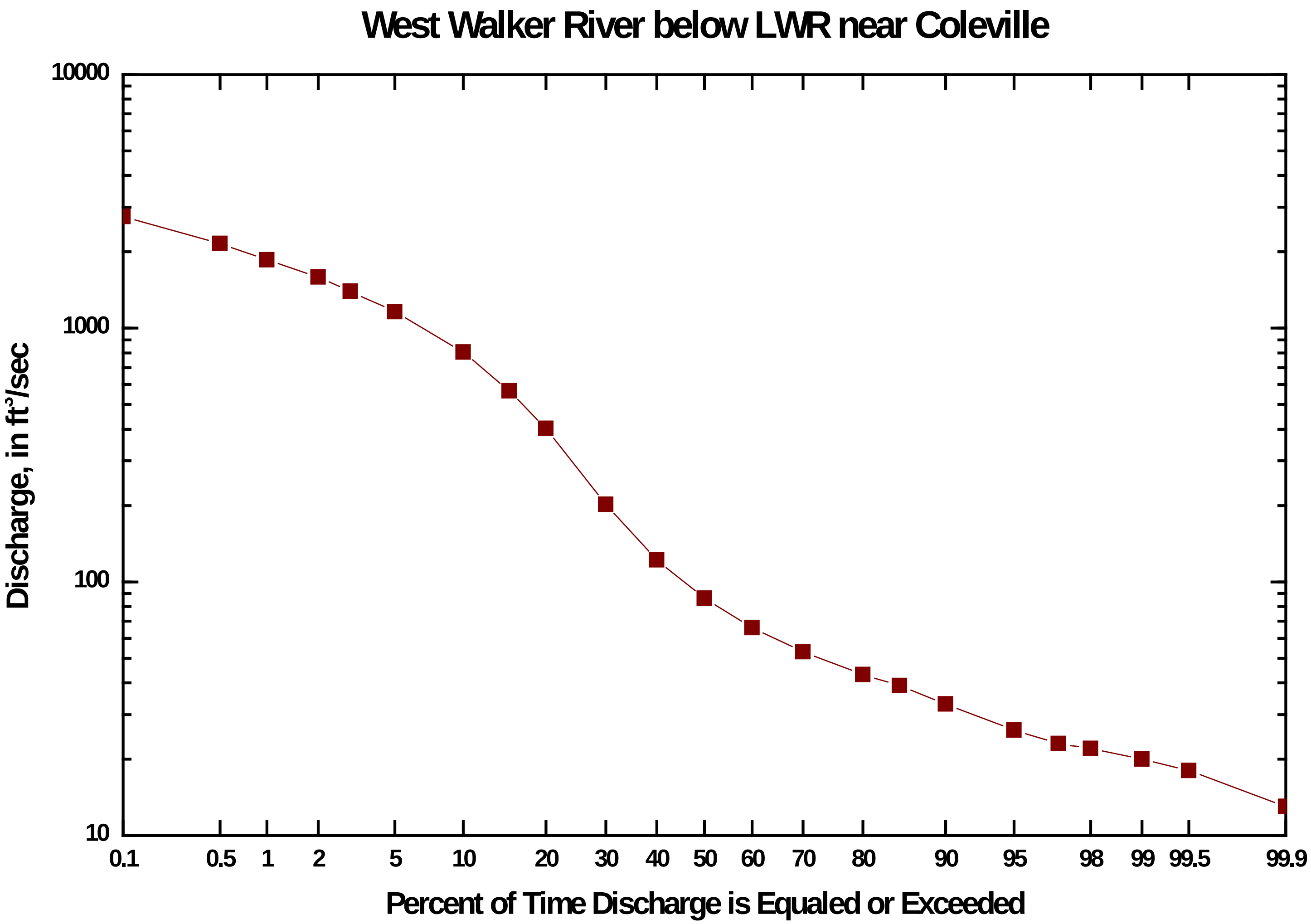


Figure 41. Duration of streamflows in the West Walker River below Lower Walker River near Coleville.

Table 6. Duration of streamflows, or the cumulative frequency distributions of streamflows (ft^3/s), over the available periods of record.

Site	Gaging Station ID	Exceedance Probability 0.01	0.05	0.1	0.5	1	5	10	15	20	30	40	50	60	70	80	85	90	95	99	99.5	99.9	99.95	99.99
Merced River at Happy Isles Bridge	11264500	6843	4198	3837	3063	2660	1670	1130	785	541	277	158	100	66	40	22	16	11	6.7	3.2	2.7	2.1	1.9	1.6
Merced River at Pohono Bridge	11266500	14690	7781	7041	5620	4790	2890	1920	1330	964	513	296	184	118	71	42	32	25	19	13	12	6	6	6
Bear Creek nr. Lake Thomas A Edison	11230500	1757	1041	951	757	662	432	292	200	140	69	41	30	23	17	12	9.5	7.0	5.2	3.6	3.2	1.9	1.4	1.2
Pitman Creek bl. Tamarack Creek	11237500	1595	841	757	576	474	227	131	82	52	23	11	5.3	2.4	1.2	0.6	0.4	0.3	0.2	0.1	0.1	0.1	0.1	0.0
Kern River nr. Kernville	11186000	15239	8970	7805	5717	4660	2800	1890	1370	1080	700	487	365	292	239	197	179	158	134	111	105	84	81	78
W. Walker River nr. Coleville	10296000	3776	2960	2750	2153	1860	1160	804	565	403	202	122	86	66	53	43	39	33	26	20	18	13	11	9.9
M. F. Tuolumne River nr. Oakland Rec. Camp	11282000	1786	1314	1040	778	656	357	238	167	120	67	35	19	11	6.4	3.7	2.6	1.7	0.8	0.06	0.0	0.0	0.0	0.0
S.F. Tuolumne River nr. Oakland Rec. Camp	11281000	4199	2608	2051	891	688	379	260	197	154	91	52	31	20	15	11	8.3	6.1	4.0	1.5	1.0	0.5	0.5	0.4
M. F. Kaweah River nr. Potwisha Camp	11206500	6391	3546	1786	1332	1144	657	472	355	279	183	125	86	56	38	26	21	17	13	9.7	9.1	7.4	7.2	7.0
Marble Fork Kaweah River at Potwisha Camp	11208000	4657	1830	1291	904	785	439	283	202	153	95	58	35	22	14	8.8	6.8	5.2	3.7	2.1	1.9	1.2	1.1	0.8
E. F. Kaweah River nr. Three Rivers	11208730	7265	1911	1489	1177	984	482	312	221	156	82	43	22	11	6.3	1.4	1.0	0.7	0.4	0.2	0.1	0.1	0.1	0.0
N. F. Kings River bl. Meadow Brook	11214000	1557	1153	1030	738	669	412	249	155	96	38	21	14	10	6.0	3.2	2.1	1.6	1.0	0.0	0.0	0.0	0.0	0.0
N. F. Kaweah River at Kaweah	11209500	6182	2572	2060	942	740	410	281	206	155	92	51	28	16	11	7.0	5.3	3.8	2.0	0.2	0.1	0.0	0.0	0.0
Falls Creek nr. Hetch Hetchy	11275000	4609	1998	1487	1080	992	672	463	323	225	115	69	47	29	13	3.8	1.5	0.4	0.0	0.0	0.0	0.0	0.0	0.0
Kings River ab. North Fork nr. Trimmer	11213500	32584	17260	14864	10400	9064	6000	4230	3080	2240	1330	860	570	400	294	215	184	155	127	100	93	80	78	70
Tenaya Creek nr. Yosemite Village	11265000	3042	1252	1180	935	815	532	360	238	155	73	41	25	13	5.0	2.4	2.0	1.7	1.3	1.0	0.9	0.7	0.6	0.6
S. F. Kaweah River at Three Rivers	11210100	7064	1965	1486	718	600	324	206	144	100	57	32	19	12	7.1	3.2	1.9	0.8	0.2	0.07	0.06	0.04	0.04	0.0
San Joaquin River at Miller Crossing	11226500	8723	6287	5993	4790	4153	2526	1710	1250	913	504	318	226	166	124	94	78	63	46	32	30	26	25	23
Clavey River nr. Buck Meadows	11283500		9375	6749	2882	2033	1140	749	557	455	302	163	94	47	27	18	15	11	7.8	3.0	1.8	1.4	1.3	
N. F. Tuolumne River nr. Long Barn	11284700		1195	810	350	252	133	88	65	50	31	16	8.4	4.3	2.6	1.5	1.1	0.8	0.5	0.2	0.09	0.07	0.07	

The comparison of flow duration among a group of streams is facilitated by dividing the range of discharges at a given gage by the mean daily discharge over the period of record. That is, streamflows are expressed as a dimensionless decimal fraction of the mean daily discharge. Dimensionless flow durations for all 20 gaging stations are plotted in Figure 42. The values for each stream are represented by a separate symbol identified by the gaging station abbreviation in the inset box. The gaging stations are listed from top to bottom in the reverse order they appear in Table 1. Stream symbols were plotted in the order they appear from top to bottom. Thus, the longest, current streamflows recorded are most prominent. The comparison is striking. Dimensionless flows equaled or exceeded more than 50 percent of the time are nearly identical for all 20 drainage basins, 19 on the west slope and one on the east slope, in the south Sierra Nevada. This result is quite useful. If the mean daily discharge at a location of interest, anywhere in the Southern Sierra Nevada, is known or can be estimated, the magnitude of streamflows equaled or exceeded more than 50 percent of the time can be determined within relatively small uncertainty. Appreciable difference between the stations begins to appear for flow equaled or exceeded less than 40 percent of the time and the difference increases as the duration decreases. In dimensionless space, the distinctive differences between southern Sierra Nevada streams and drainage basins are found in the relatively infrequent high flows whereas the frequent low flows are quite similar.

In the previous discussion of flood frequency, annual peak floods recorded at the Merced River at Happy Isles Bridge and Merced River at Pohono Bridge were compared. The contributing drainage area at the Pohono Bridge gage, 321 mi^2, is 1.77 times the drainage area at the Happy Isles gage. Mean daily discharge increases proportionally with drainage area between the two gages. Annual peak floods, however, increase in magnitude much more than either drainage area or mean daily discharge. The annual peak flood equaled or exceeded 50 percent of the time, i.e. the 2-year flood, at the Pohono Bridge gage is 2.88 times larger than the corresponding value at the Happy Isles Bridge gage. The calculated 100-year flood at the Pohono Bridge gage is 2.36 times the 100-year flood at Happy Isles Bridge gage. The comparison of observed dimensionless flow duration at the two gages shown in Figure 42 demonstrates that the differences apparent in the annual peak floods extend over the range of relatively high, though infrequent, flows, i.e. those equaled or exceed less than 30 percent of the time.

The regional dimensionless flow duration curve for the southern Sierra Nevada gaging stations are shown in Figure 42. The usefulness of this relation is demonstrated by applying it to estimate the duration of streamflows at the South Fork Merced River at Wawona. This gage was operated for 10 years from 1956-1965. Relatively low flows were reduced by diversion for domestic water supply and to irrigate a golf course. The diverted flow represents an appreciable portion of the low flow at times, though an insignificant fraction of the mean daily discharge. Thus, the observed mean daily discharge is a reasonable estimate of unimpaired streamflow at the Wawona gage, however the ten years of available record may not be long enough to calculate a reasonable estimate of long-term annual mean flow, i.e. runoff during the water years 1956 to 1965 may not be typical. Indeed, the annual mean flow at the Merced River at Happy Isles Bridge gage for the water year 1956 to 1965 is 303 ft^3/s compared to 354 ft^3/s for the water years 1916-2009. Thus, annual mean flows recorded at the South Fork Merced River at Wawona were regressed against annual mean flows at the Merced River at Happy Isles Bridge, R^2=0.994. Estimated annual mean flows at the South Fork Merced River gage were calculated for the water years 1916 to 2009 using the regression equation and the Merced River at Happy Isles record. The estimated mean annual flow for the water years 1916 to 2009 at the South Fork Merced at Wawona is 243 ft^3/s, approximately 40 percent greater than for water years 1956 to 1965. An estimate of streamflow duration in the South Fork Merced River at Wawona was determined by multiplying the dimensionless flow duration shown in Figure 42 by the calculated mean daily discharge and is shown in Figure 43.

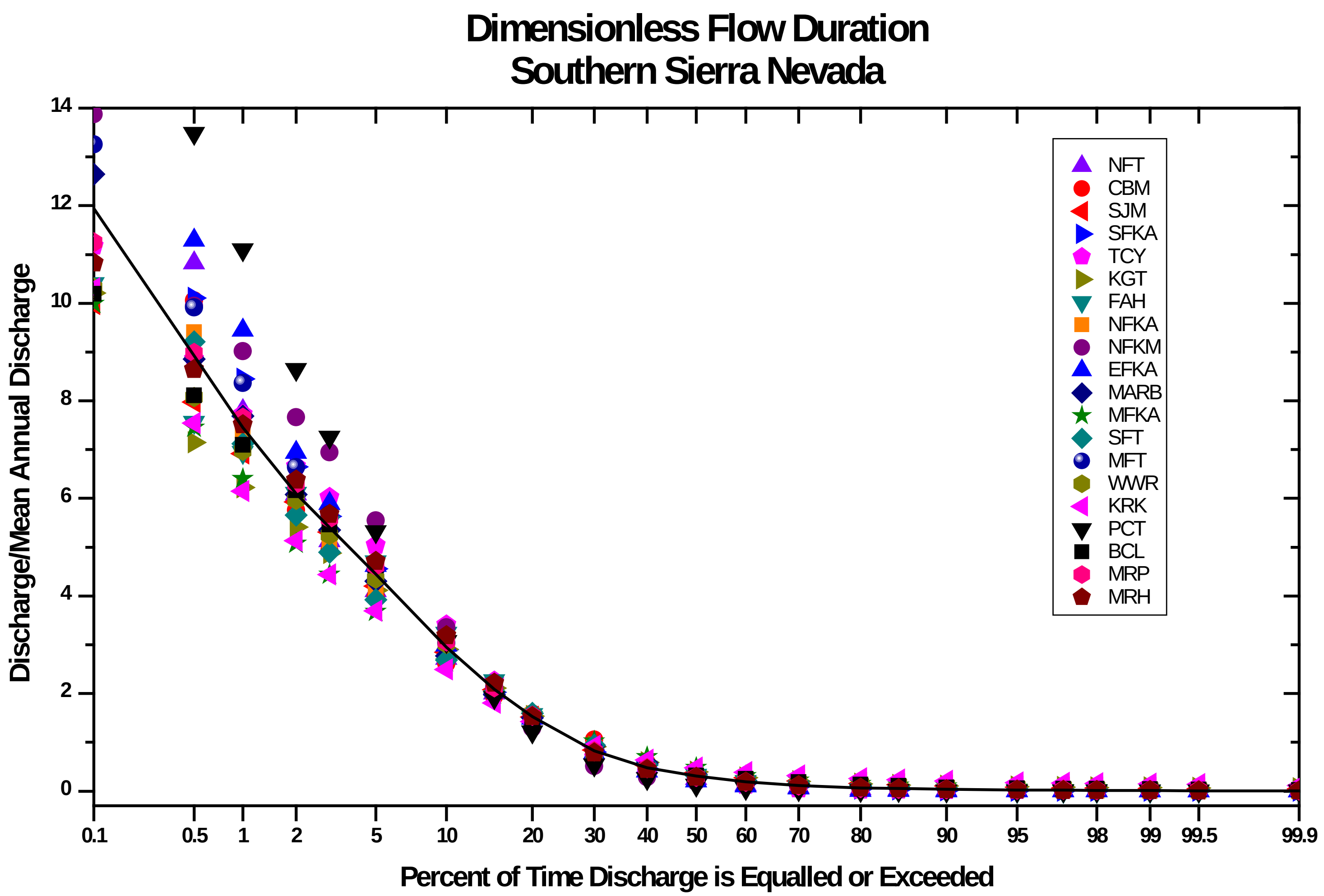


Figure 42. Dimensionless streamflow duration recorded at 20 gaging stations within and adjacent to the SIEN national parks.

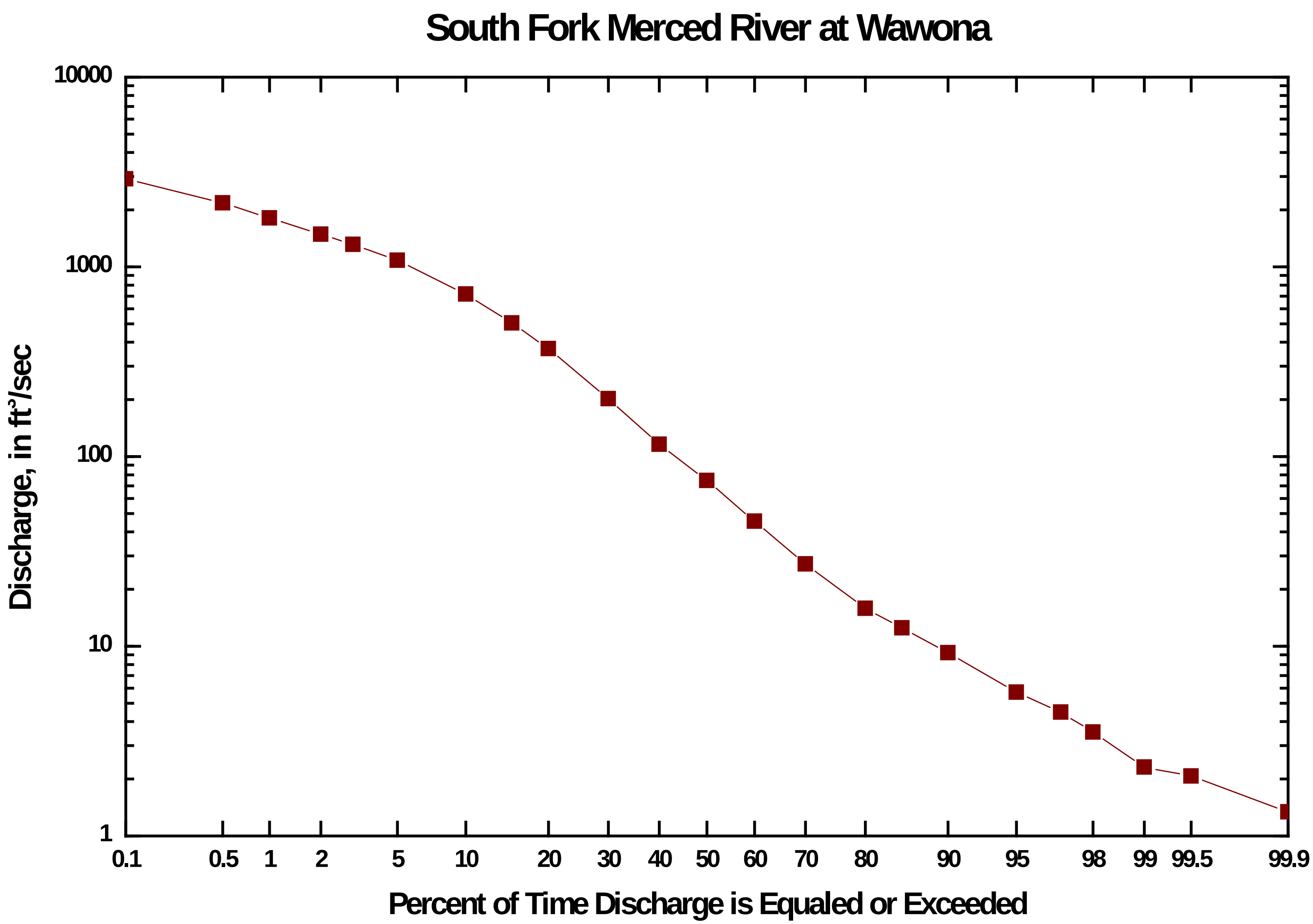


Figure 43. Estimated duration of streamflows at the South Fork Merced River gage, 1916–2009, calculated from the regional duration of dimensionless streamflows.

5.7. Flux of Suspended Sediments in the Merced River

The concentration of suspended sediment in streamflows typically varies substantially with variation in discharge as well as from day-to-day or year-to-year even within a relatively narrow range of discharge. Consequently, the concentration of suspended sediment must be sampled over a wide range of streamflows, especially the relatively high flows which transport a majority of the sediment load, as well as over an appreciable number of years, in order to define the relation between suspended sediment concentration and streamflow. Suspended sediment has been sampled at a number of gaging stations in the southern Sierra Nevada, however, the only sediment record with a sufficient number of samples and period of record to enable calculation of an estimate of the long-term mean suspended sediment load is the one collected at the Merced River at Happy Isles Bridge gage. A total of 119 suspended sediment samples have been collected at the Happy Isles Bridge gage from 1970 to 1996 by the U.S. Geological Survey as part of the National Benchmark Gaging Station Network.

The daily suspended sediment load (tons/day) is the product of the sediment concentration in milligrams per liter multiplied by the discharge (cubic feet per second) times 0.0027. The observed daily suspended sediment loads at the Happy Isles Bridge gage are shown in Figure 44 as a function of the associated streamflow. The linear least-squares regression has been fit to the log-transformed values. The coefficient of correlation, R^2, is 0.912. A rather striking feature of Figure 44 is the alignment of values along diagonally upward rising trends. The U.S. Geological Survey reports suspended sediment concentration in increments of 1 mg/liter (1 mg/l) beginning with 1 mg/l. The linear trends shown in Figure 44 represent suspended sediment concentrations of 1, 2, and 3 mg/l. These are exceptionally low concentrations. The maximum concentration sampled at the Happy Isles Bridge gage was only 26 mg/l.

Annual sediment loads and the long-term mean sediment load can be estimated for the period of streamflow record assuming that the regression relation shown in Figure 44 is representative of the entire streamflow record. The sequence of annual suspended sediment loads calculated for the Merced River at Happy Isles Bridge is shown in Figure 45. The mean annual sediment load is 1115 tons. Annual sediment loads have varied from about 200 tons in 1977 to nearly 3,000 tons in 1983. The mean annual yield of suspended sediment from the Merced River Basin upstream from the Happy Isles Bridge has been 6.2 tons/mi^2-yr. over the period water years 1916-2009, which is within the typical range for a Sierra Nevada drainage basin (Kattelman 1996).

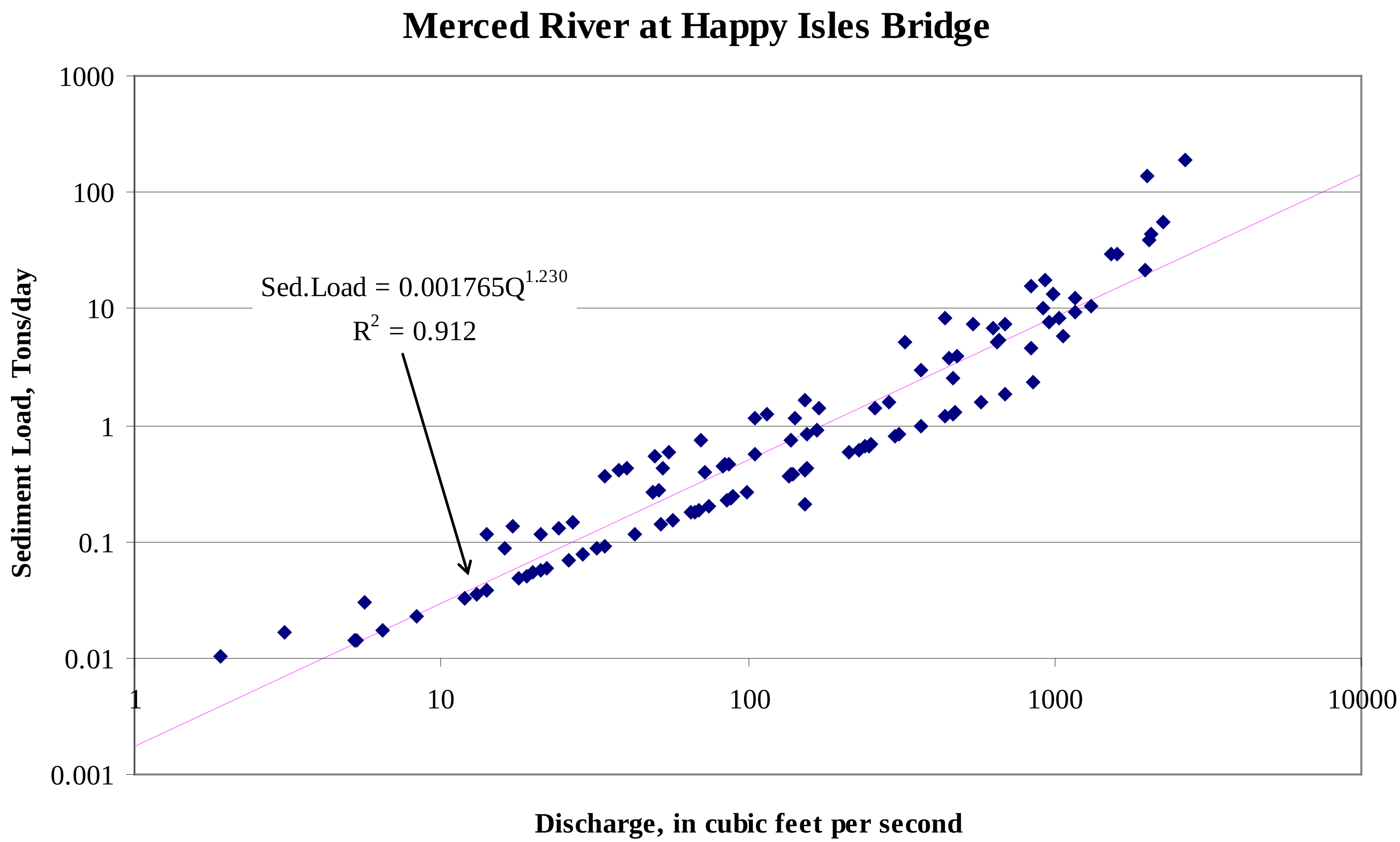


Figure 44. Variation of daily suspended sediment load as a function of streamflow at the Merced River at Happy Isles Bridge.

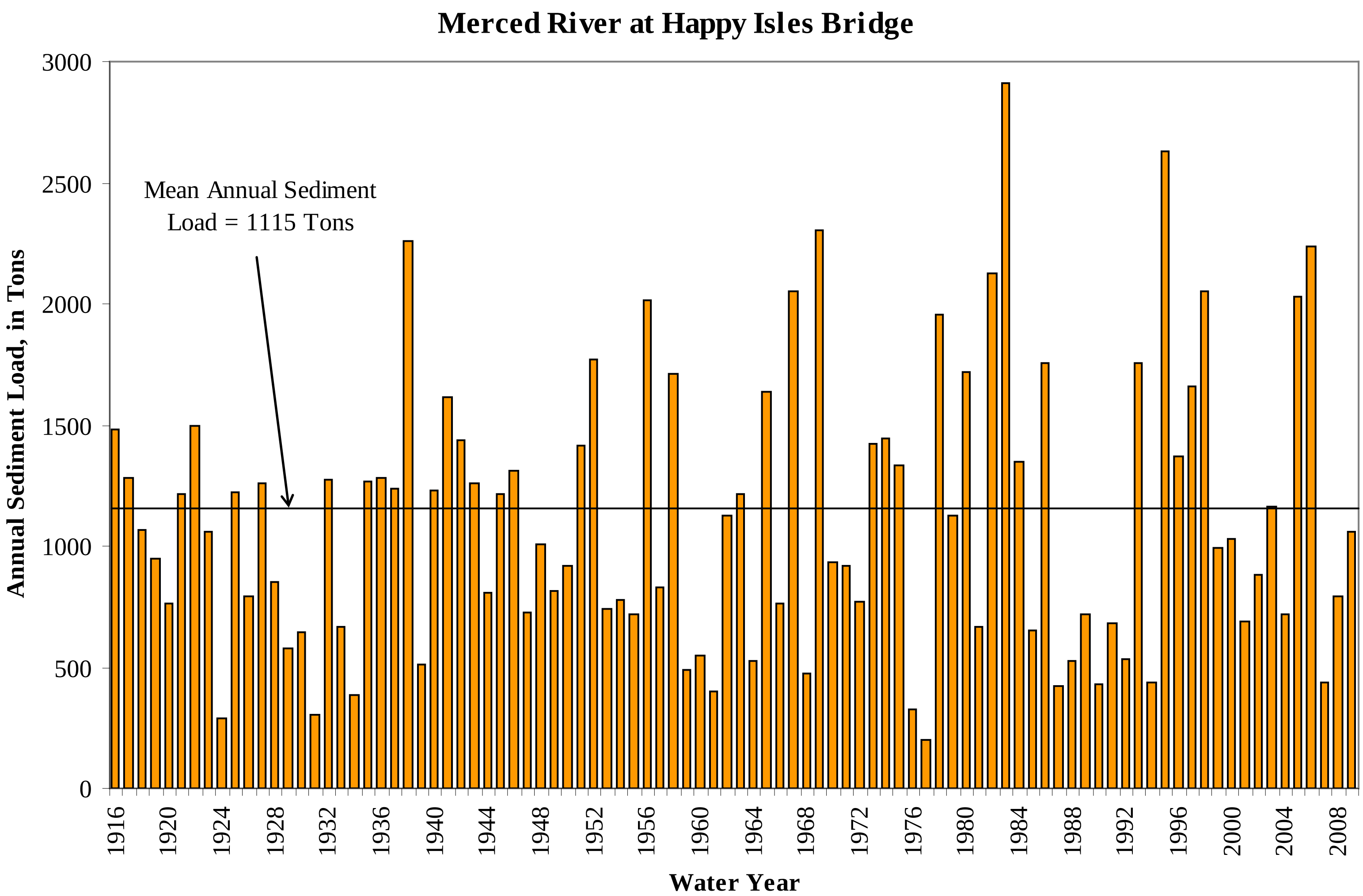


Figure 45. Calculated sequence of annual suspended sediment loads at the Merced River at Happy Isles Bridge gage.

5.8. Trends in Early Spring Snowpack

Annual surveys of snow courses occur near the end of the snow accumulation season, on or about April 1. The results are reported as the April 1 Snow Water Equivalent (April 1 SWE). The April 1 SWE has shown a response to warming across western North America, including the SIEN area (Mote et al. 2005, McCabe and Clark 2006, Mote 2006, and McCabe and Wolock 2009). Trends in April 1 SWE are consistent with a general regional warming of 0.8-1.0°C though none of the trends are statistically significant. The largest decreases in SWE have been recorded at snow courses near the lower elevation limits of the annual snow accumulation zone. The lower end of the snow accumulation zone in the SIEN is typically around 1800 meters (5900 ft). The decreasing trend in SWE drops off at higher elevations where there are lower mean winter air temperatures.

The method of analysis used by Mote (2006) was replicated to evaluate SWE trends for 68 snow courses located within and adjacent to the SIEN. This analysis extends the period of record evaluated by Mote (2006) from 2002 to 2008. Most, if not all, of the long-term snow course records evaluated herein have been previously analyzed by investigators cited above for their regional studies. The SIEN area snow courses are listed in Table 7 together with their California Data Exchange Center (CDEC) abbreviation, elevation, latitude, longitude, and median April 1 SWE for the period of record. A least-squares regression was fit to the time-series of measured April 1 SWE. The slope of the linear trend and its associated *p*-value are shown. The magnitude and percent change in April 1 SWE, along the linear trend from the beginning to the end of the available records, are shown in Table 7. Snow course locations are shown in Figure 46. The magnitude of the linear trend is indicated as a percent change by the symbol size. The red symbols indicate a trend of decreasing April 1 SWE, where black symbols indicate a trend of increasing April 1 SWE. None of the trends are statistically significant at the 95 percent confidence limit. Only two of the 68 snow courses have statistically significant trends at the 90 percent confidence limit. By chance alone, one would expect at least six trends would appear to be statistically significant. The two snow courses with apparently significant trends in April 1 SWE are both positive (increasing SWE) and are located at relatively high elevation along the east slope of the Sierra Nevada. The East Piute Pass snow course is at 10,800 ft in the Owens River drainage, whereas the Saddlebag Lake snow course is at 9,750 ft in the Mono Lake drainage. Two additional snow courses, Tioga Pass ($p = 0.12$) and Gem Pass ($p = 0.13$) both at relatively high elevations, have positive trends of April 1 SWE that almost meet the 90 percent confidence limit.

Null hypothesis testing for statistical significance assumes that each snow course record of April 1 SWE is an independent, random sample. If this were, in fact, true, one would conclude that there is no reliable trend in April 1 SWE, either positive or negative, anywhere within or adjacent to the SIEN parks. The several snow course records, however, are not independent. Trends in April 1 SWE follow a fairly consistent pattern that is apparent in Figure 47 where the percent change in SWE calculated along the trend line is plotted versus the snow course elevation. Snow courses located well west of the Sierra Nevada crest, and accordingly, at relatively low elevations within the snow accumulation zone, tend to show trends of decreasing April 1 SWE. Conversely, snow courses located at relatively high elevations near the Sierra Nevada crest tend to show trends of increasing April 1 SWE. Trends in April 1 SWE are highly correlated with elevation. Snow courses located near the lower limit of the snow accumulative zone, <7,000 feet, show the largest decreases. Snow courses located above 10,500 feet show the largest increases in

April 1 SWE. The crossover elevation from negative trends to positive occurs, on average, at about 8,500 feet, as indicated by the fitted least square regression.

The progressive decrease of April 1 SWE with elevation below 8,500 feet is consistent with the observed warming, earlier snowmelt, as well as the trend for an increasing portion of the total precipitation to fall as rain versus snow (Knowles and Cayan 2006). The progressive increase in April 1 SWE with elevation above 8,500 feet is remarkable and, as yet, not fully explained. The increase may represent nothing more than a multi-decadal fluctuation in precipitation. Alternatively, the increase of April 1 SWE over the highest, and therefore, coldest areas within and adjacent to the SIEN may be related to global warming. The IPCC (2001) assessment predicts that the mass of the Antarctic ice sheet will grow during the 21st century due to increased precipitation. The prediction is based on a hypothesized global increase of atmospheric moisture as the climate warms. In the coldest regions, where mean annual or seasonal temperatures remain well below freezing, a globally warmer climate may result in increased snowfall.

Table 7. Characteristics of 68 snow courses within and adjacent to the SIEN national parks and results from trend analyses.

Snow Course Name	ID	Elev (feet)	Lat	Long	Period of Record	Median April 1 SWE (inches)	Slope	P-Value	Difference (inches)	Percent Change
Beehive Meadow	BHV	6500	37.995	119.780	1930-2008	22.1	-0.082	0.192	-6.39	-0.22
Bond Pass	BNP	9300	38.178	119.623	1948-2008	31.1	0.040	0.770	2.43	0.06
Dana Meadows	DAN	9800	37.897	119.257	1927-2008	33.4	0.043	0.395	3.47	0.12
Huckleberry Lake	HCL	7800	38.102	119.745	1948-2000	37	0.022	0.892	1.13	0.03
Horse Meadow	HRS	8400	38.158	119.662	1948-2008	35	0.007	0.961	0.40	0.01
Lower Kibbie	LKB	6700	38.033	119.878	1937-2000	30	-0.119	0.237	-7.50	-0.25
New Grace Meadow	NGM	8900	38.150	119.617	1966-2000	42.6	-0.178	0.613	-6.04	-0.12
Paradise Meadow	PDS	7650	38.047	119.670	1946-2008	40.5	0.034	0.786	2.10	0.05
Rafferty Meadows	RFM	9400	37.837	119.325	1948-2008	27.6	0.117	0.212	7.01	0.24
Sachse Springs	SAS	7900	38.085	119.837	1948-2008	30.85	0.015	0.908	0.91	0.02
Spotted Fawn	SPF	7800	38.092	119.758	1948-2000	40.1	0.017	0.920	0.90	0.02
Tuolumne Meadows	TUM	8600	37.873	119.350	1930-2008	18	0.024	0.661	1.88	0.09
Upper Kibbie Ridge	UKR	6700	38.043	119.887	1947-2000	7.5	-0.034	0.785	-1.78	-0.09
Vernon Lake	VNN	6700	38.017	119.717	1947-2000	18.2	-0.054	0.633	-2.88	-0.12
Wilma Lake	WLW	8000	38.083	119.633	1946-2000	45.2	0.081	0.609	4.38	0.11
Gin Flat	GFI	7000	37.765	119.773	1930-2008	29.75	-0.044	0.578	-3.42	-0.10
Peregoy Meadow	PGM	7000	37.667	119.625	1931-2008	26.8	-0.103	0.121	-7.96	-0.23
Snow Flat	SNF	8700	37.827	119.497	1930-2008	39.35	0.011	0.895	0.87	0.02
Ostrander Lake	STR	8200	37.637	119.550	1938-2008	43.9	-0.006	0.945	-0.40	-0.01
Tenaya Lake	TNY	8150	37.838	119.448	1930-2008	28.65	-0.004	0.959	-0.28	-0.01
Agnew	AGP	9450	37.724	119.143	1930-2008	24.6	0.026	0.701	2.04	0.07
Colby Meadow	CBM	9700	37.178	118.720	1944-2008	19.15	0.040	0.597	2.58	0.12
Clover Meadow	CLM	7000	37.528	119.275	1939-2008	15.3	0.021	0.798	1.46	0.07
Cora Lakes	CRA	8400	37.598	119.267	1939-2008	23.55	0.014	0.882	0.97	0.03
Emerald Lake	EML	10600	37.183	118.762	1944-2000	29.95	0.026	0.841	1.48	0.04
Piute Pass	PPS	11300	37.240	118.687	1930-2008	28.45	0.088	0.244	6.85	0.21
Blackcap	BCB	10300	37.067	118.770	1930-2008	27.6	0.006	0.936	0.47	0.01
Bullfrog Lake	BLF	10650	36.770	118.398	1955-2008	26.95	0.108	0.367	5.73	0.22
Big Meadows	BMS	7600	36.715	118.842	1930-2008	26.65	-0.033	0.672	-2.59	-0.10
Bishop Pass	BSH	11200	37.100	118.557	1930-2008	26.85	0.104	0.167	8.14	0.28

Table 7. Characteristics of 68 snow courses within and adjacent to the SIEN national parks and results from trend analyses (continued).

Snow Course Name	ID	Elev (feet)	Lat	Long	Period of Record	Median April 1 SWE (inches)	Slope	P-Value	Difference (inches)	Percent Change
Charlotte Ridge	CLT	10700	36.770	118.415	1955-2008	29.25	0.079	0.548	4.18	0.14
Grant Grove	GNG	6600	36.742	118.963	1930-2008	8	-0.061	0.362	-4.77	-0.29
Horse Corral Mdw	HCM	7600	36.752	118.750	1930-2008	17.5	-0.040	0.362	-3.12	-0.17
Rattlesnake Creek	RTT	9900	36.982	118.720	1973-2000	41.85	-0.167	0.737	-4.51	-0.11
Rowell Meadow	RWM	8850	36.717	118.737	1933-2008	29	0.013	0.857	1.00	0.04
Vidette Meadow	VDM	9500	36.758	118.410	1956-1996	28.55	0.202	0.265	8.07	0.44
Farewell Gap	FRW	9500	36.412	118.583	1952-2008	49.55	0.033	0.832	1.87	0.06
Giant Forest	GFR	6400	36.570	118.768	1930-2008	16.15	-0.074	0.198	-5.79	-0.31
Hockett Meadows	HKM	8500	36.382	118.655	1930-2008	32.8	-0.064	0.379	-4.96	-0.16
Mineral King	MNK	8000	36.437	118.587	1948-2008	23.5	0.034	0.725	2.06	0.10
Panther Meadow	PTM	8600	36.588	118.717	1930-2008	36.35	-0.001	0.987	-0.10	0.00
Bighorn Plateau	BGH	11350	36.615	118.377	1949-2008	20.25	0.009	0.923	0.51	0.02
Big Whitney Mdw	BWH	9750	36.440	118.255	1948-2008	13.25	0.026	0.720	1.58	0.10
Beach Meadow	BHM	7650	36.122	118.293	1930-2008	8.25	-0.046	0.284	-3.56	-0.33
Crabtree Meadow	CBT	10700	36.563	118.345	1949-2008	18.1	0.024	0.768	1.43	0.08
Cottonwood Pass	CWP	11050	36.450	118.217	1948-2008	8.95	0.090	0.209	5.42	0.45
Guyot Flat	GYF	10650	36.523	118.348	1949-2008	19	0.031	0.714	1.81	0.09
Rock Creek	RCR	9600	36.497	118.333	1949-2008	16.95	0.041	0.614	2.42	0.15
Sand Meadows	SDM	10650	36.572	118.367	1949-2008	17.45	0.025	0.757	1.49	0.08
Siberian Pass	SIB	10900	36.473	118.267	1948-2008	14.45	0.046	0.568	2.77	0.16
Tyndall Creek	TND	10650	36.632	118.392	1949-2008	17.55	0.045	0.574	2.63	0.15
Little Whitney Mdw	LWM	8500	36.378	118.347	1930-2008	15.65	-0.004	0.938	-0.30	-0.02
Quinn Ranger Station	QRS	8350	36.328	118.573	1931-2008	16.6	-0.076	0.291	-5.86	-0.26
Big Pine Creek 1	BP1	10000	37.125	118.483	1950-2000	17.9	-0.015	0.903	-0.76	-0.03
Big Pine Creek 2	BP2	9700	37.127	118.470	1950-2000	12.5	-0.037	0.716	-1.83	-0.12
Big Pine Creek 3	BP3	9800	37.128	118.475	1950-2000	14.8	0.080	0.492	4.02	0.25
Bishop Lake	BSP	11300	37.123	118.545	1951-2008	17.35	0.085	0.358	4.84	0.24
Cottonwood Lakes 1	CW1	10150	36.483	118.177	1931-2008	7.75	0.020	0.634	1.52	0.13
Cottonwood Lakes 2	CW2	11100	36.483	118.217	1944-2000	15.65	0.035	0.618	1.96	0.14
East Piute Pass	EPP	10800	37.235	118.687	1950-2000	13.15	0.178	0.059	8.91	0.83
Sawmill	SWM	10200	37.162	118.562	1950-2000	18.85	0.087	0.383	4.34	0.25

Table 7. Characteristics of 68 snow courses within and adjacent to the SIEN national parks and results from trend analyses (continued).

Snow Course Name	ID	Elev (feet)	Lat	Long	Period of Record	Median April 1 SWE (inches)	Slope	P-Value	Difference (inches)	Percent Change
Ellery Lake	Ell	9600	37.928	119.248	1927-2008	36.6	0.074	0.215	6.01	0.24
Gem Pass	GEM	10750	37.780	119.170	1931-2008	22.35	0.137	0.134	10.52	0.40
Saddlebag Lake	SDL	9750	37.957	119.267	1926-2008	15.45	0.112	0.092	9.21	0.37
Tioga Pass	TGP	9800	37.917	119.253	1927-2008	26.65	0.086	0.116	6.93	0.31
Center Mountian	CTM	9400	38.150	119.467	1930-1984	35.8	0.141	0.262	7.59	0.22
Virginia Lakes	VGL	9400	38.057	119.247	1947-2000	18.4	0.015	0.846	0.81	0.05
Virginia Lakes Ridge	VRG	9300	38.077	119.234	1969-2008	29.65	0.003	0.980	0.12	0.01

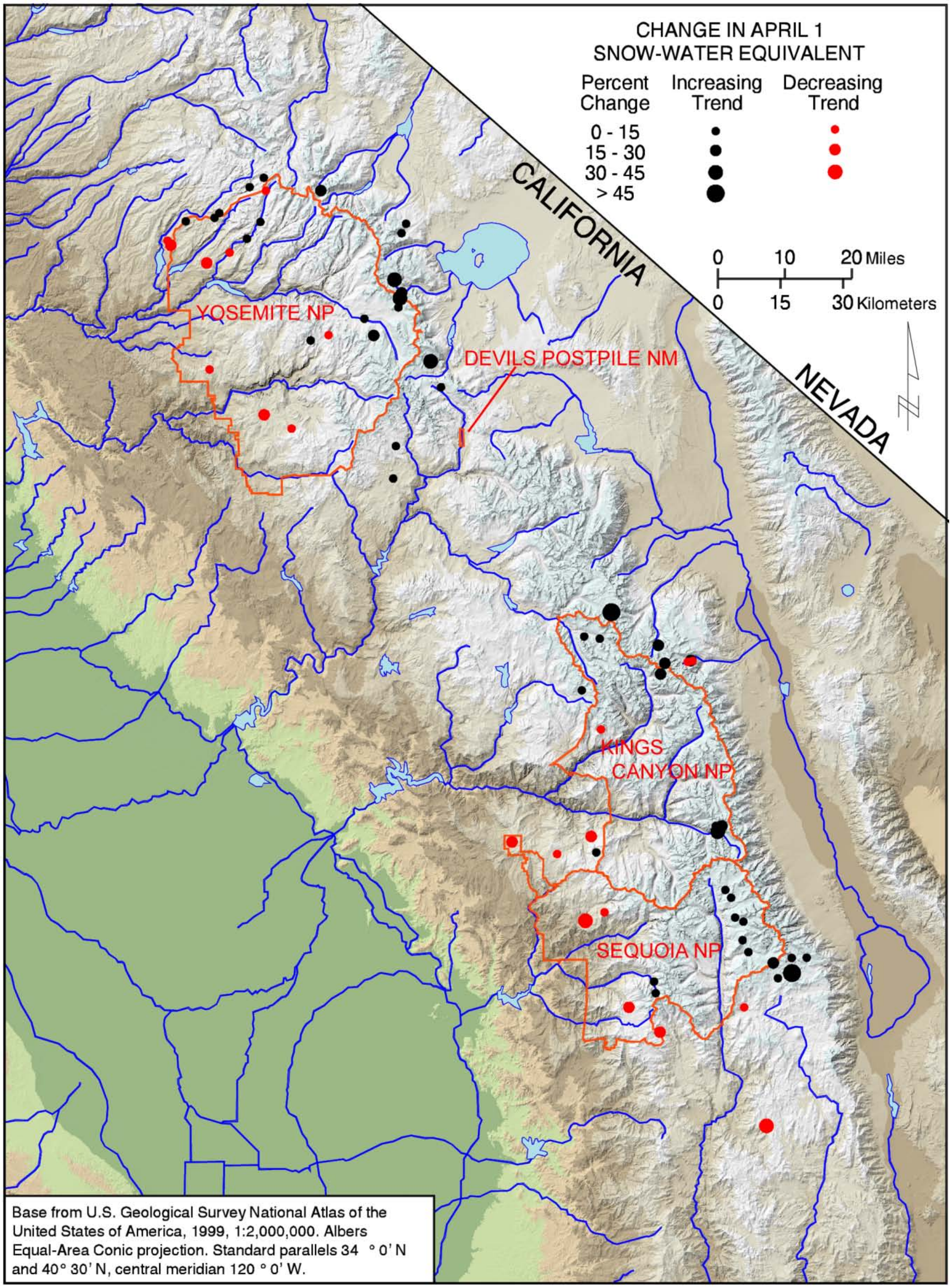


Figure 46. Map of the southern Sierra Nevada showing the locations of long-term snow courses and the observed trends in April 1 snow water equivalent.

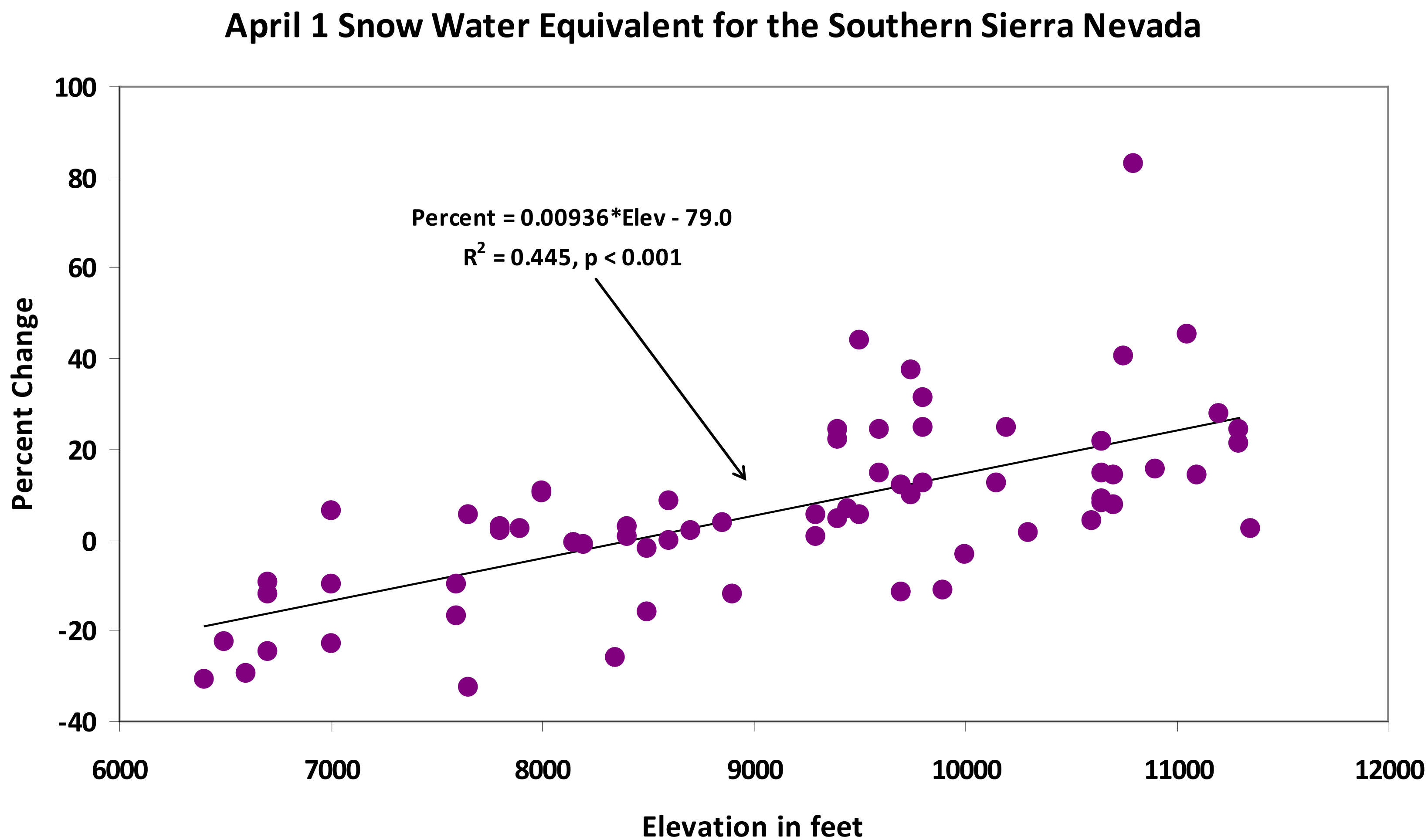


Figure 47. Variation in the percent change in April 1 snow water equivalent calculated along the linear trend line for the period of record versus the snow course elevation.

6. Considerations for the Development of a Hydrologic Monitoring Plan for the SIEN National Parks

The Sierra Nevada Network Vital Signs Monitoring Plan identified 13 vital signs for which monitoring protocols should be developed (Mutch et al. 2008). This study has considered the status and trends in two of the 13, namely snowpack and surface water dynamics. A third vital sign, wetland water dynamics, is closely related because wetlands will be affected by changes in nearby snow fields to shifts in the temporal distribution of snowmelt runoff, which typically represents more than 70 percent of the annual total water supply to wetlands. This study has identified a number of issues to be considered and addressed when developing a monitoring plan for the streams and snowpack of the SIEN national parks.

Issue 1: Multi-agency, regional-scale monitoring efforts are essential.

Essential information about the hydrology of the SIEN is provided by stream gaging stations and snow courses, many of which are located outside of the parks, operated by a number of federal, state, and municipal agencies as well as water supply districts and private corporations. National Park Service participation in the measurement and assessment of snowpack and streamflows throughout the greater southern Sierra Nevada region will be a cost-effective way to achieve a portion of the SIEN monitoring objectives for hydrology.

The southern Sierra Nevada region is the source of essential water supply to California. The cities of San Francisco and Los Angeles as well as the irrigated agriculture of the San Joaquin Valley depend upon runoff from the southern Sierra Nevada. A substantial portion of this runoff comes from the SIEN national parks. Major hydroelectric power generation facilities have been constructed on both the west and east slope in order to utilize the abundant runoff and steep topography.

An extensive network of streamflow gaging stations and snowpack survey courses have been established over the past 100 years to provide the information needed to develop and manage the water supply contributed by the southern Sierra Nevada. Although many of the measurement sites, especially the stream gages are located outside of the four national parks, the SIEN has benefitted from these observational networks, and will depend on them to a substantial degree in the future. Establishing and maintaining an equivalent hydrologic monitoring network within the SIEN would be very expensive. In the past, important decisions concerning whether to continue a streamgage or snowcourse, change the location or reconfigure facilities have sometimes been made by others without input from the National Park Service. This study examined all available long-term snow course and streamflow gaging station records to identify those records that describe hydrologic conditions within and adjacent to the SIEN. Twenty-seven gaging stations and 68 snow courses were identified and evaluated. Many of these gages and snow courses were established between 1910- 1950. Over the past few decades, and especially within the past 10 years, a number of the gaging stations and snow courses that provide hydrologic information directly relevant to the SIEN have been discontinued or reconfigured so that the current observations are no longer consistent with prior operations. During 2008, only seven of the 20 gage stations with long-term records of unimpaired daily flow and 50 of the 68 snow courses were active. The objectives of the SIEN hydrology monitoring program will be enhanced by maintaining as many of the existing measurement sites, and when possible, the re-establishment of some of these long-term gages that have been discontinued.

The vast majority of gaging stations operated by the USGS nationwide are supported by a cooperative funding agreement between the USGS and a non-federal governmental entity. All of the currently active gaging stations recording unimpaired flow within and adjacent to the SIEN are exceptions. The Merced River at Happy Isles Bridge and Pohono Bridge are part of the National Benchmark Network and funded by a direct Congressional Appropriation. Three of the gaging stations, Bear Creek near Lake Thomas A. Edison, Pitman Creek below Tamarack Creek, and Kern River near Kernville, are operated by Southern California Edison Company (SCE) with the supervision of the USGS as required by hydropower licenses issued by the Federal Energy Regulatory Commission (FERC). The streamgage on the Middle Fork of the Kaweah River, which was included in this study, is also operated by SCE.

One specific example will be discussed in order to highlight some of the relevant issues and future opportunities. Southern California Edison Company (SCE) operates hydropower generation facilities that divert flow from the branches of the Kaweah River. Some of the diversions occur within Sequoia National Park. The company operates the facilities under a license issued by FERC. The license requires SCE to gage in-channel flow below the diversion to demonstrate that certain minimum flows are satisfied. It is incidental that the manner in which the stream and diversions were gaged for nearly 50 years provided a record of unimpaired daily flows. FERC hydropower licenses are re-issued every 50 years. When the new licenses covering diversions from the Kaweah River were issued in 2001 and 2002, SCE was permitted to discontinue one of the gages, the Marble Fork Kaweah at Potwisha. The Middle Fork Kaweah at Potwisha and the combined flows of the Middle and Marble Forks near the powerhouse, as well as the discharge in the diversions (flumes), continue to be gaged. Additionally, the gage on the East Fork Kaweah diversion was moved. The calculated values for the East and Marble Forks of the Kaweah are available from SCE, however, it is difficult to estimate how close these values might be to the actual values that were previously available.

The Kaweah River streamgages operated by SCE record most of the runoff from Sequoia National Park west of the Great Western Divide. If a way could be found to once again measure the diverted flow at the point(s) of diversion on the Marble Fork of the Kaweah, so that the unimpaired streamflows could be determined, it would provide valuable hydrologic information concerning Sequoia National Park and meet objectives of the SIEN monitoring plan.

Issue 2: Deficiencies in numbers of gages, river basin sizes, and elevational ranges represented

The currently active streamgages considered in this study are deficient in a significant aspect and are unlikely to provide essential information needed to achieve the hydrologic objectives of the SIEN Inventory and Monitoring Program. The gaged river basins are relatively large, >20 mi^2, and span a wide range of elevation. Consequently, streamflows recorded at these gages represent the combined, integrated runoff from spatially diverse drainage basins. The streamflow records will not be sufficient to resolve hydrologic differences and trends in sub-basins distributed along the western slope of the Sierra Nevada from 3,000 to over 14,000 feet.

Hydroclimatologic model simulations supported by empirical evidence indicate that the magnitude and, in some instances, the direction of expected hydrologic changes during the coming century will vary substantially from the low to high elevation parts of the SIEN. Quite simply, the spatially-averaged mean for a given hydrologic quantity calculated for a relatively large drainage basin that extends from the Sierra crest to a gaging site in the western foothills will be representative of the larger watershed but will not allow the SIEN to obtain information about conditions within the smaller sub-watersheds.

Predicted changes in April 1 SWE through 2090 across the Sierra Nevada including the SIEN Parks are shown in Figure 48, which is reproduced from Knowles and Cayan (2002). These results were discussed previously in Chapter 2. The figure is presented here because it clearly illustrates an important hydrologic gradient from the low to high elevation parts of the SIEN. The predicted average decrease in April 1 SWE for all of the southern Sierra Nevada is about 30 percent by 2060. As shown in Figure 48, however, April 1 SWE is expected to decrease by 70 percent or more at the low to middle elevation part of the southern Sierra Nevada by 2060. Conversely, April 1 SWE in the high elevation catchments, those above 10,500 will remain essentially unchanged from late 20th Century conditions. The analysis of snow course measurements presented in Chapter 5 show that April 1 SWE has been increasing in catchments above 8500 feet during recent decades. Accordingly, the predicted changes in April 1 SWE across the Sierra Nevada elevation gradient shown in Figure 48 may actually understate the magnitude of change. For April 1 SWE as well as other aspects of the SIEN hydrology, average basin-wide conditions and trends determined for large river basins from records collected at far downstream gaging stations are unlikely to correctly represent significant parts of the upper portions of the basins.

The establishment of a more extensive stream gaging network in relatively small basins, <20 mi^2, would contribute significantly to the SIEN vital signs monitoring objectives. Some streamflow records exist for small, high elevation drainage basins, however, these records are either unavailable at this time or relatively short, <10 years. These streamflow records and the experience gained while collecting them do provide important insights with which to formulate a network of stream gages for the SIEN and will be discussed below. Streamflows have apparently been gaged at one or more locations in the upper Marble Fork of the Kaweah Watershed in Sequoia National Park for 18 to 25 years. The record of daily streamflow has not been made available by the investigators, so the quality of the record, especially period of estimated or missing record is unknown. It is quite possible that long-term streamflow records collected in this basin may be a valuable asset. The analysis of hydrologic trends in the previous sections has demonstrated that elevation, through the combined effects of temperature and precipitation, has and will continue to be a significant discriminating factor. Streamflows draining from a few, perhaps 5-10, small basins should be gaged in order to clearly define the hydrologic conditions and any trends that may develop.

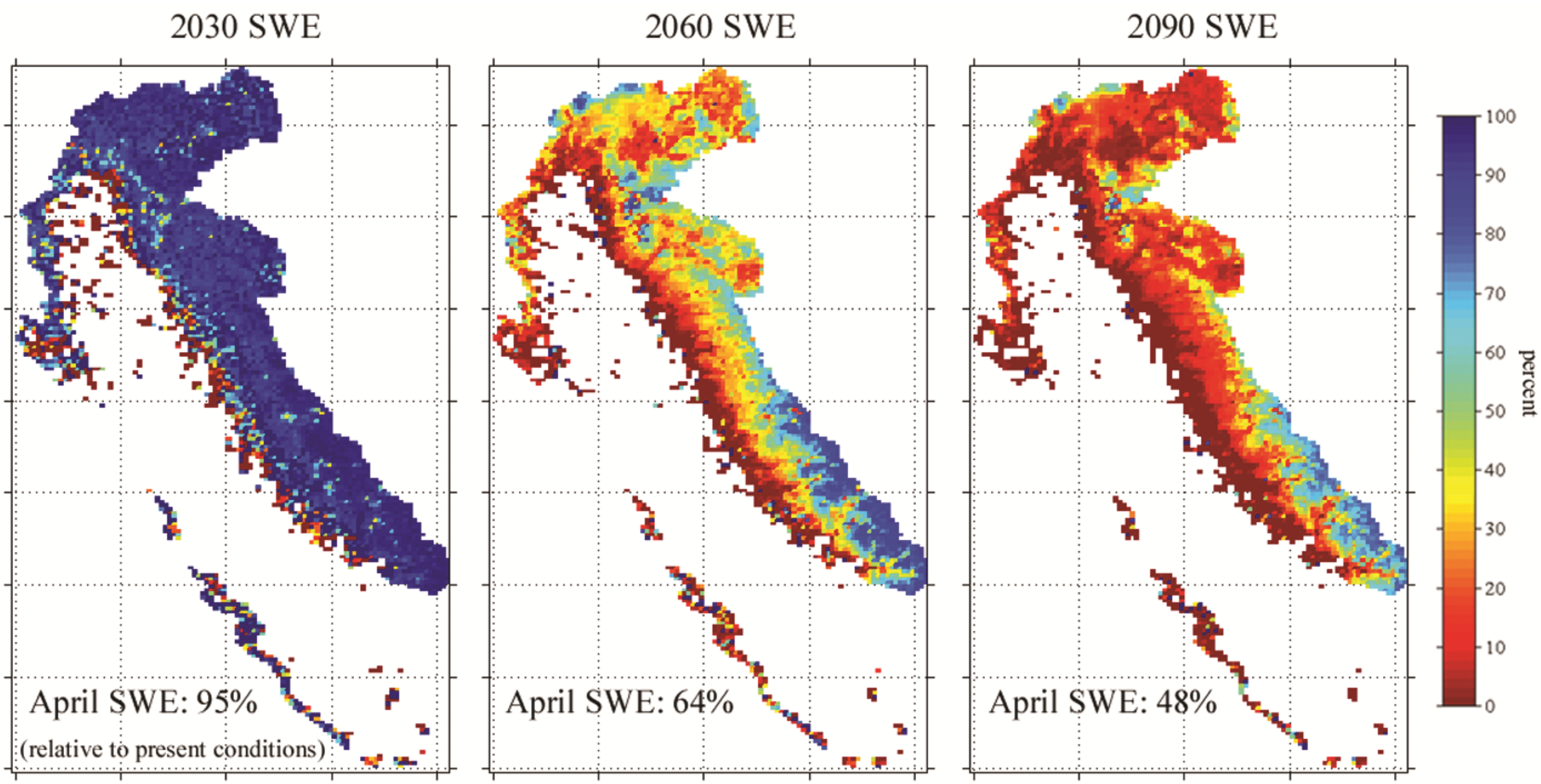


Figure 48. Predicted change in April 1 snow water equivalent in percent compared to mid-20th century due to calculated mean annual temperature increases of 0.6°C by 2030, 1.6°C by 2060, and 2.1°C by 2090. (Reproduced from Knowles and Cayan [2002] with authors' permission).

The establishment of a SIEN stream gaging network will need to address and resolve, to some degree, at least three challenges:

1. Gage instrumentation and facilities that are compatible with the wilderness setting, within designated wilderness boundaries or nearby.
2. The frequency and travel time required to visit a streamgage.
3. The effects of ice buildup within channel upon the stage-discharge relation.

Unless suitable instrumentation, methods, and procedures are developed and applied consistently over time, any one of these challenges would be sufficient to compromise the streamflow records to the extent that uncertainty obscures the trends and details the hydrologic network is designed to detect. The challenge can be resolved substantially, although not entirely, by the selection of favorable stream reaches in which to gage. The ideal location for a SIEN backcountry gage is a naturally flume-like reach with a southern exposure.

The standard USGS gaging station is a cost-effective design that has evolved over decades to provide a stable measurement platform and protect the instruments, within limits, from flood, floating debris, ice, bank erosion, appreciable changes in stream bed elevation, and vandalism. The structures are substantial and commonly involve a significant quantity of concrete. The standard USGS gaging station structure is unlikely to be regarded as consistent with wilderness values.

The Yosemite Hydroclimate Project (a consortium of USGS and academic researchers working collaboratively to make distributed measurements of temperature, humidity, water depth, and streamflow in the upper Merced and Tuolumne River watersheds) has successfully operated 20 or more gaging stations annually since 2001. Our experience indicates that it is possible to locate and operate gaging stations that are largely, if not entirely, concealed and require minimal disturbance of the stream bed and banks. The integrity of the gaging station is not as substantial as a standard USGS design; however, increased risks have been, for the most part, acceptable. The most reliable gaging stations are those located in very stable reaches, i.e. an abundance of exposed bedrock in the channel bed and bank, together with boulders which can be entrained by only the most extreme flood, if at all. The bed and banks of most stream channels are composed primarily of alluvium, sediment particles that the stream has previously deposited and which it is likely to entrain again. Stream channels draining the small high elevation basins through the SIEN are typically not alluvial. It would be possible to select very stable reaches in which to locate gaging stations. In short, the natural stability of the selected reach is substituted for the structural stability of standard gaging station infrastructure.

Typical gaging stations are visited every two to six weeks to make discharge measurements, check for shifts in the stage-discharge relation, and download the record of river stages, where real-time satellite data links are not available. The time required to hike or ski to gages located throughout the SIEN backcountry would make frequent site visits impractical. The selection of highly stable reaches, which have stable stage-discharge relationships, will minimize the need for frequent site visits.

In recent years, an approach founded on fluid dynamic principles has been developed to calculate stage-discharge relations based upon only a detailed channel survey (Kean and Smith 2005). An example of this approach is shown in Figure 49 for Clyde Creek, one of the streams gaged by the Yosemite Hydroclimate Project. The stage-discharge curve was computed solely from a channel survey. The plotted discharge measurements are shown for comparison. This result demonstrates that highly accurate stage-discharge relations can be obtained without making dozens of discharge measurements with a current meter over the range of prevailing streamflows. Utilizing analytical stage-discharge relations together with a few current meter discharge measurements per year will likely produce a highly accurate and reliable stage-discharge relation for stream gages with very stable cross-sections. The number of required site visits per year may be as few as 3 to 4.

Identifying a group of 10 or so drainage basins distributed throughout the SIEN, with a range of desired characteristics and reasonably accessible streamgages, will require some thought as well as inevitable trade-offs. Many high elevation basins can be reached within a few hours hike from the Tioga Pass and Devils Postpile Roads. The Yosemite Hydroclimate Project has operated approximately two dozen stream gages in the vicinity of Tuolumne Meadows. Most of these gages can be served with a day trip. Many of the gages are adjacent to the road or within a short hike. Several years of flow record have already been collected at these gages, and there are a number that would be ideal candidates for the SIEN monitoring program. Similarly, there are a number of drainage basins above 9000 feet, which can be reached in a few hours from the Devils Postpile Road. These drainage basins are not within Devils Postpile, although they contribute runoff to SIEN.

Site visits to streamgages in drainage basins above 9,000 feet in SEKI will require more time and effort. Co-locating a stream gage at a site together with other physical and ecological monitoring would likely yield multiple benefits and be an efficient use of time. Alternately, or in addition, gaging stations could be located near one or more of the wilderness ranger stations, such as Bench Lake, Granite Basin, and Rock Creek. In summary, it would seem reasonable to budget annually about one week for site visits and one week in the office to calculate daily streamflows per gage. Thus, a network of 10 stream gages in relatively small, high elevation drainage basins would likely require one-half of a full time position.

The accumulation of ice, or typically an ice/snow mixture, within stream channels when and wherever daily minimum temperature consistently falls below 20°F can cause significant changes to channel configuration, and thus, the stage-discharge relationship. Appreciable accumulations of ice within a channel for periods of days to months are a substantial impediment to the collection of accurate stream records. The difficulties should not be minimized and cannot be totally avoided when frigid conditions prevail. The buildup of ice and snow on the channel bed and banks reduces the channel area. Flow depth and stage are increased for a given discharge above what would otherwise be the condition when the channel is free of ice. Thus, the buildup of channel ice will indicate a larger apparent discharge than actual. The buildup of channel ice typically causes the largest relative errors in flow estimation during December and January, though substantial effects can extend well into the snowmelt runoff season if the gaged cross-section happens to be under a snow bank.

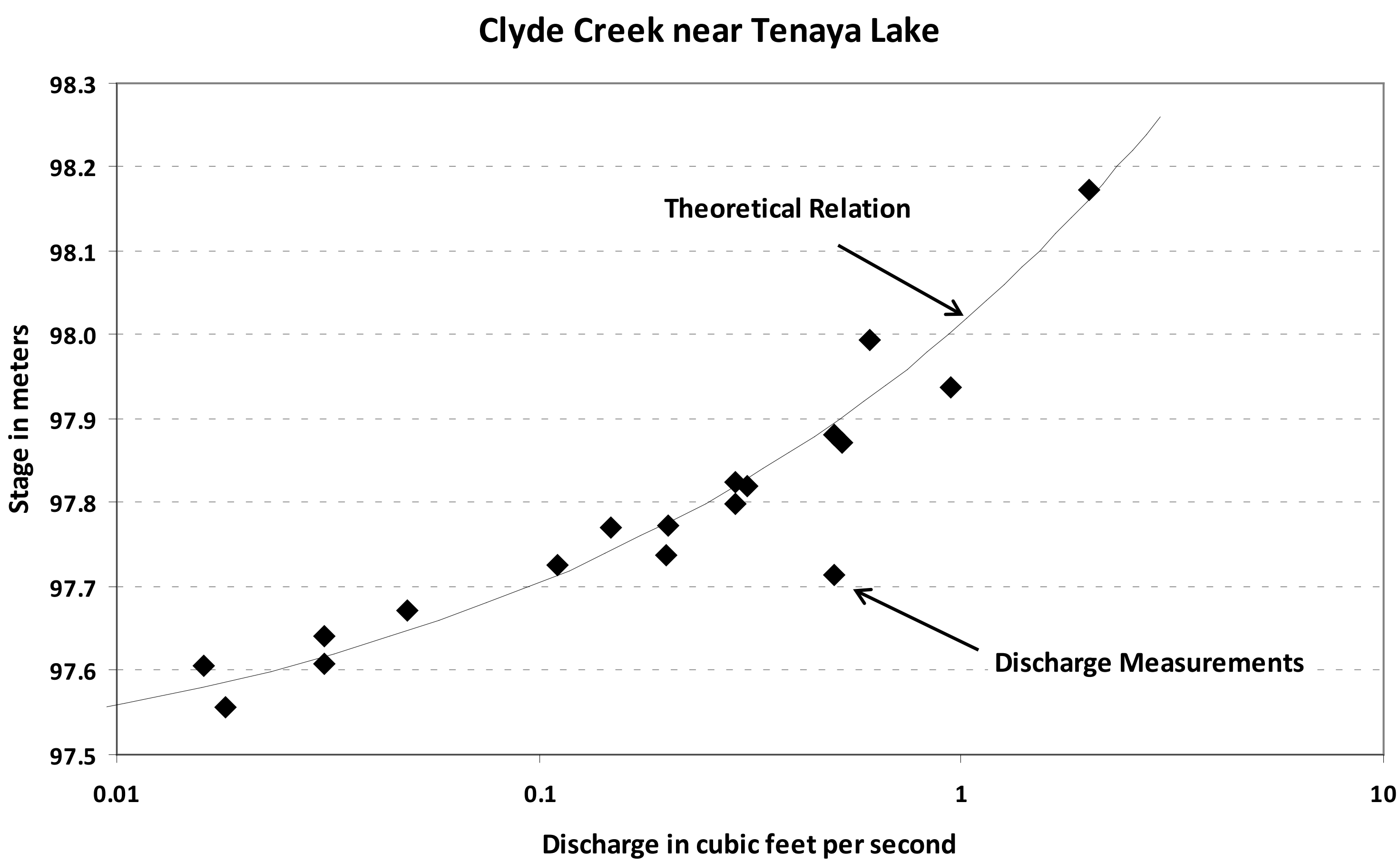


Figure 49. Comparison of theoretically derived stage-discharge with measured discharges made in Clyde Creek near Tenaya Lake.

The accumulation of channel ice is considerably less in reaches that receive a good deal of sunlight, even when the air temperature may be well below freezing. Even at relatively high elevations in the SIEN, snow and ice will melt on south facing bedrock surfaces within a few days after a storm. Selecting stream gage sites that receive maximum sun exposure will significantly reduce the measurement uncertainty and errors created by the buildup of channel ice. Seeking to locate gaging stations in reaches with maximum sun exposure does not limit or require that the drainage basin has a predominantly south exposure.

Water temperature is an important, and in some instances, a critical attribute or cue for the aquatic ecosystem. At relatively low flow, water temperature responds quickly to changes in air temperature and sunlight, as well as the source and volume of flow. Except at the Merced River at Happy Isles Bridge, water temperature has not been measured consistently anywhere in the SIEN. Instrumentation to measure and record water temperature is inexpensive and easily concealed in a stream channel. Water temperature should be recorded at all stream gaging stations established for the SIEN monitoring program. It would be quite feasible and worthwhile to record water temperature longitudinally along a channel through reaches with a variety of geomorphic settings and ecological communities.

Issue 3: Use of simpler, lower impact equipment recommended to address some questions

Many of the ecologically relevant questions concerning the temporal and spatial distribution of water across the SIEN can be evaluated and answered using less costly and more wilderness compatible methods and techniques than the streamflow gaging station.

Conventional streamflow gaging stations are designed and operated primarily to provide the information required to manage water supply facilities and protect against floods, such as daily, monthly, and annual runoff volume as well as the instantaneous annual maximum discharge. Gaging stations will, most certainly, continue to be an important and, most likely, essential component of any SIEN vital signs monitoring program. These are not, however, the only approaches for hydrologic monitoring. Many hydrologic attributes of aquatic and riparian ecosystems can be measured using much simpler, less costly and wilderness-compatible methods and techniques. There are, in fact, an abundance of hydrologic monitoring instruments and techniques that would provide valuable information. New instrumentation and applications are being developed at a rapid pace. The following examples are illustrative of only some of the opportunities and possibilities.

1) **Water temperature** is a principal controlling factor influencing an aquatic ecosystem. A variety of small, relatively inexpensive devices are available to measure and record temperature. They can be deployed for a year at a time. Retrieval, downloading, and redeployment takes only a few minutes. Several water temperature recorders could be deployed longitudinally along a select stream and maintained with only a few days of effort per year.

   Water temperature is especially sensitive to small changes in water discharge during periods of low flow. In some stream reaches, water temperature may provide a superior method to determine ecologically significant changes in streamflow. In mid-to late summer when temperature stresses are greatest, water temperature will spike upward again when the channel dries. The dates on which a) an ecologically significant temperature was exceeded, b) longitudinally continuous flow ceases, and/or c) pool refugia dry out would be worthwhile and informative attributes to monitor.

2) **Flow depth and area inundated**, which can be determined directly from the stream water surface elevation (stage), are typically more relevant flow characteristics when evaluating the aquatic ecosystem than is the associated discharge. When and where the water discharge does not need to be determined, stream stage can be measured and recorded without the time-consuming effort to make numerous discharge measurements over a wide range of stages and construct a stage-discharge relationship. Among the several advantages of monitoring stream stage rather than discharge is that the challenges posed by ice-buildup in the vicinity of the gage are largely, though not entirely, avoidable. As described above, the buildup of channel ice alters the hydraulic characteristics of the channel and distorts the stage-discharge relation at the gage. When channel ice is present, a stage recorder measures the correct water surface elevation, channel depth and area of inundation. The water slope, flow velocity, and discharge, however, are not the same as when the ice is absent.

   Crest stage gages are commonly used and are a straightforward way to determine the maximum stage over some period of time, typically a year. A crest stage gage can be constructed from a length of PVC pipe, a meter stick and some ground cork. They are inexpensive, easy to deploy in a concealed location, and the annual maximum water surface elevation is measured directly.

3) **Soil moisture** is an important metric in understanding vegetation patterns and trends. Soil moisture probes have been improved greatly in recent years. They are now much more accurate and cost less, although they are not inexpensive. A network of soil moisture probes would probably be most valuable where they are deployed at sites where the status of other vital signs such as wetlands and/or forest dynamics are being monitored.

4) **Evaporation rates** from water bodies could provide useful information about how warming temperatures are affecting water levels in lakes and ponds. Pan evaporation rates do not provide a representative measure of evaporation from lakes and ponds. They are, however, inexpensive and provide a consistent reproducible measure of evaporation. A network of evaporation pans at carefully selected sites could provide valuable information concerning long-term trends in evaporation from water bodies.

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Appendix A. Flood Frequency

Figures

Page

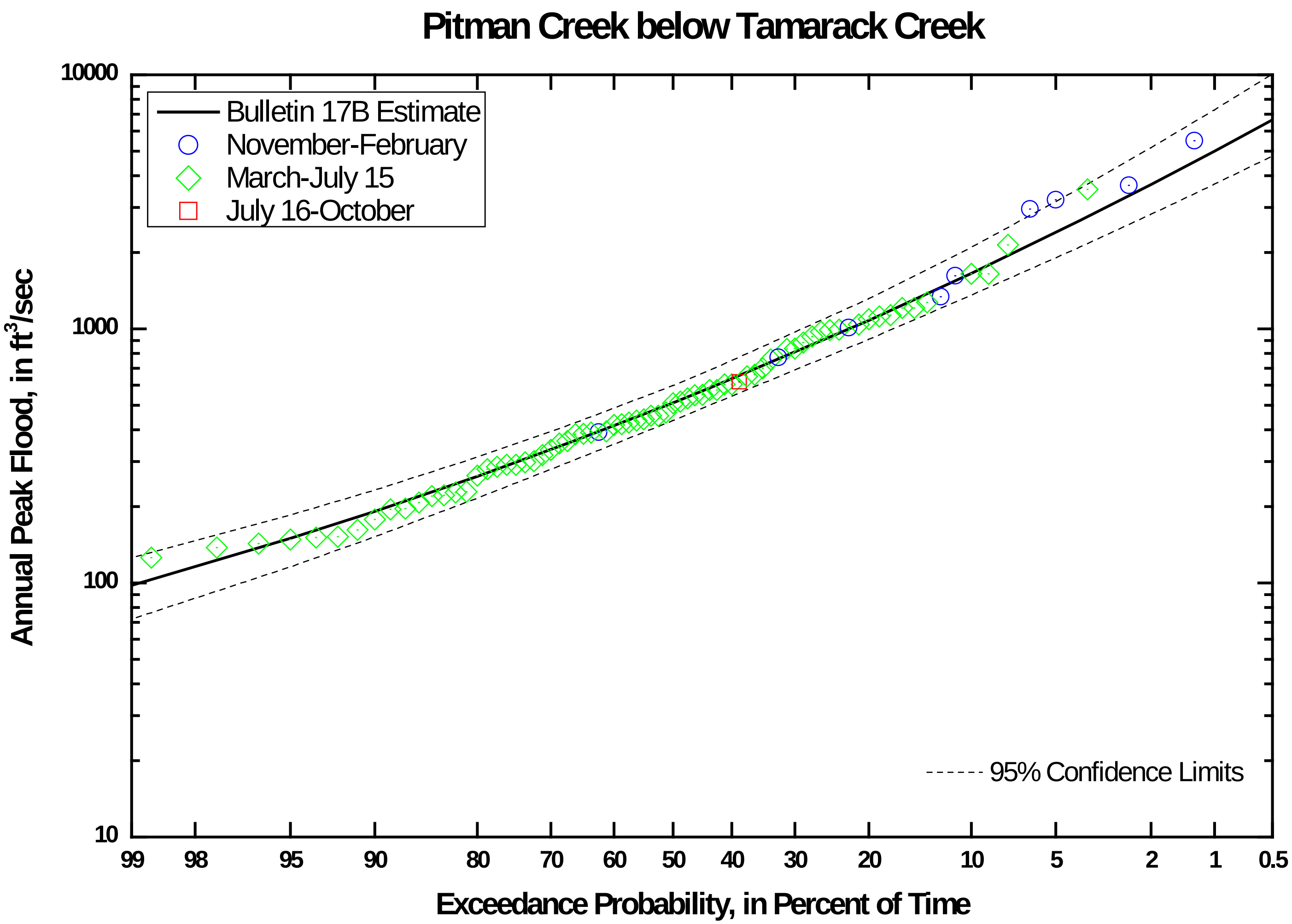


Figure A1. Calculated frequency of annual peak floods at Pitman Creek below Tamarack Creek and observed annual peak floods.

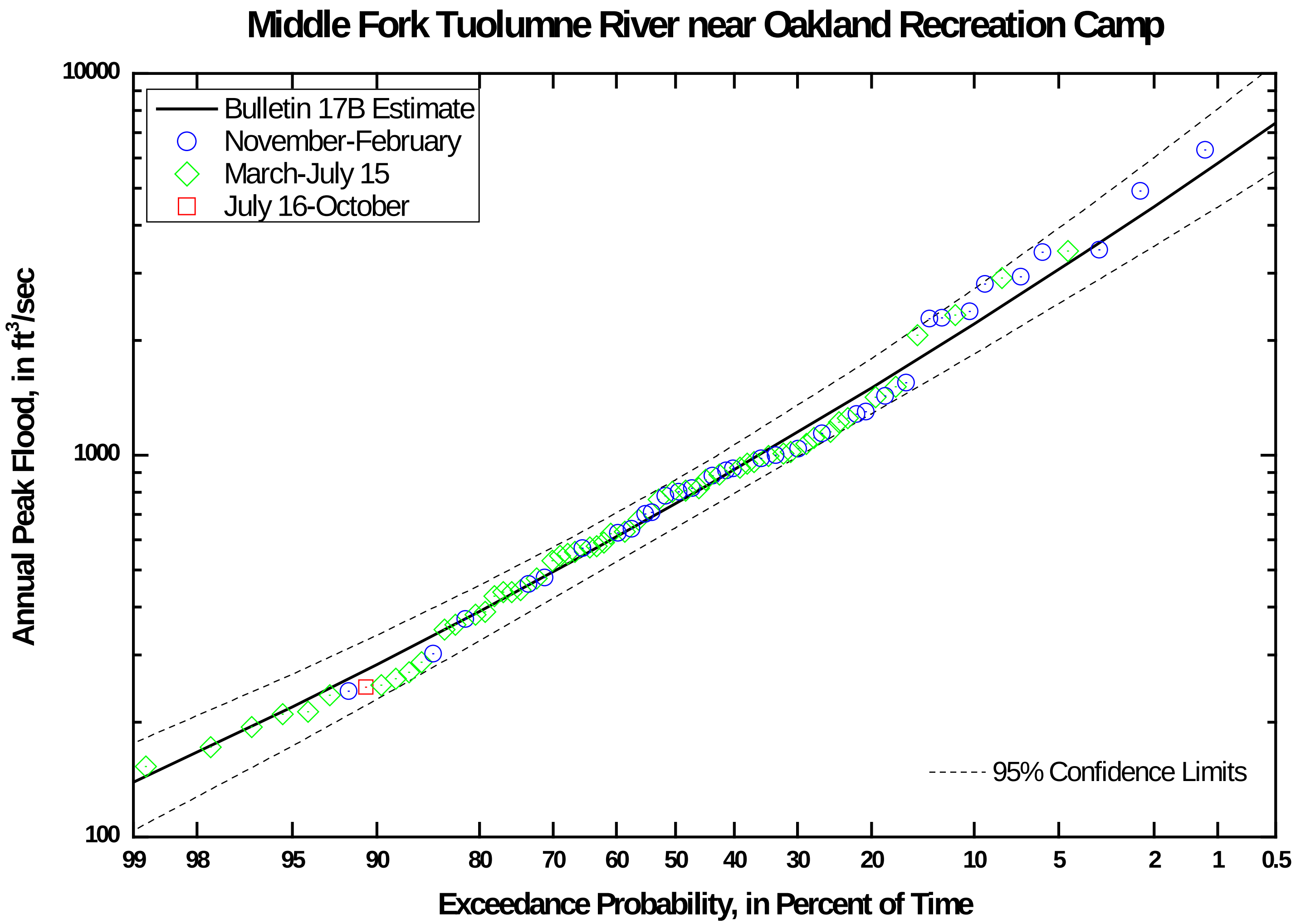


Figure A2. Calculated frequency of annual peak floods at Middle Fork Tuolumne River near Oakland Recreation Camp and observed annual peak floods.

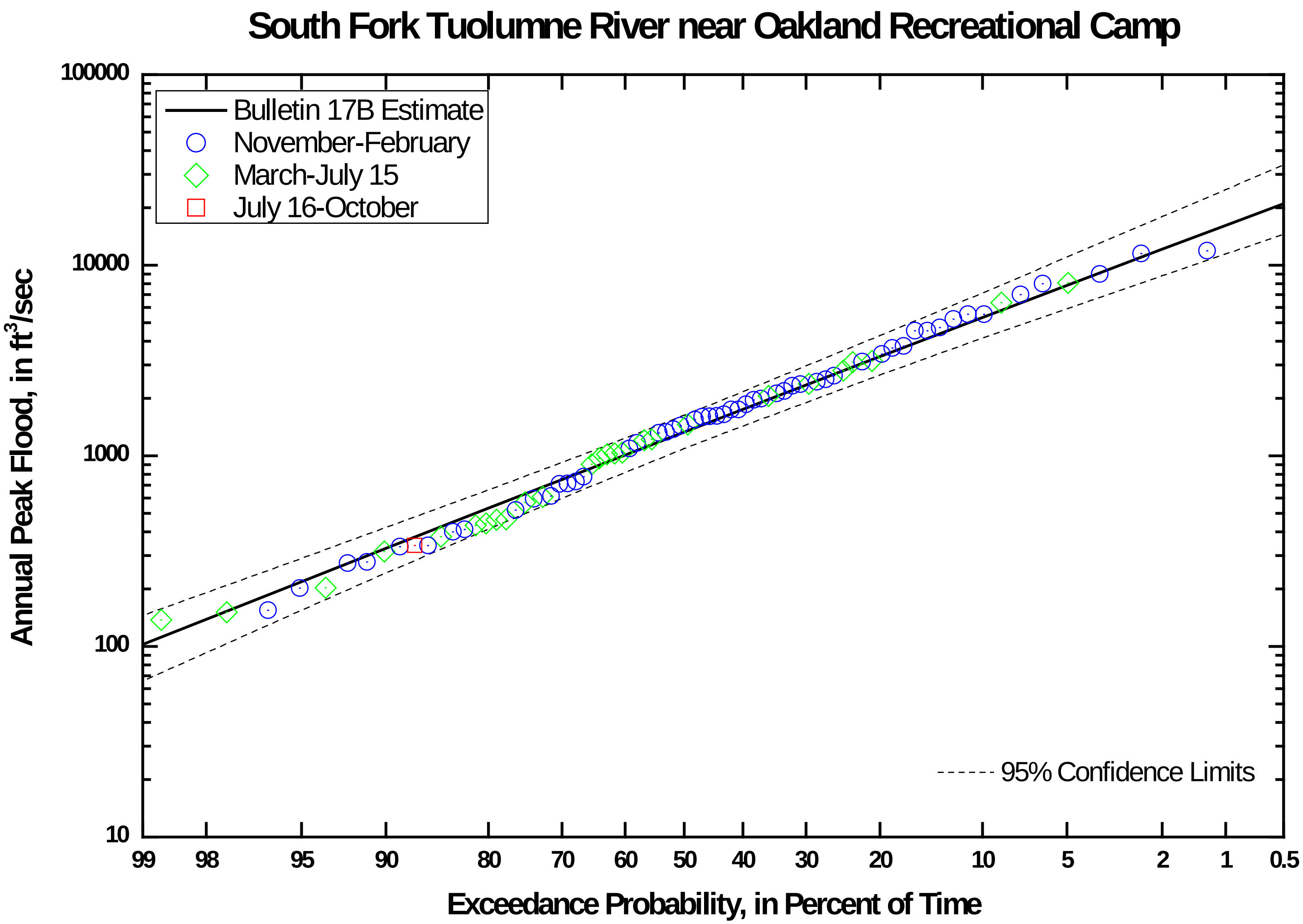


Figure A3. Calculated frequency of annual peak floods at South Fork Tuolumne River near Oakland Recreation Camp and observed annual peak floods.

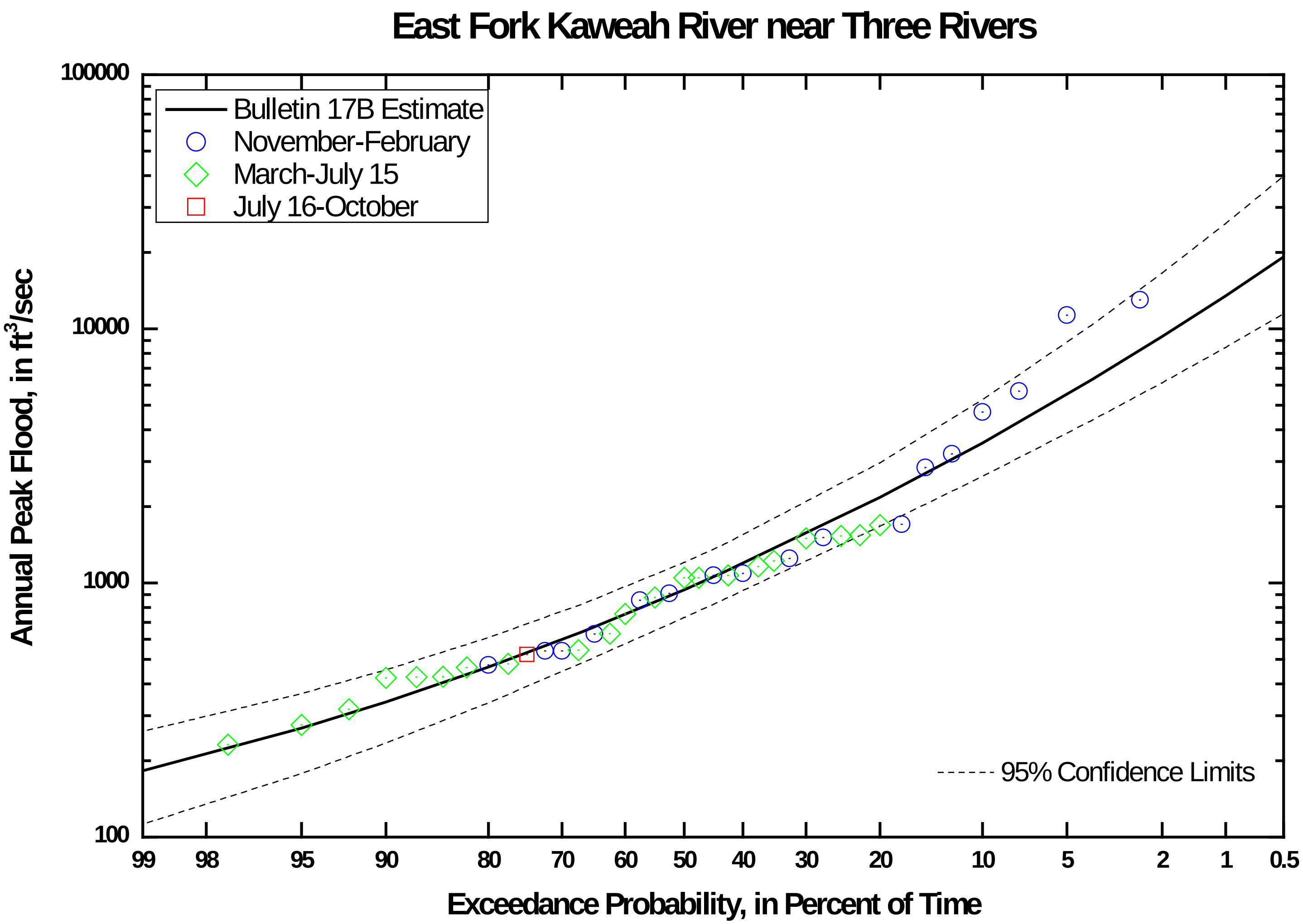


Figure A4. Calculated frequency of annual peak floods at East Fork Kaweah River near Three Rivers and observed annual peak floods.

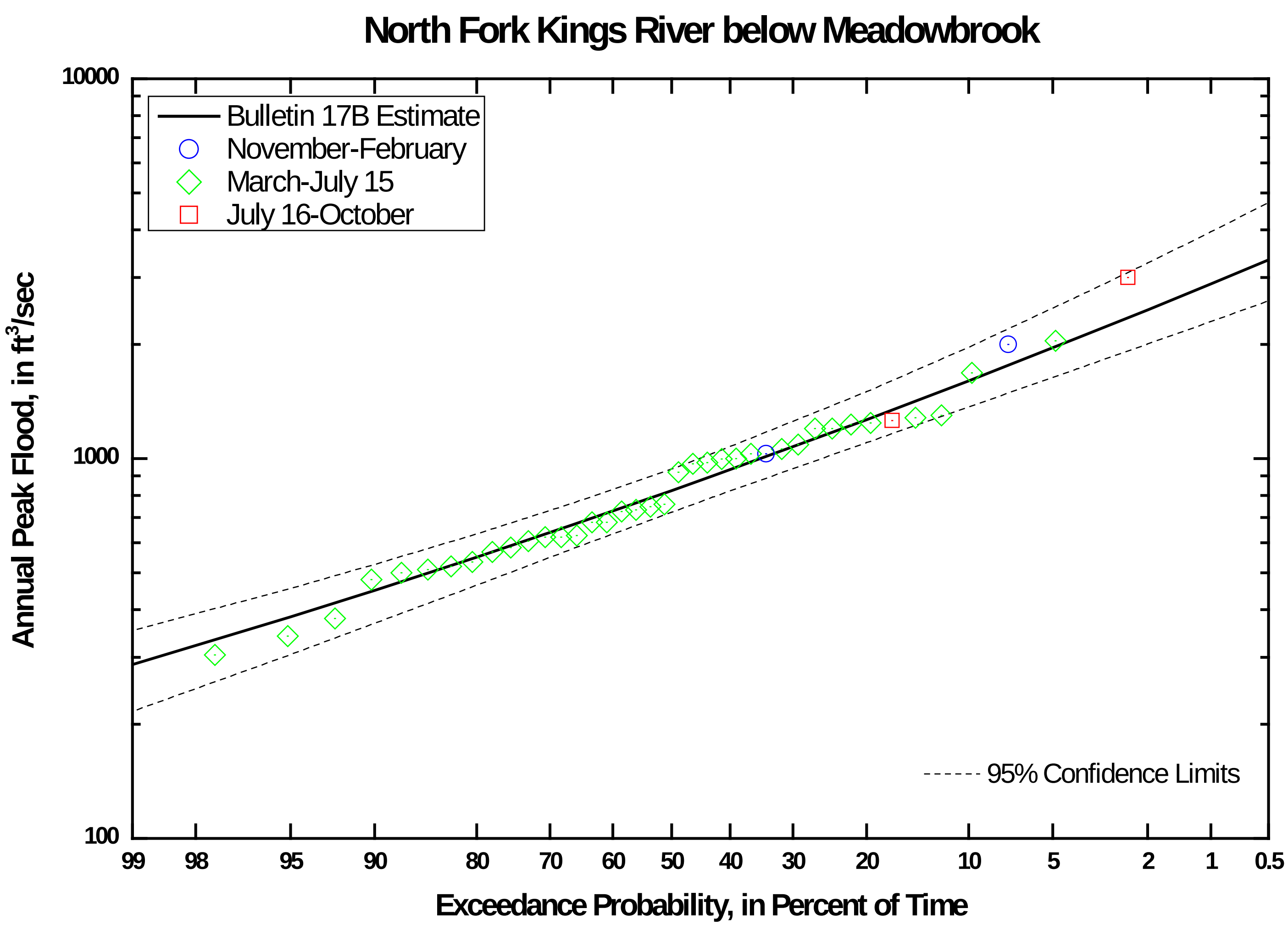


Figure A5. Calculated frequency of annual peak floods at North Fork Kings River below Meadowbrook and observed annual peak floods.

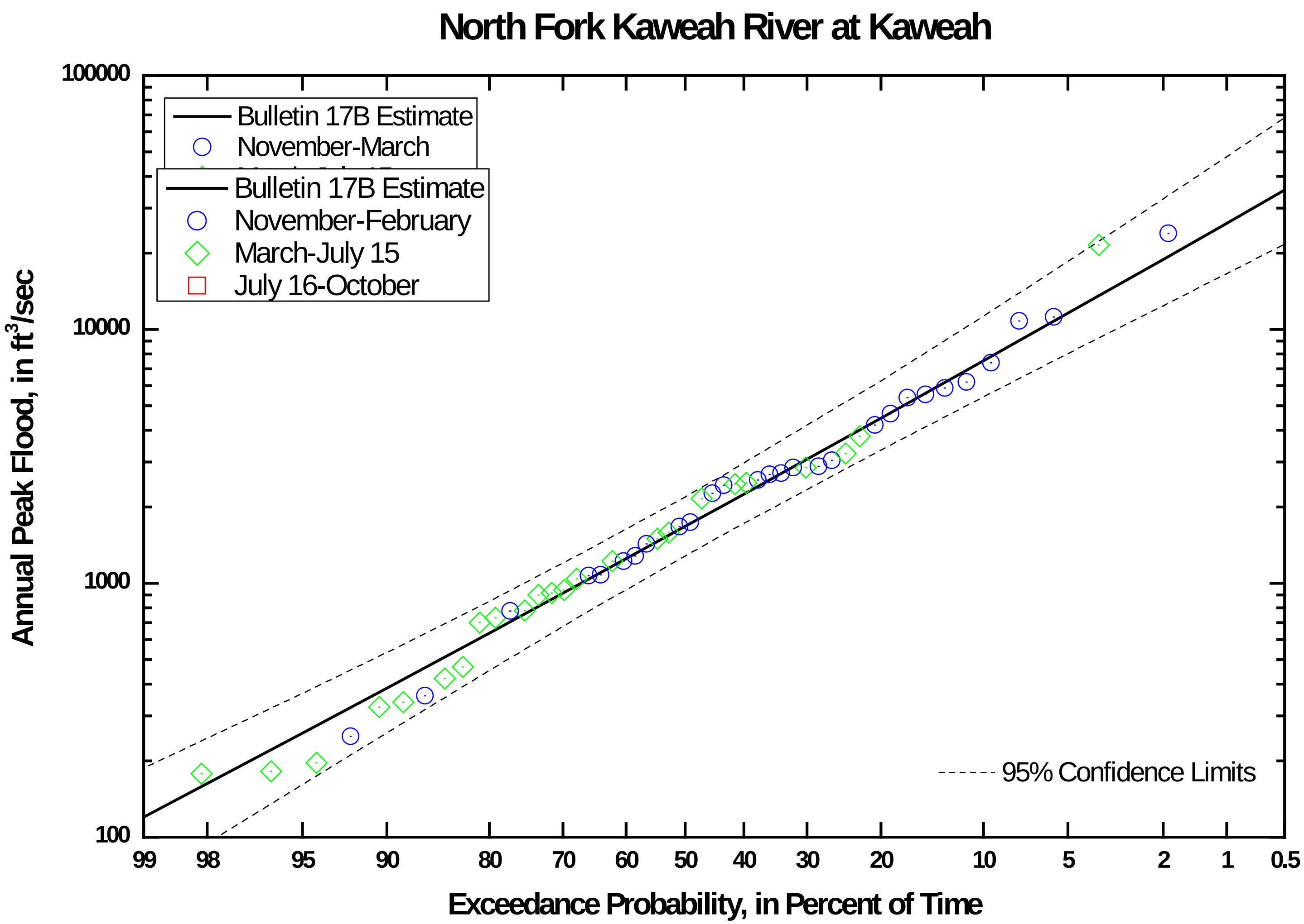


Figure A6. Calculated frequency of annual peak floods at North Fork Kaweah River at Kaweah and observed annual peak floods.

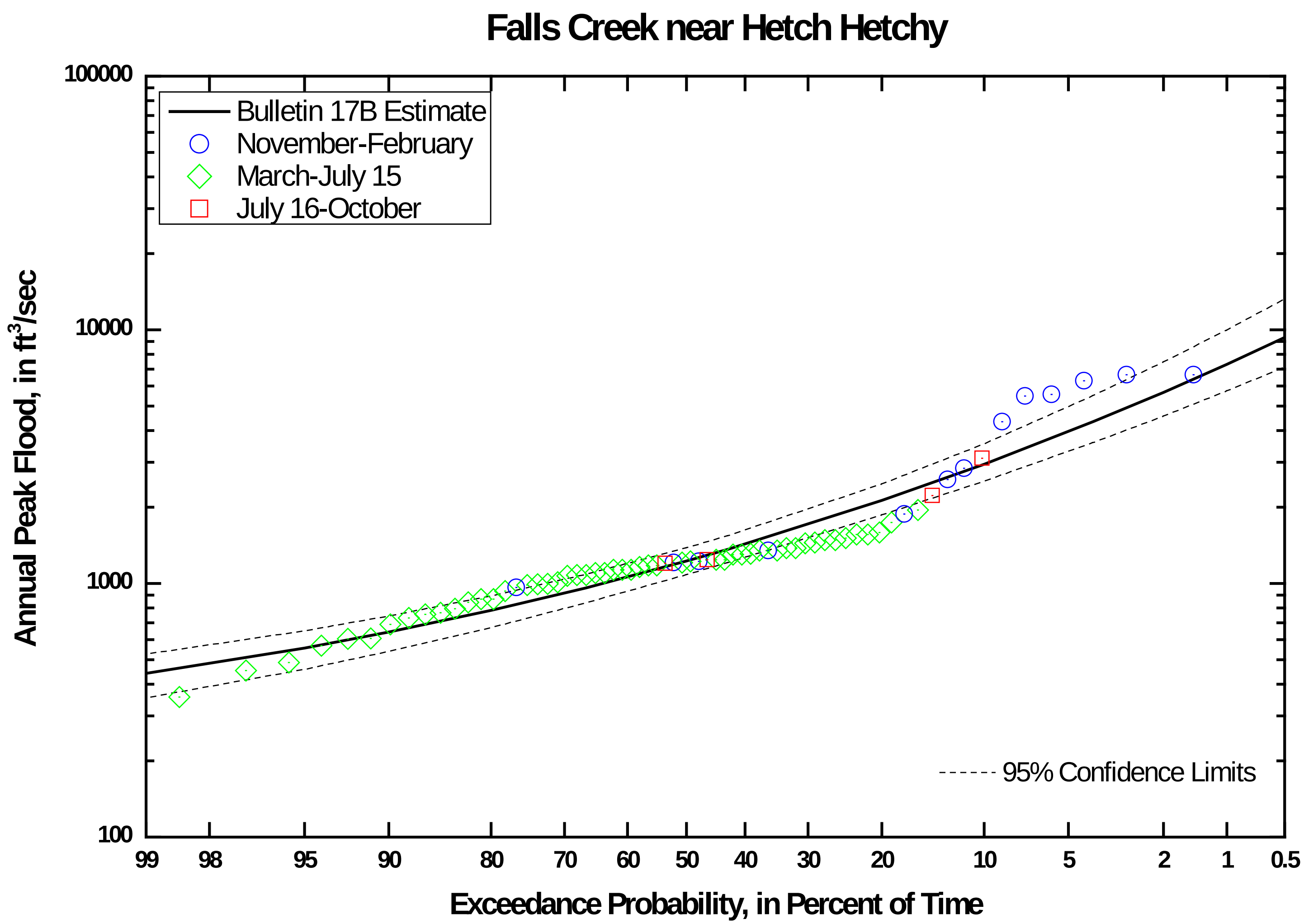


Figure A7. Calculated frequency of annual peak floods at Falls Creek near Hetch Hetchy and observed annual peak floods.

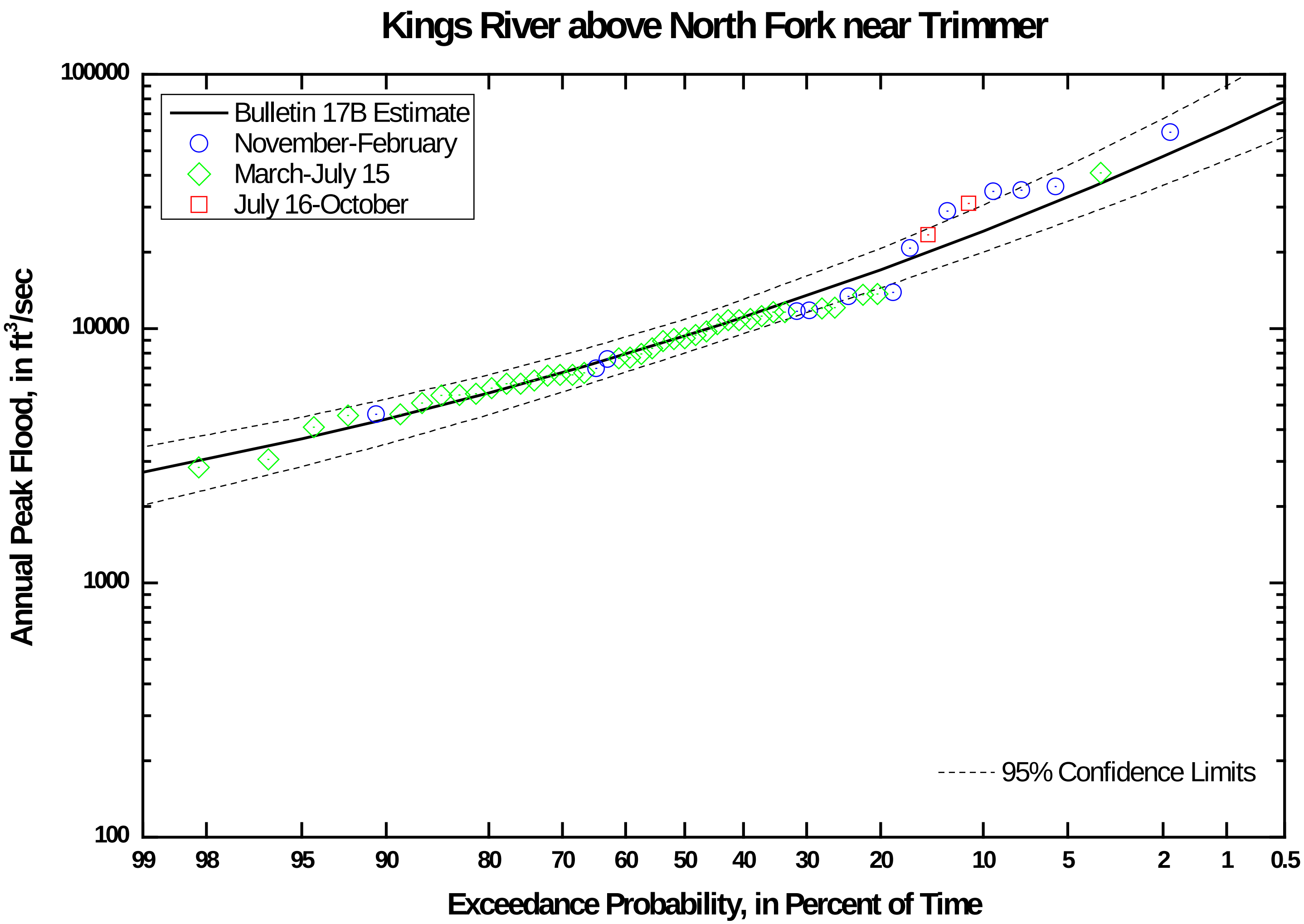


Figure A8. Calculated frequency of annual peak floods at Kings River above North Fork near Trimmer and observed annual peak floods.

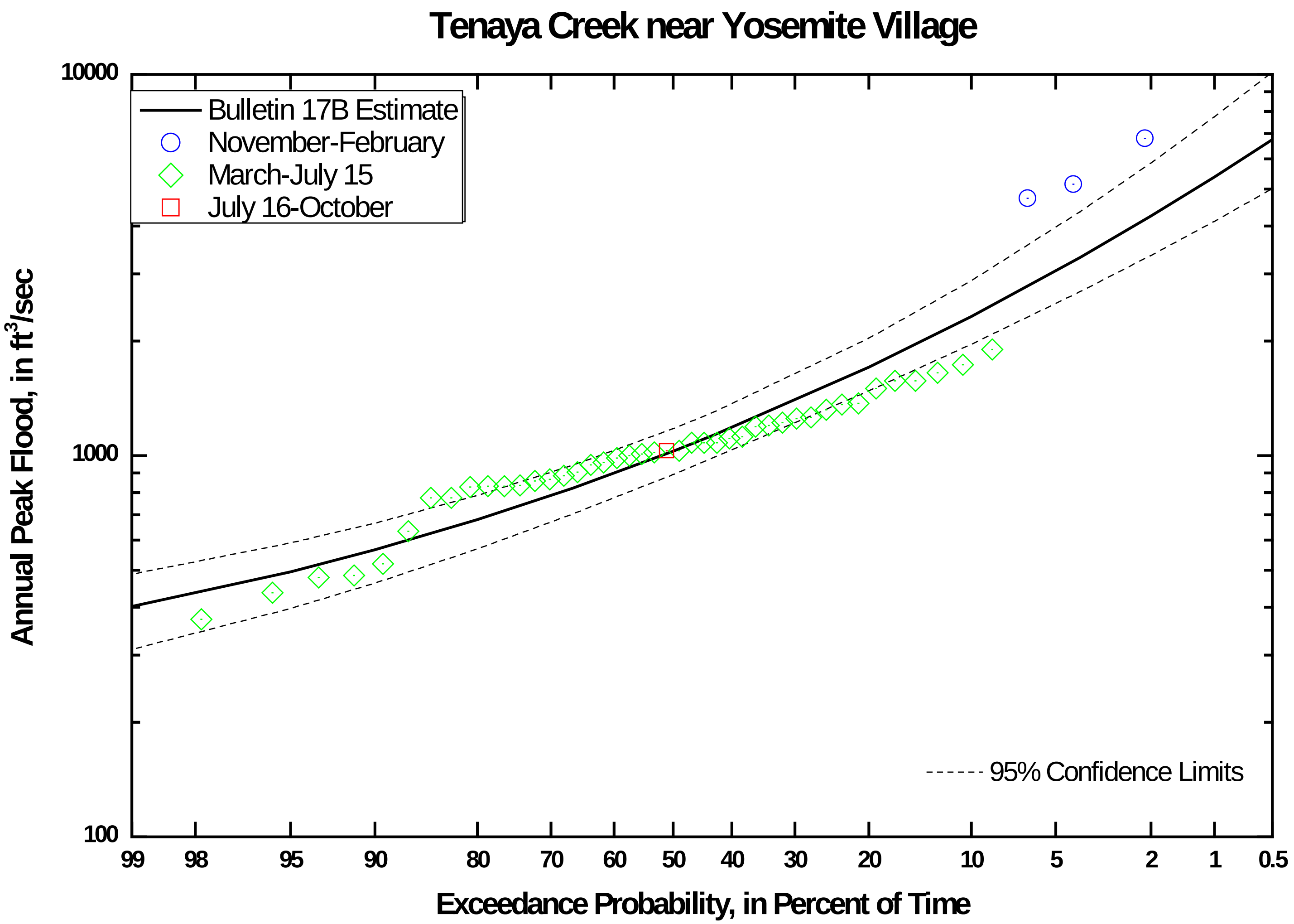


Figure A9. Calculated frequency of annual peak floods at Tenaya Creek near Yosemite Village and observed annual peak floods.

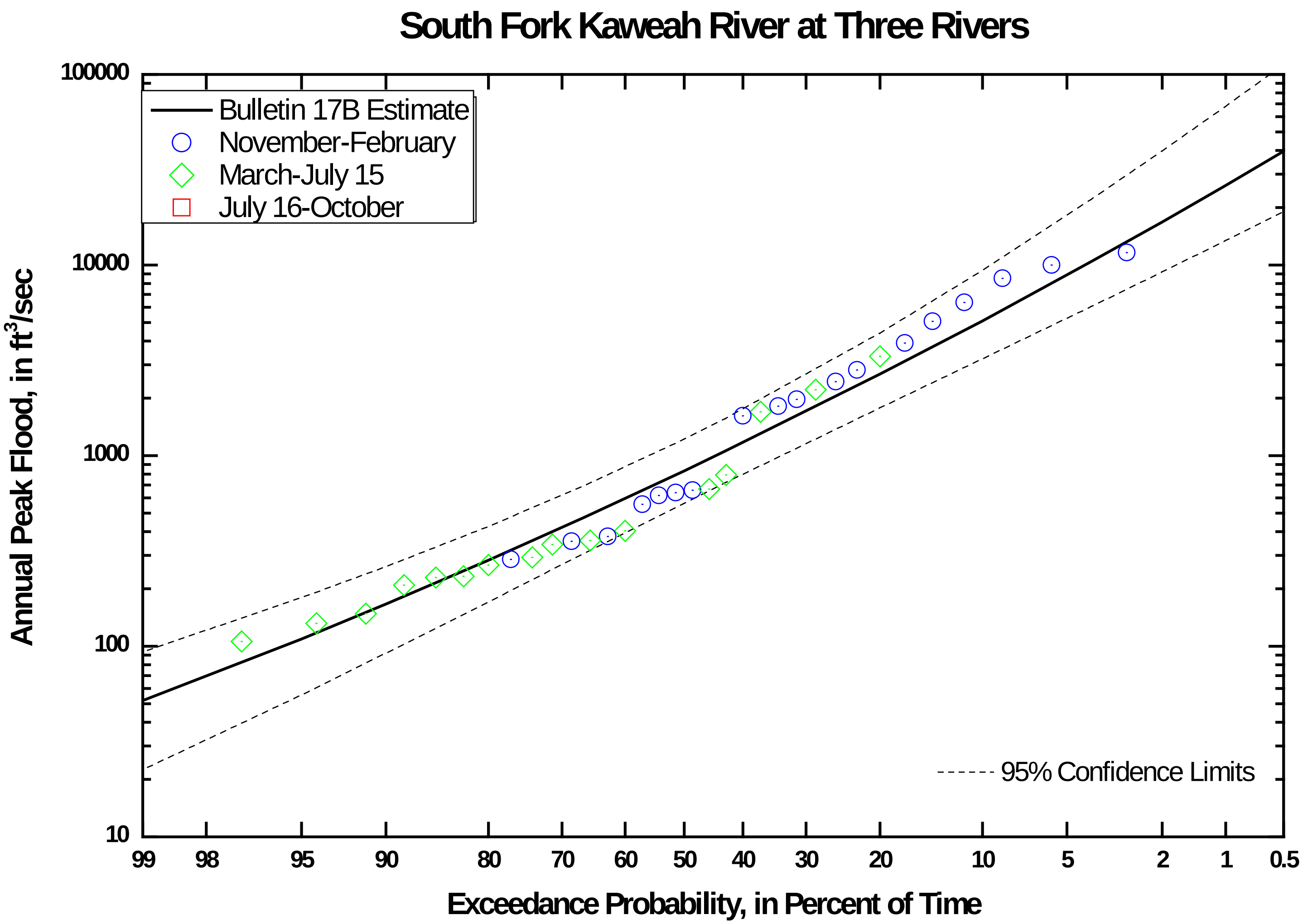


Figure A10. Calculated frequency of annual peak floods at South Fork Kaweah River at Three Rivers and observed annual peak floods.

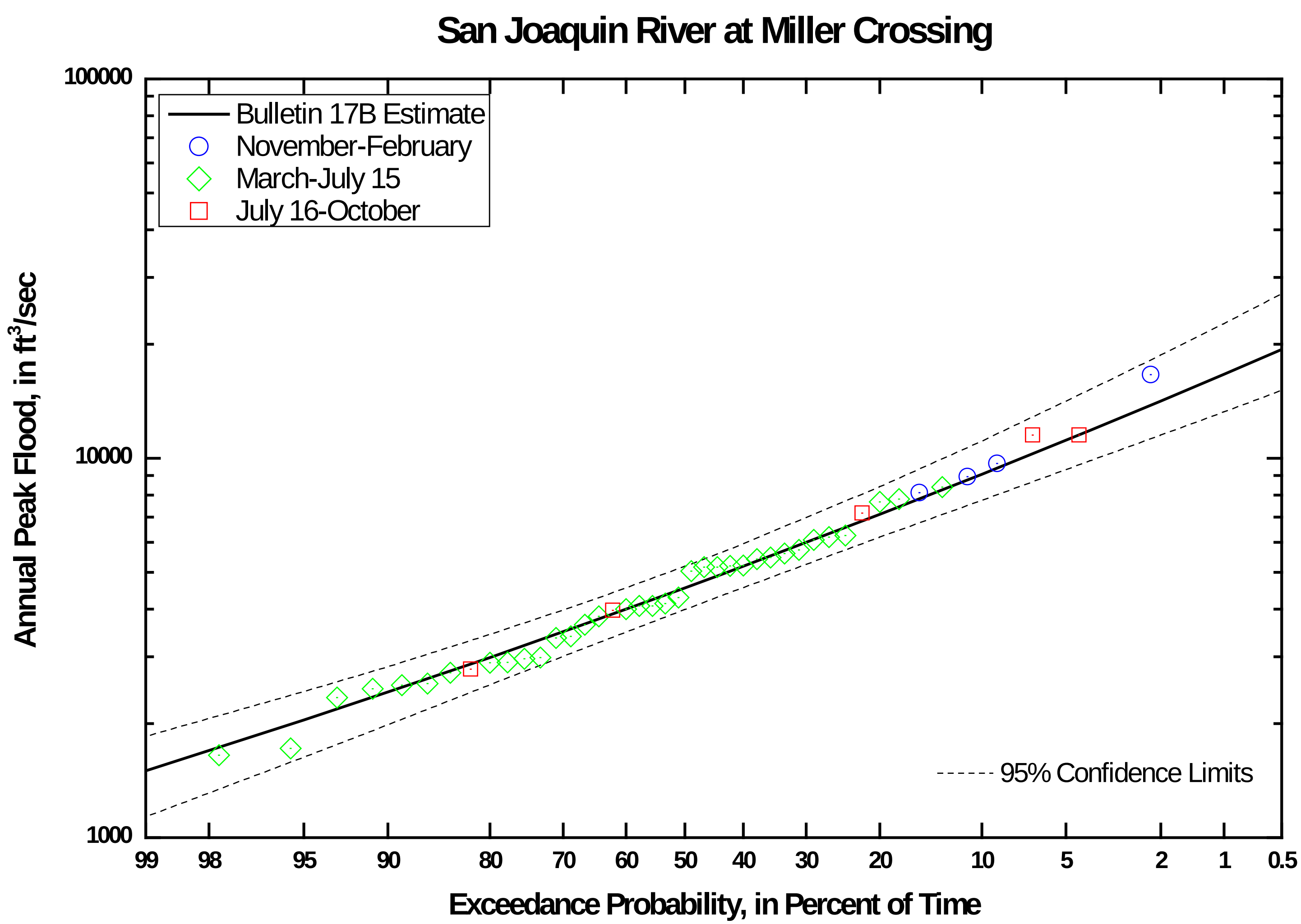


Figure A11. Calculated frequency of annual peak floods San Joaquin River at Miller Crossing and observed annual peak floods.

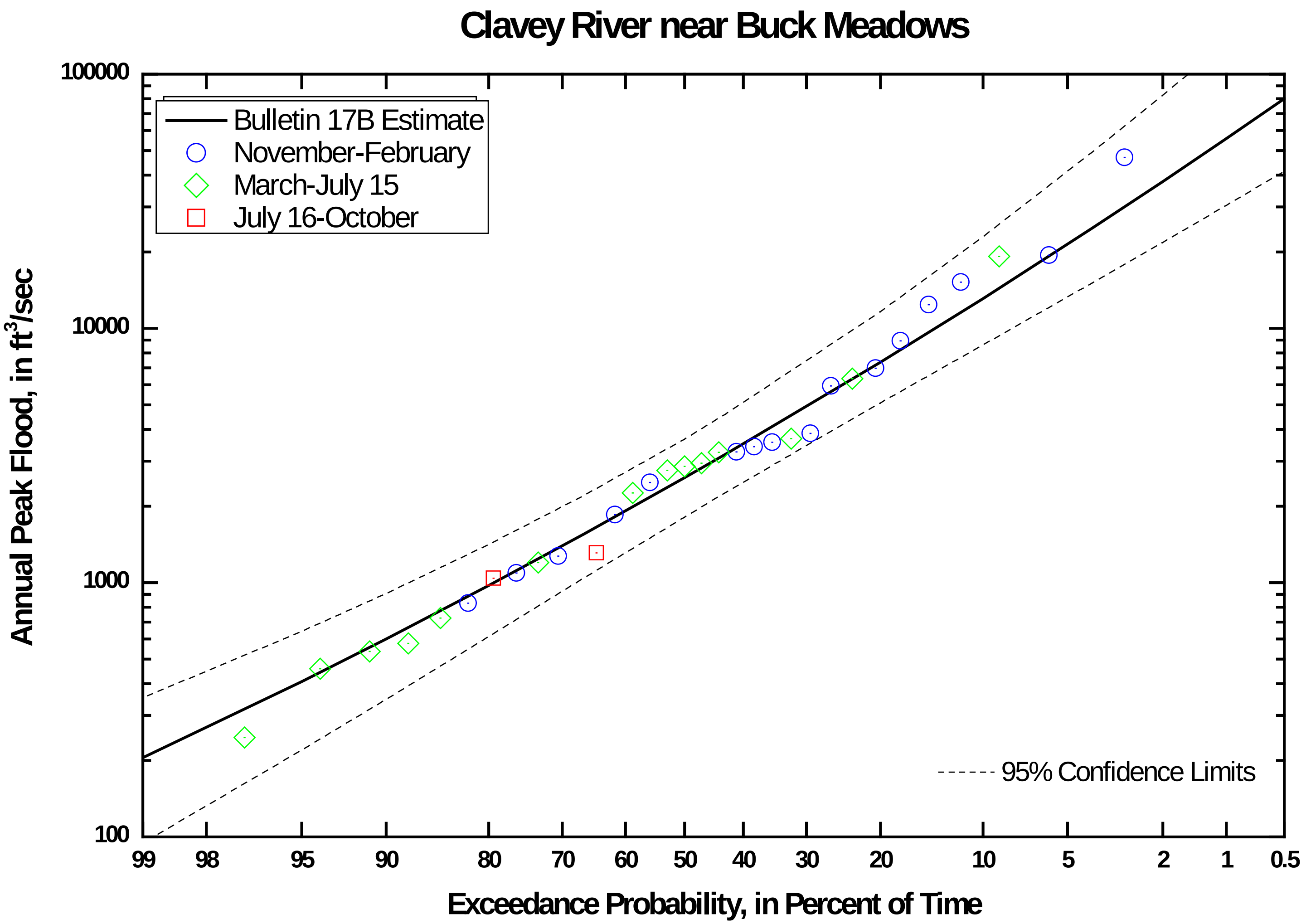


Figure A12. Calculated frequency of annual peak floods at Clavey River near Buck Meadows and observed annual peak floods.

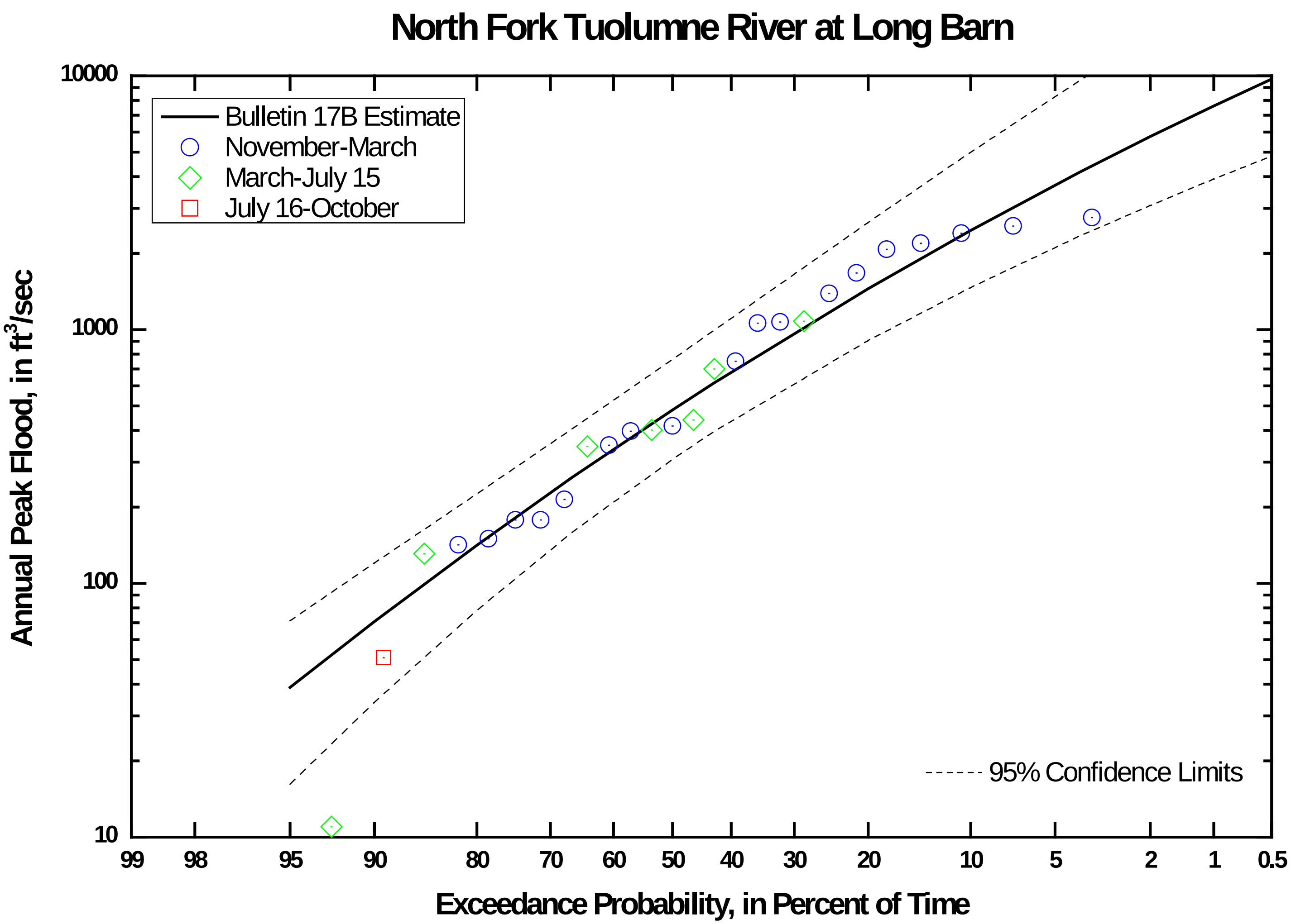


Figure A13. Calculated frequency of annual peak floods at North Fork Tuolumne River at Long Barn and observed annual peak floods.

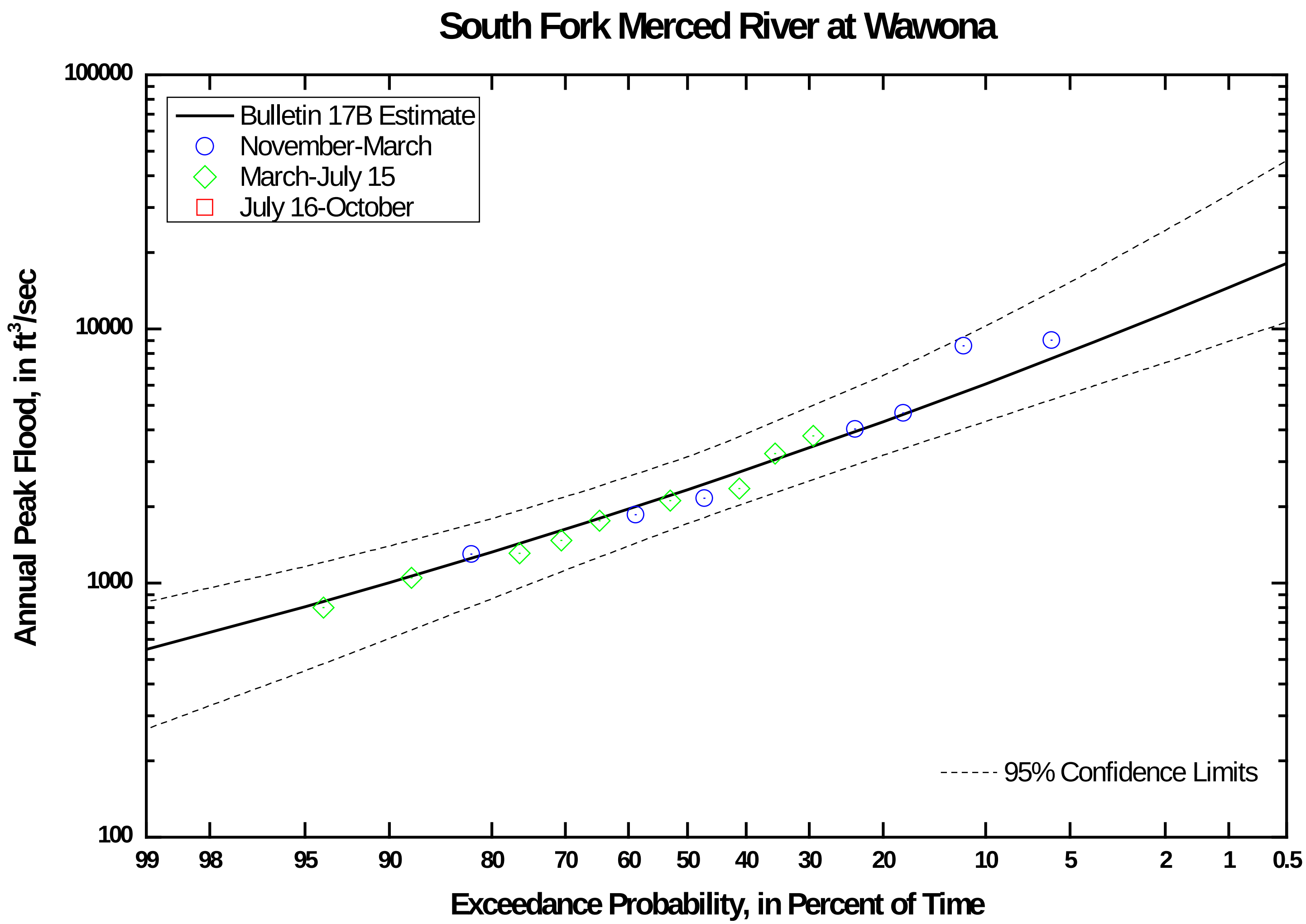


Figure A14. Calculated frequency of annual peak floods at South Fork Merced River at Wawona and observed annual peak floods.

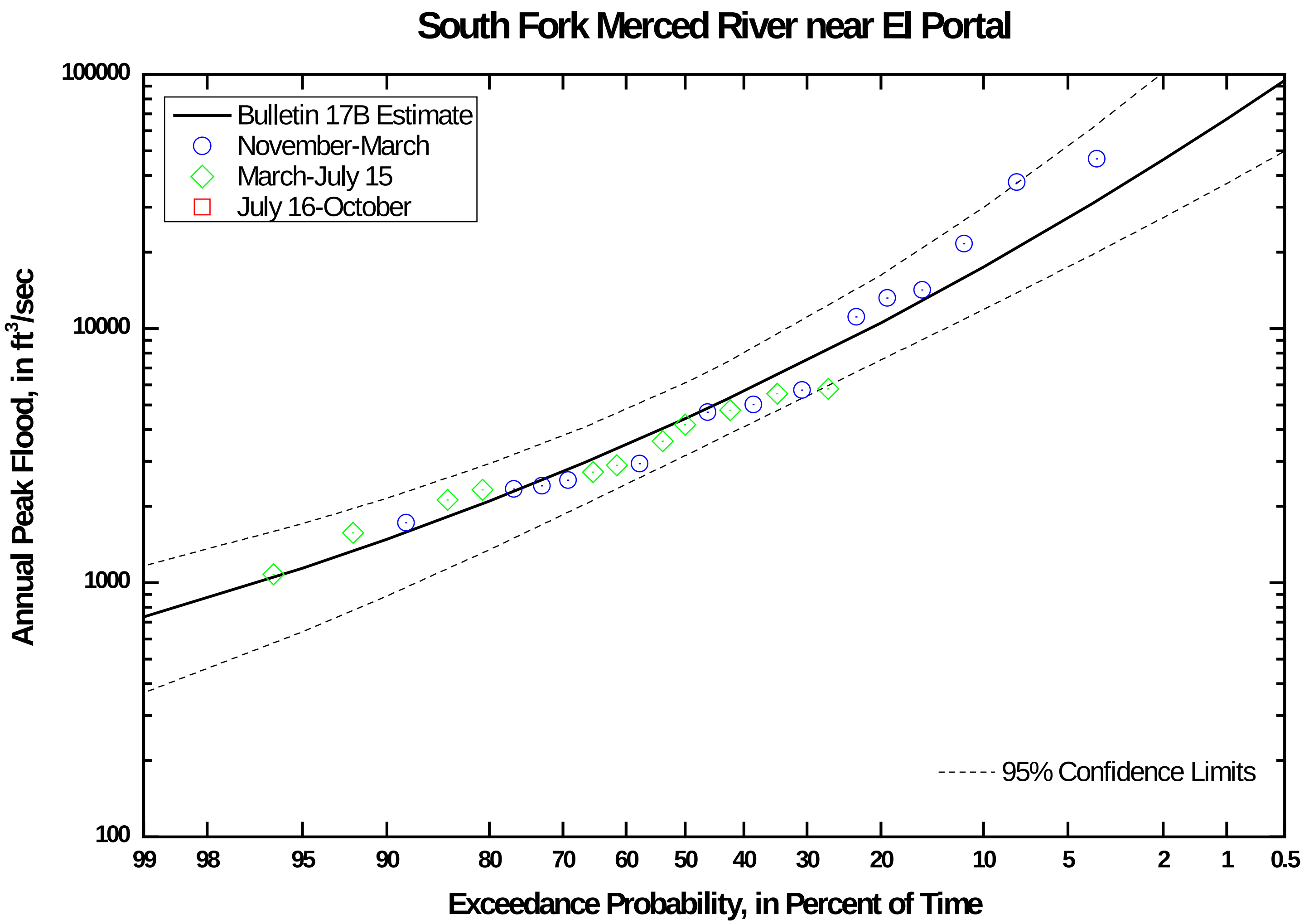


Figure A15. Calculated frequency of annual peak floods at South Fork Merced River near El Portal and observed annual peak floods.

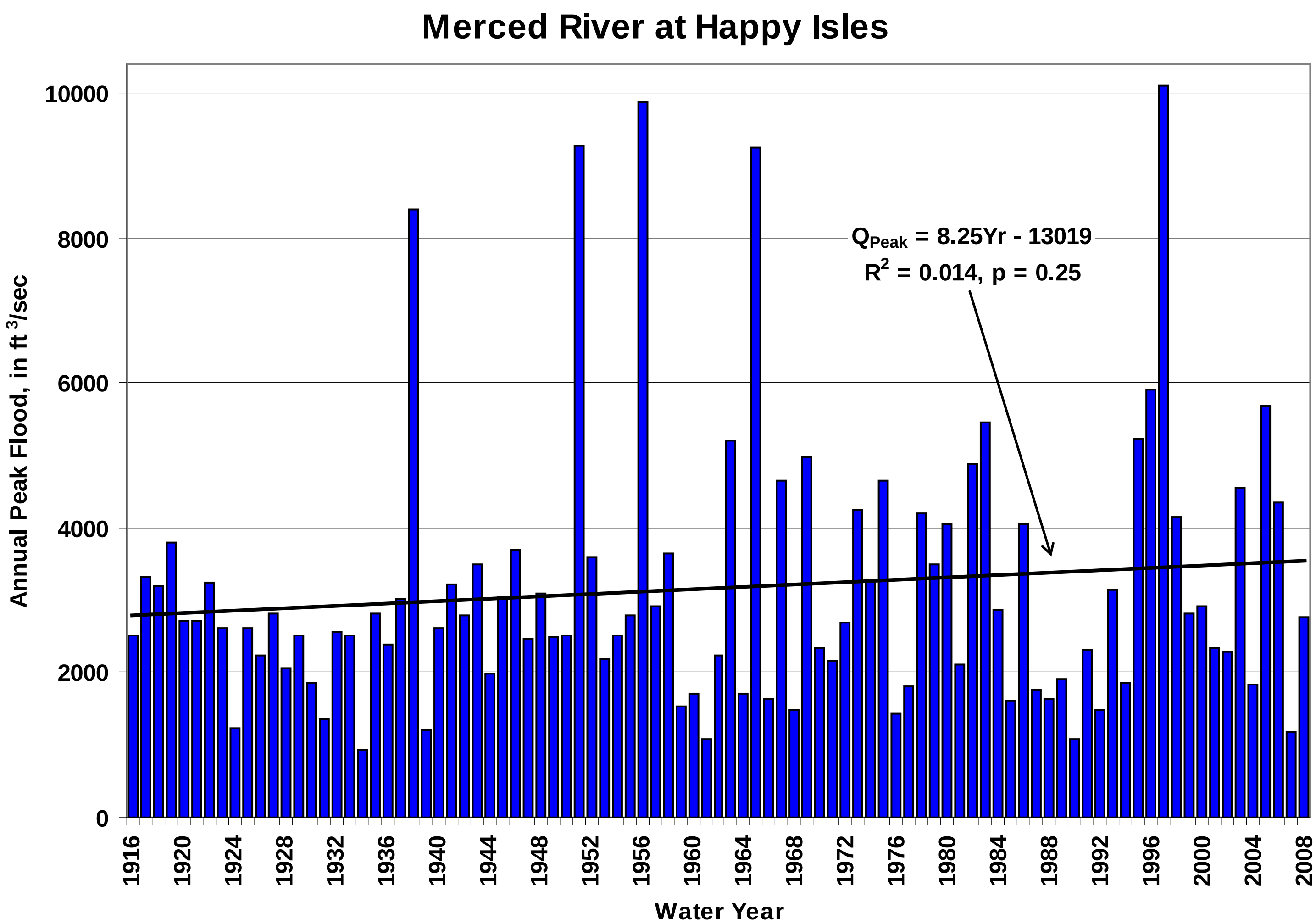


Figure A16. Observed sequence of annual peak floods with fitted regression trend line at Merced River at Happy Isles Bridge.

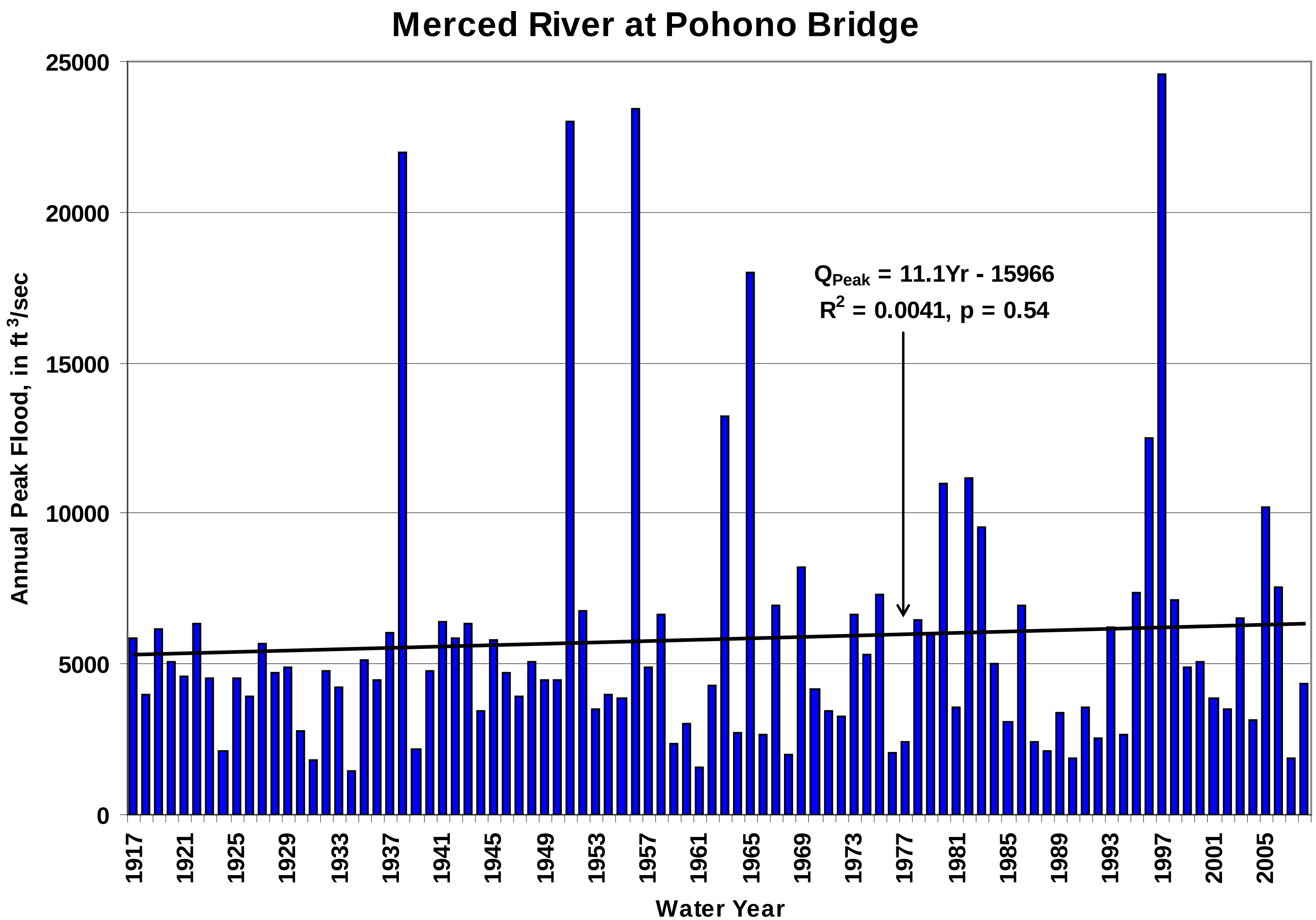


Figure A17. Observed sequence of annual peak floods with fitted regression trend line at Merced River at Pohono Bridge.

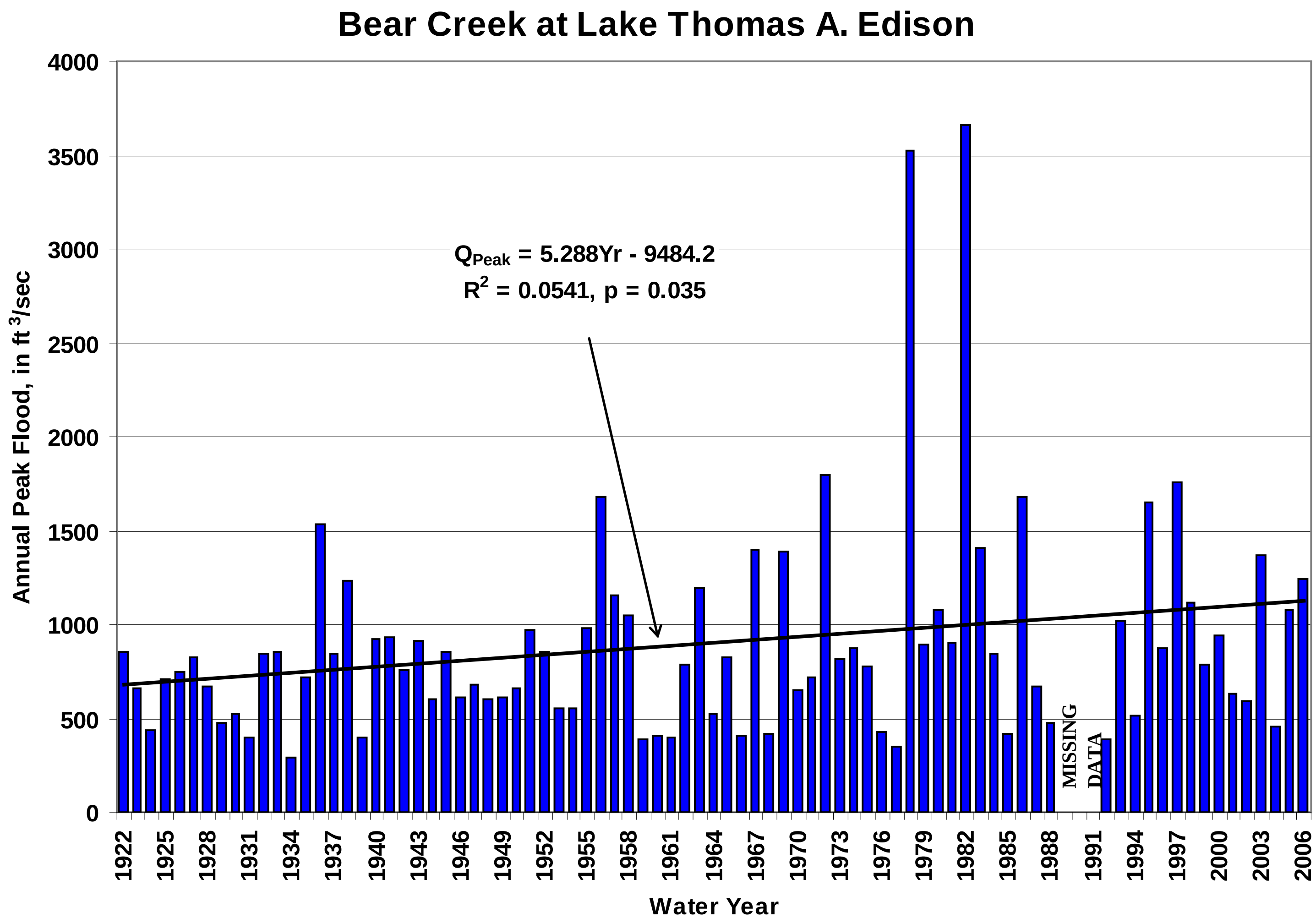


Figure A18. Observed sequence of annual peak floods with fitted regression trend line at Bear Creek at Lake Thomas A. Edison.

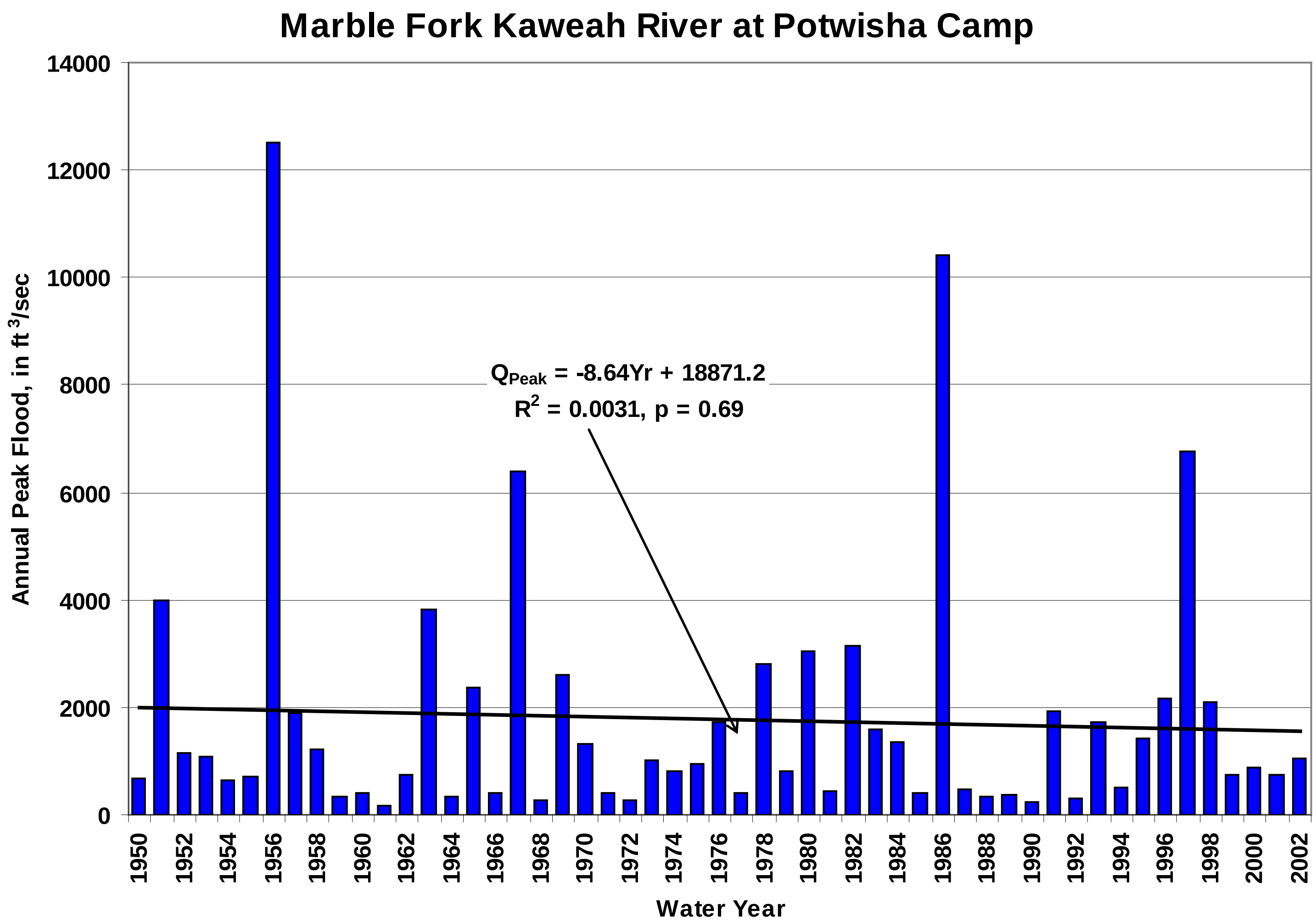


Figure A19. Observed sequence of annual peak floods with fitted regression trend line at Marble Fork River at Potwisha Camp.

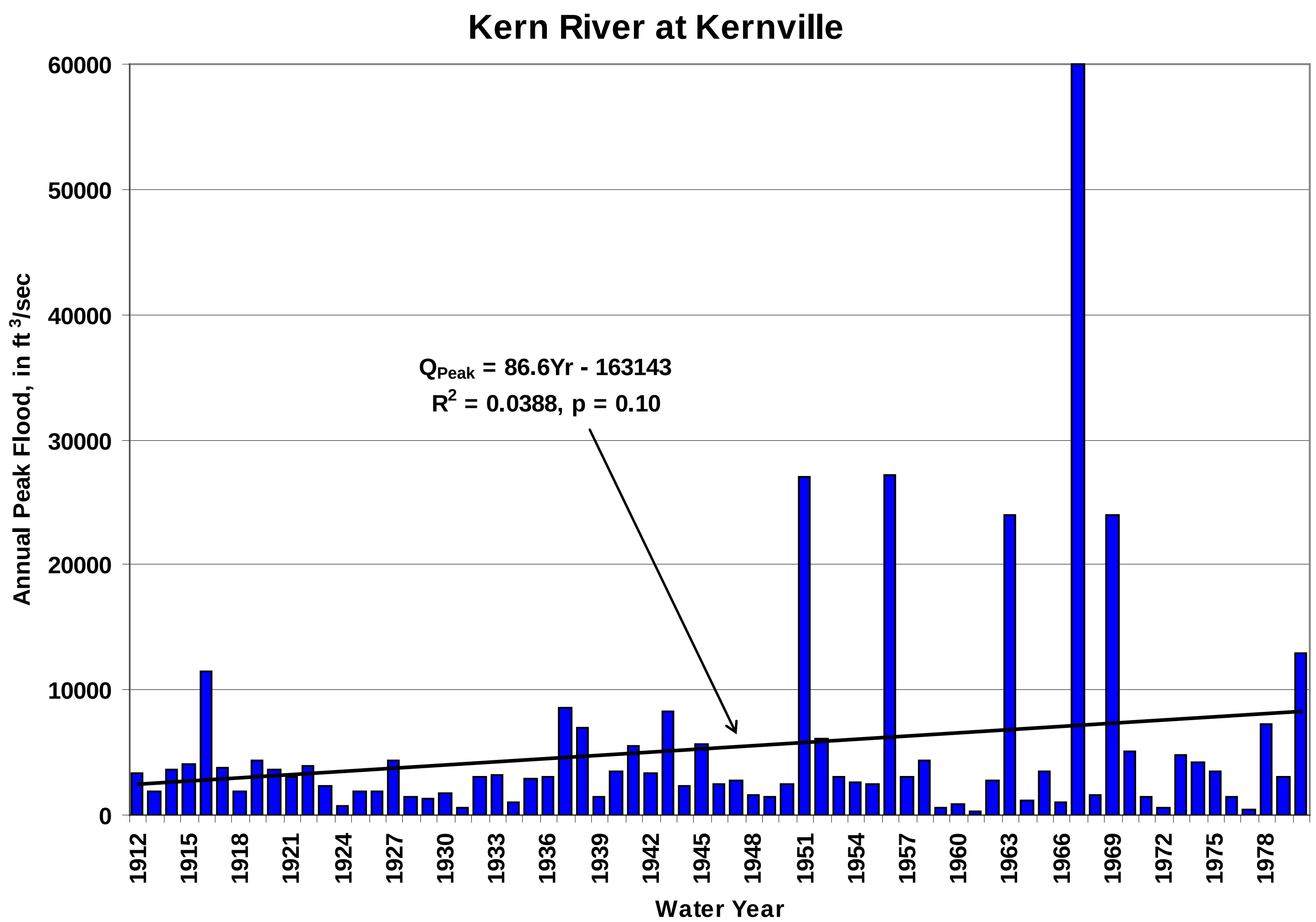


Figure A20. Observed sequence of annual peak floods with fitted regression trend line at Kern River at Kernville.

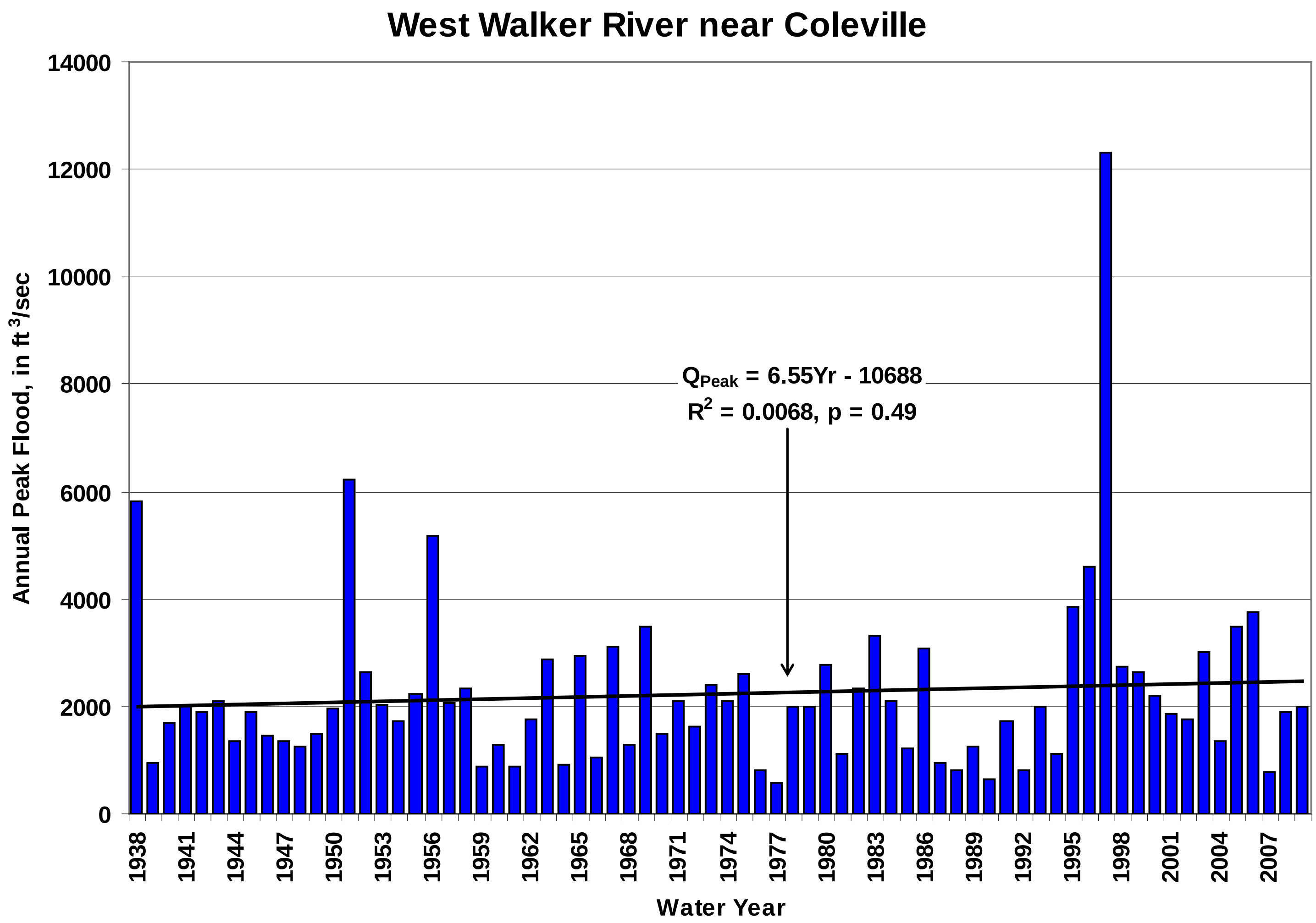


Figure A21. Observed sequence of annual peak floods with fitted regression trend line at West Walker River below LWR near Coleville.

Appendix B. Trends in Snowmelt Runoff

Figures

Page

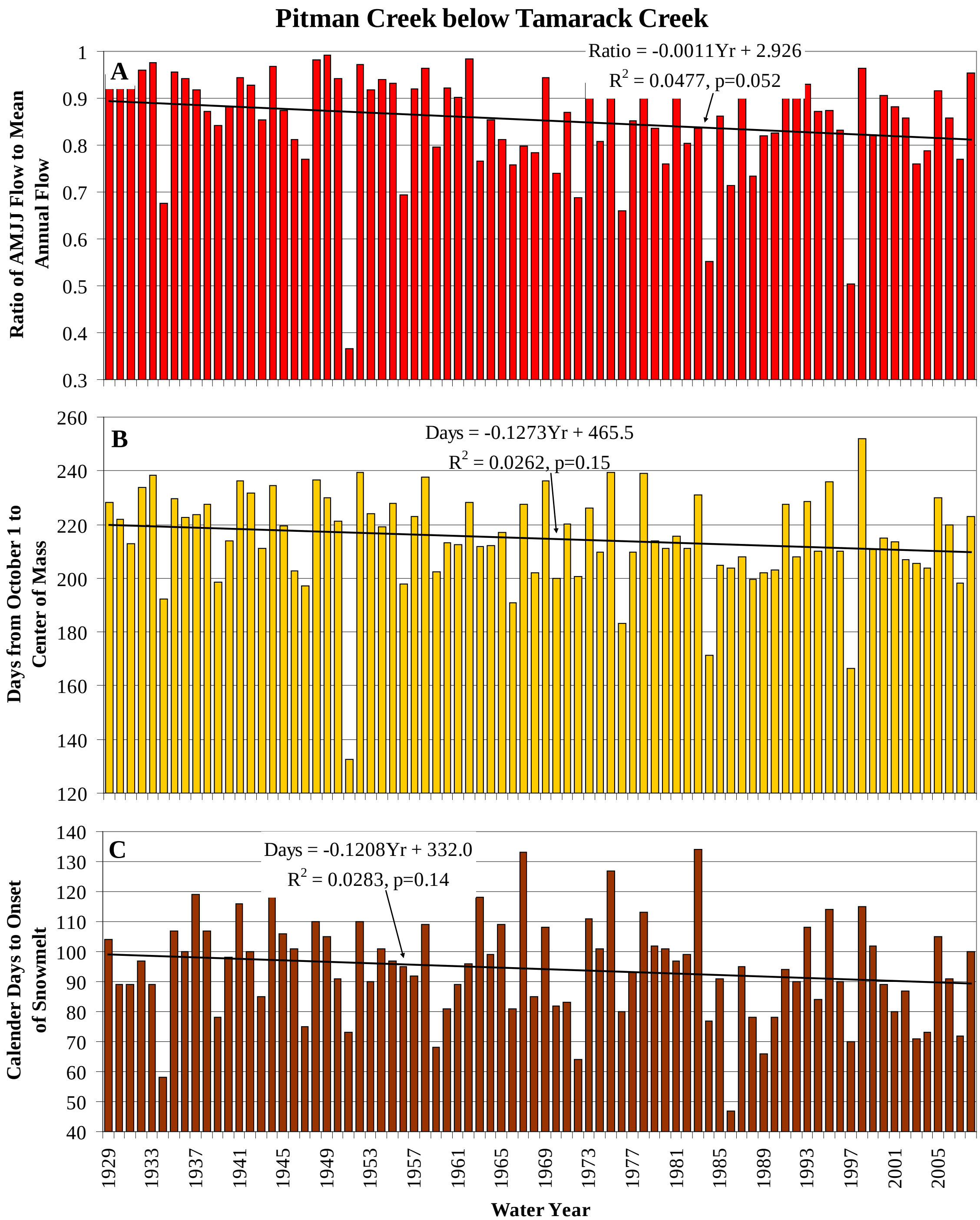


Figure B1. Graphs showing the observed sequence of (a) the ratio of AMJJ/annual runoff, (b) the number of water years/days to the runoff center of mass, and (c) number of calendar days to the onset of snowmelt runoff in the Pitman Creek below Tamarak Creek.

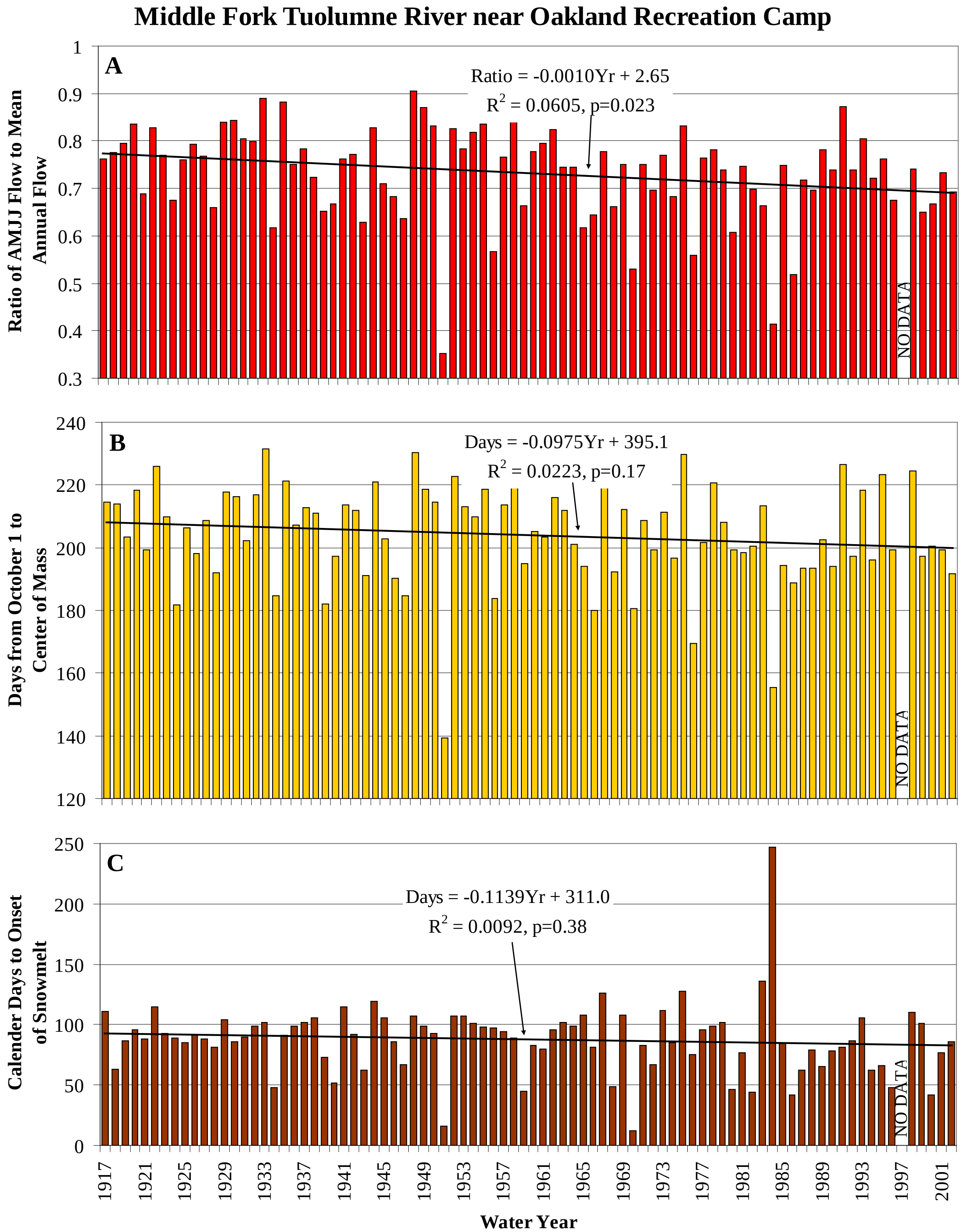


Figure B2. Graphs showing the observed sequence of (a) the ratio of AMJJ/annual runoff, (b) the number of water years/days to the runoff center of mass, and (c) number of calendar days to the onset of snowmelt runoff in the Middle Fork Tuolumne River near Oakland Recreation Camp.

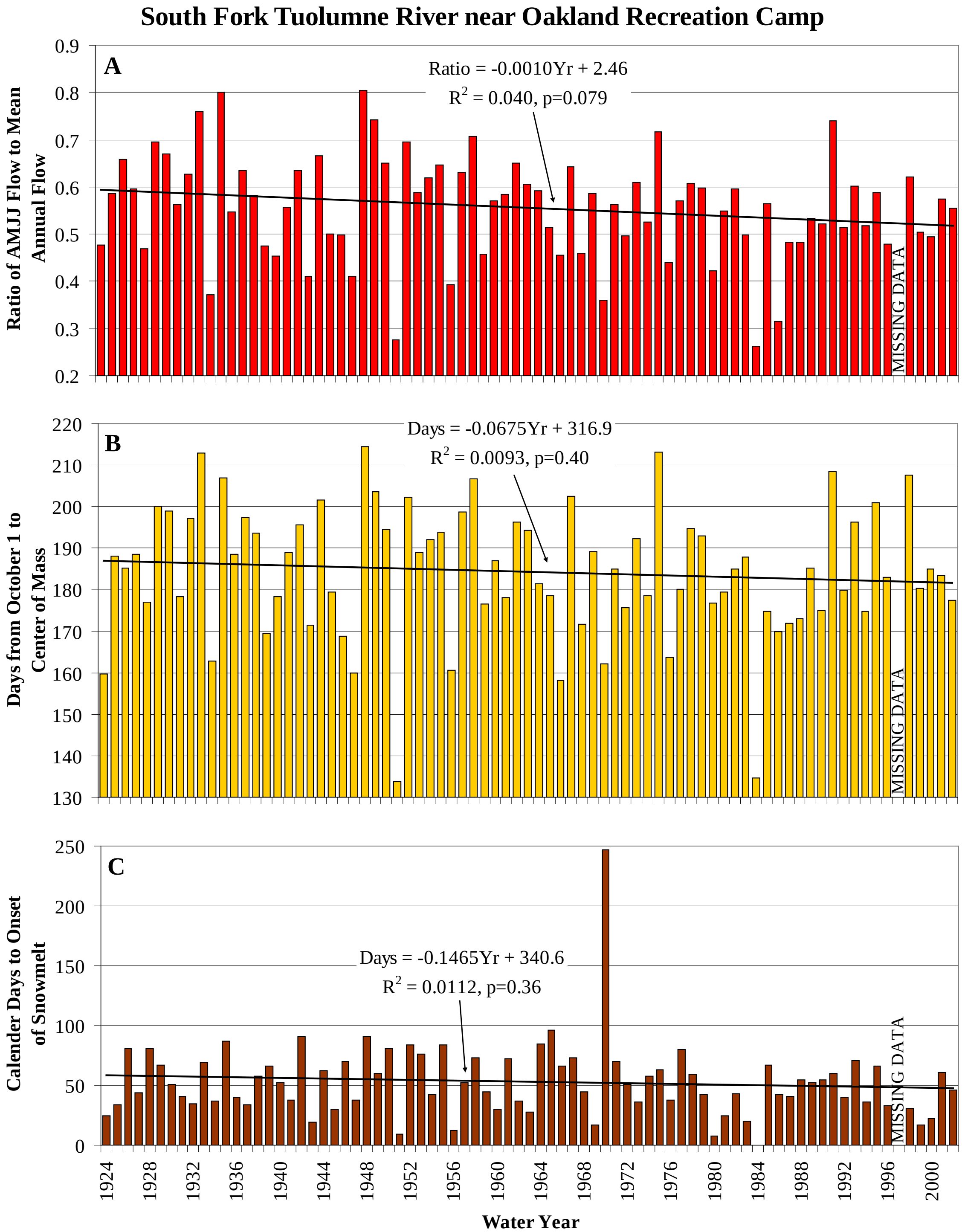


Figure B3. Graphs showing the observed sequence of (a) the ratio of AMJJ/annual runoff, (b) the number of water years/days to the runoff center of mass, and (c) number of calendar days to the onset of snowmelt runoff in the South Fork Tuolumne River near Oakland Recreation Camp.

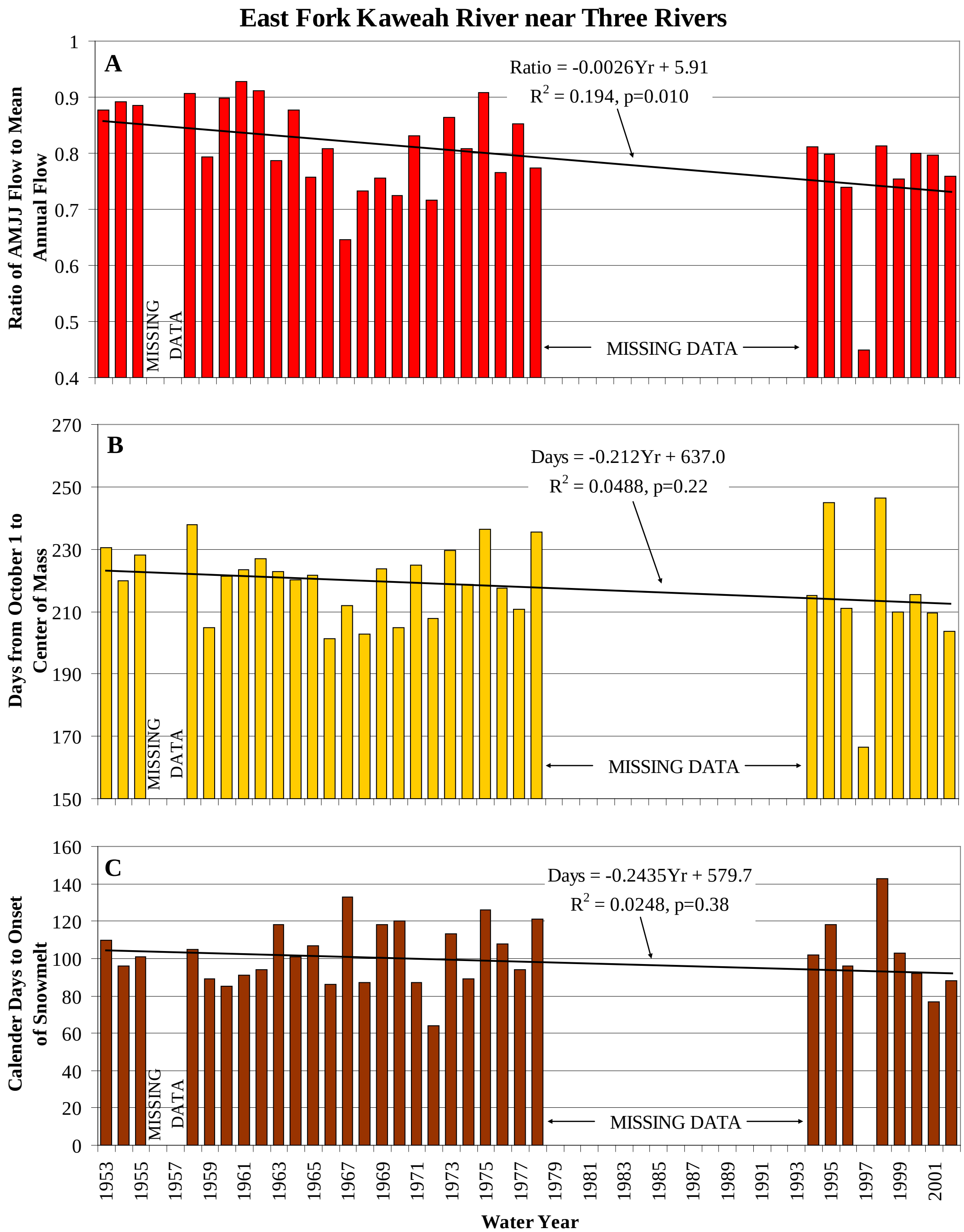


Figure B4. Graphs showing the observed sequence of (a) the ratio of AMJJ/annual runoff, (b) the number of water years/days to the runoff center of mass, and (c) number of calendar days to the onset of snowmelt runoff in the East Fork Kaweah River near Three Rivers.

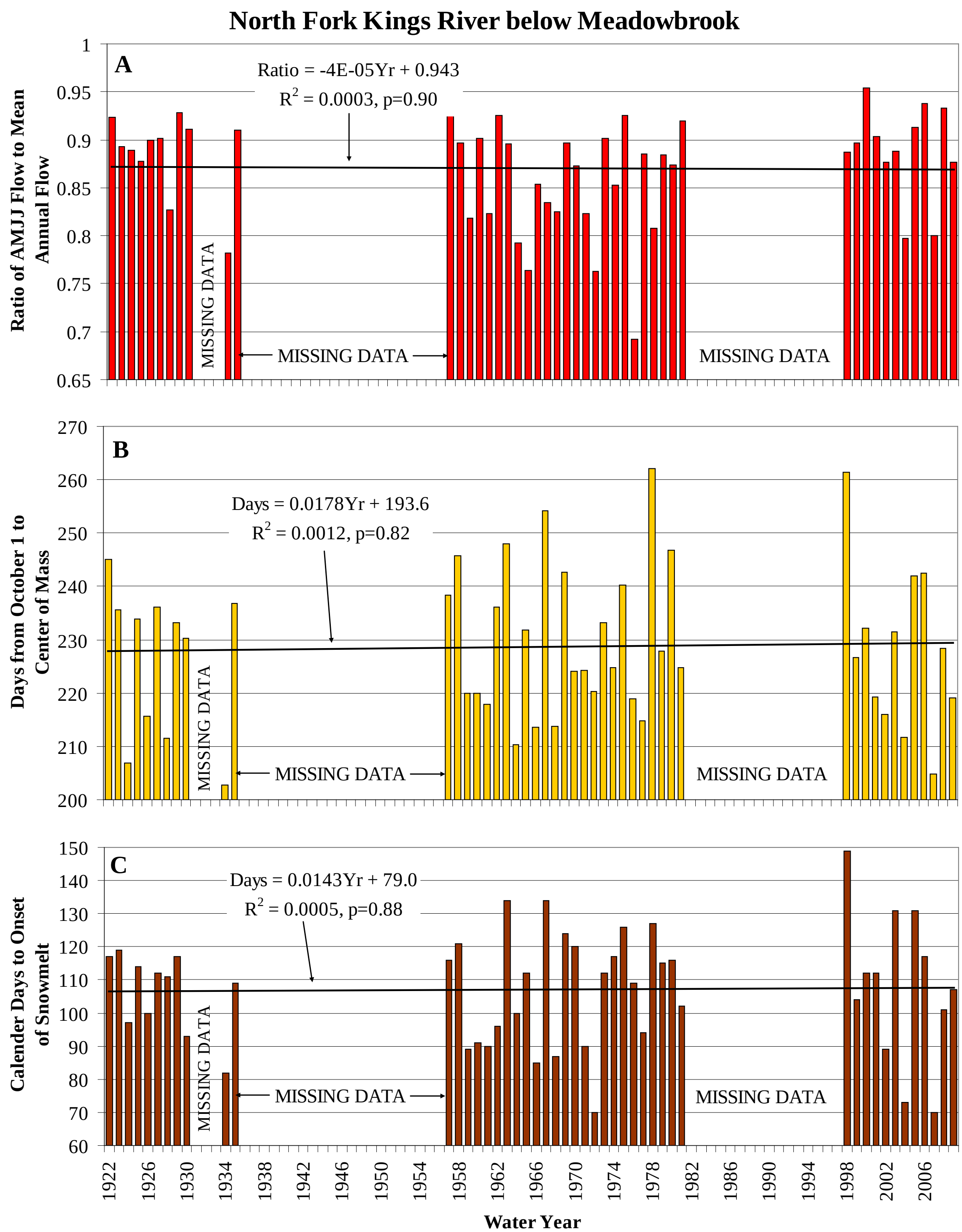


Figure B5. Graphs showing the observed sequence of (a) the ratio of AMJJ/annual runoff, (b) the number of water years/days to the runoff center of mass, and (c) number of calendar days to the onset of snowmelt runoff in the North Fork Kings River below Meadowbrook.

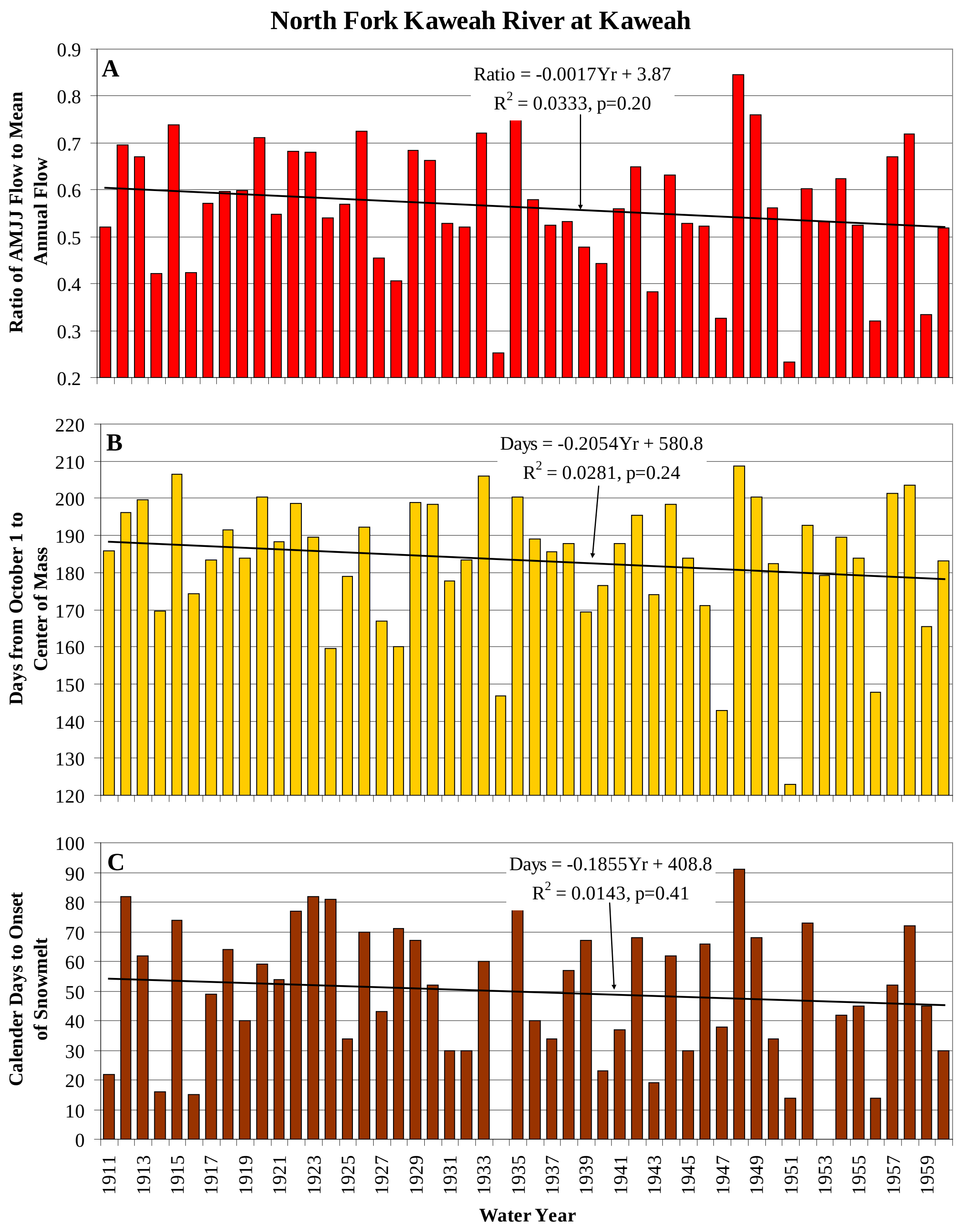


Figure B6. Graphs showing the observed sequence of (a) the ratio of AMJJ/annual runoff, (b) the number of water years/days to the runoff center of mass, and (c) number of calendar days to the onset of snowmelt runoff in the North Fork Kaweah River at Kaweah.

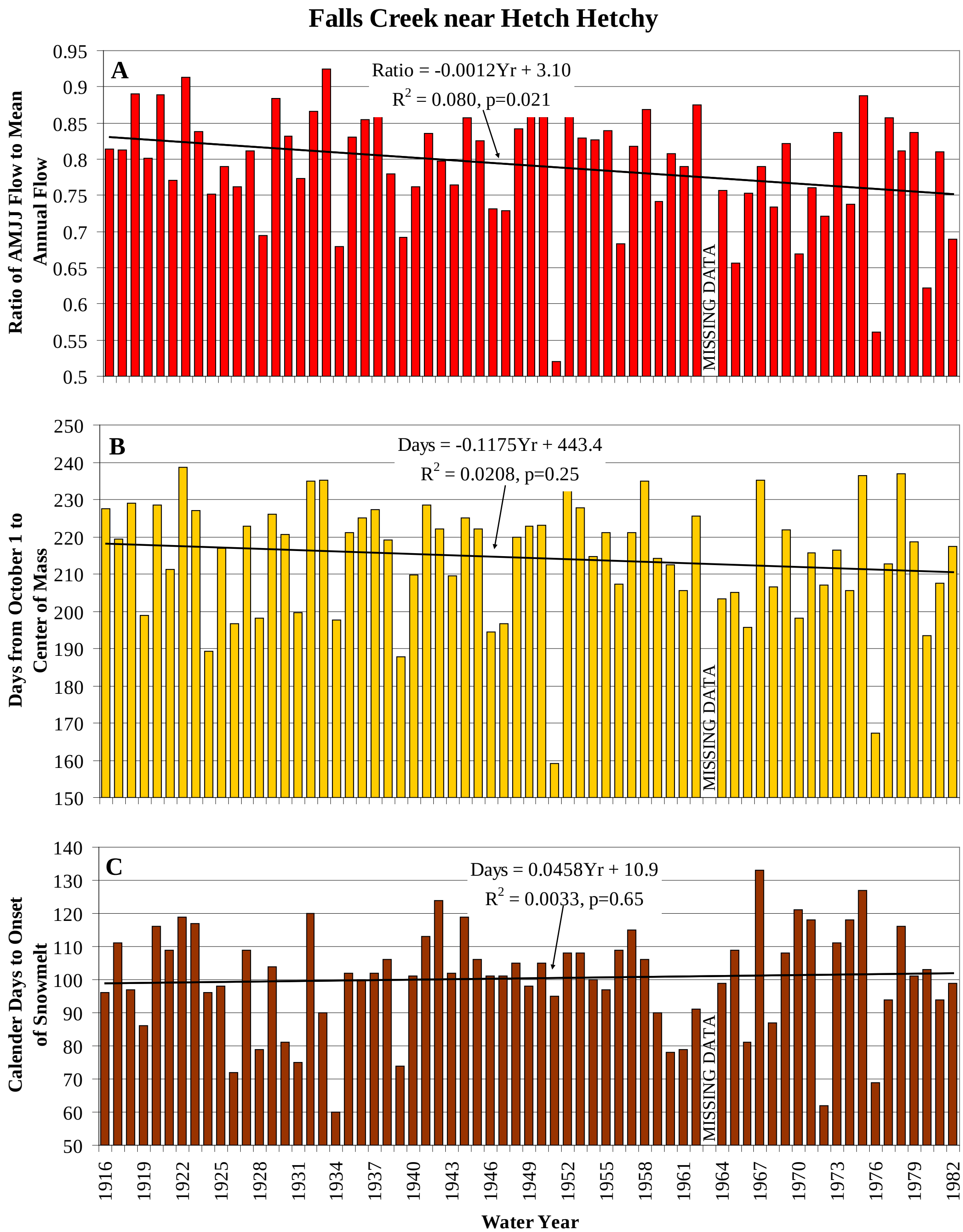


Figure B7. Graphs showing the observed sequence of (a) the ratio of AMJJ/annual runoff, (b) the number of water years/days to the runoff center of mass, and (c) number of calendar days to the onset of snowmelt runoff in the Falls Creek near Hetch-Hetchy.

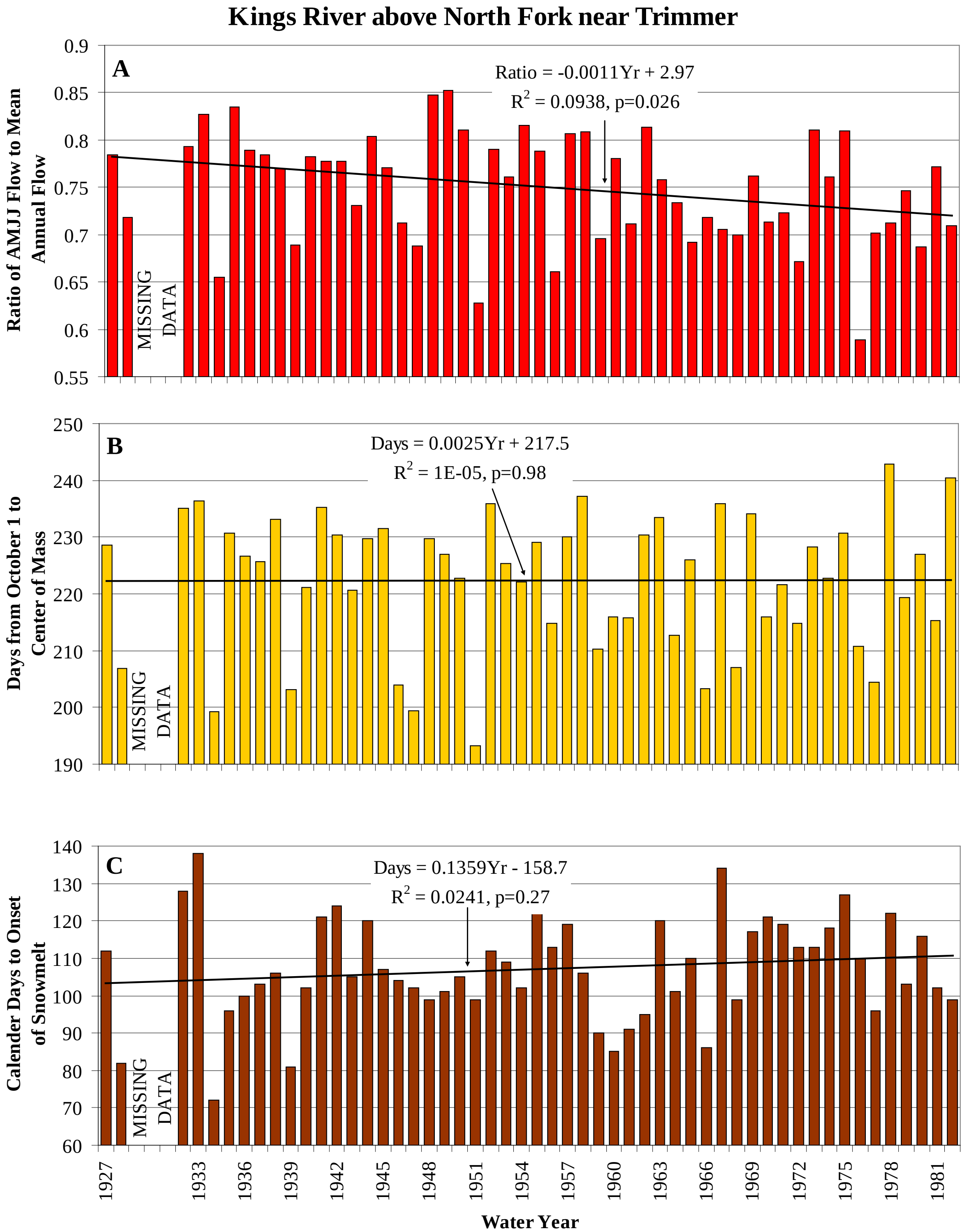
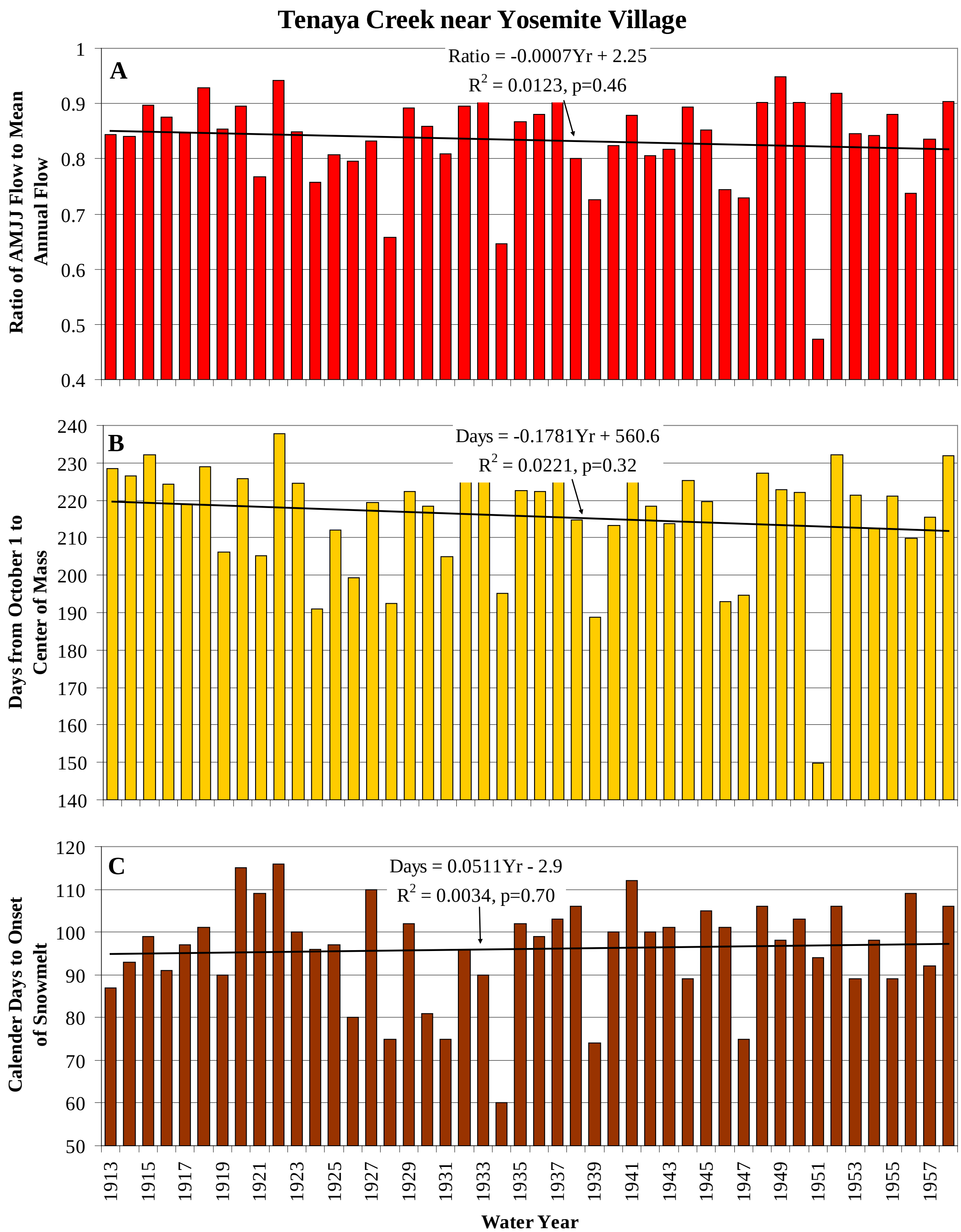


Figure B8. Graphs showing the observed sequence of (a) the ratio of AMJJ/annual runoff, (b) the number of water years/days to the runoff center of mass, and (c) number of calendar days to the onset of snowmelt runoff in the Kings River above North Fork near Trimmer.



B9. Graphs showing the observed sequence of (a) the ratio of AMJJ/annual runoff, (b) the number of water years/days to the runoff center of mass, and (c) number of calendar days to the onset of **Figure** snowmelt runoff in the Tenaya Creek near Yosemite Village.

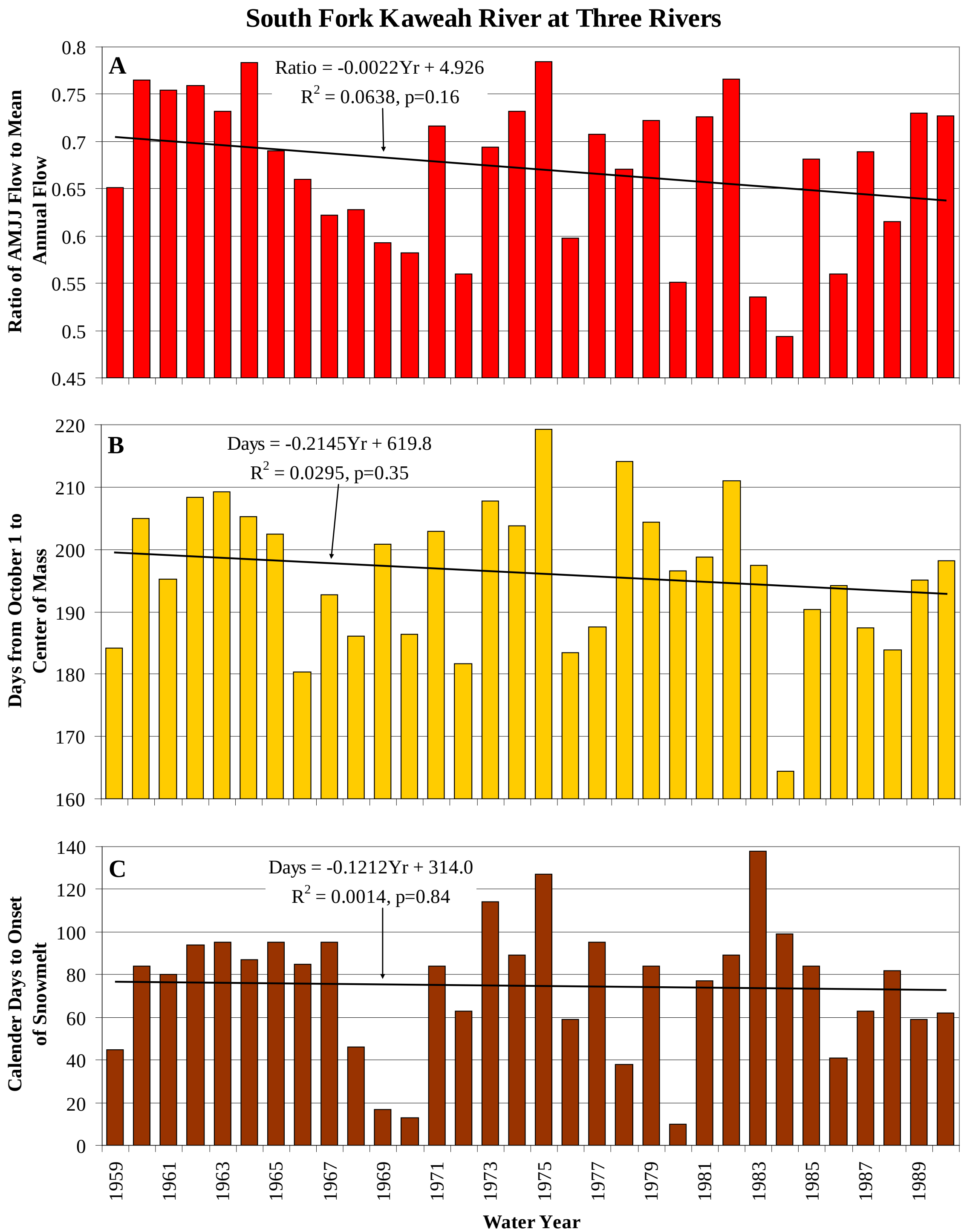


Figure B10. Graphs showing the observed sequence of (a) the ratio of AMJJ/annual runoff, (b) the number of water years/days to the runoff center of mass, and (c) number of calendar days to the onset of snowmelt runoff in the South Fork Kaweah River at Three Rivers.

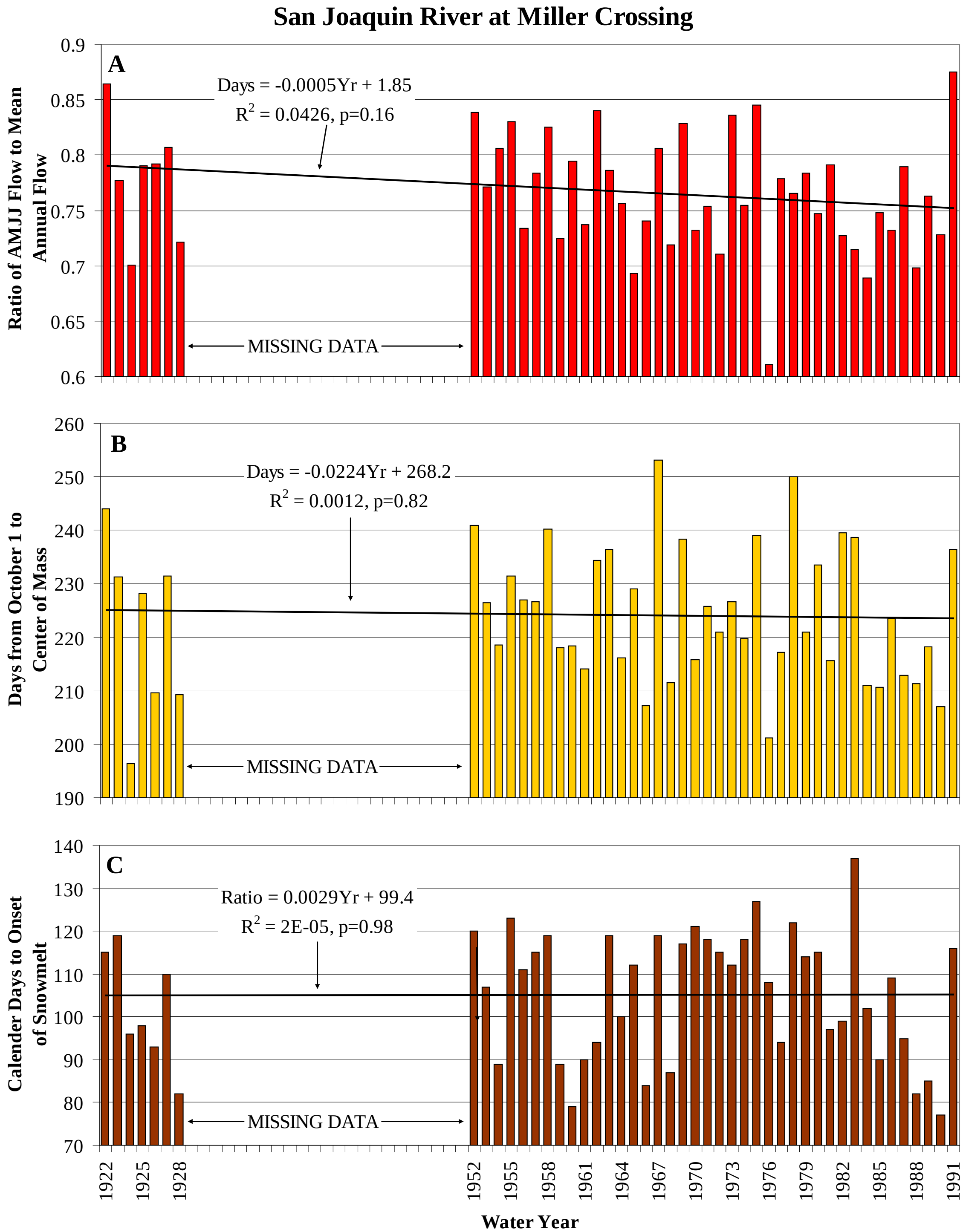


Figure B11. Graphs showing the observed sequence of (a) the ratio of AMJJ/annual runoff, (b) the number of water years/days to the runoff center of mass, and (c) number of calendar days to the onset of snowmelt runoff in the San Joaquin River at Miller Crossing.

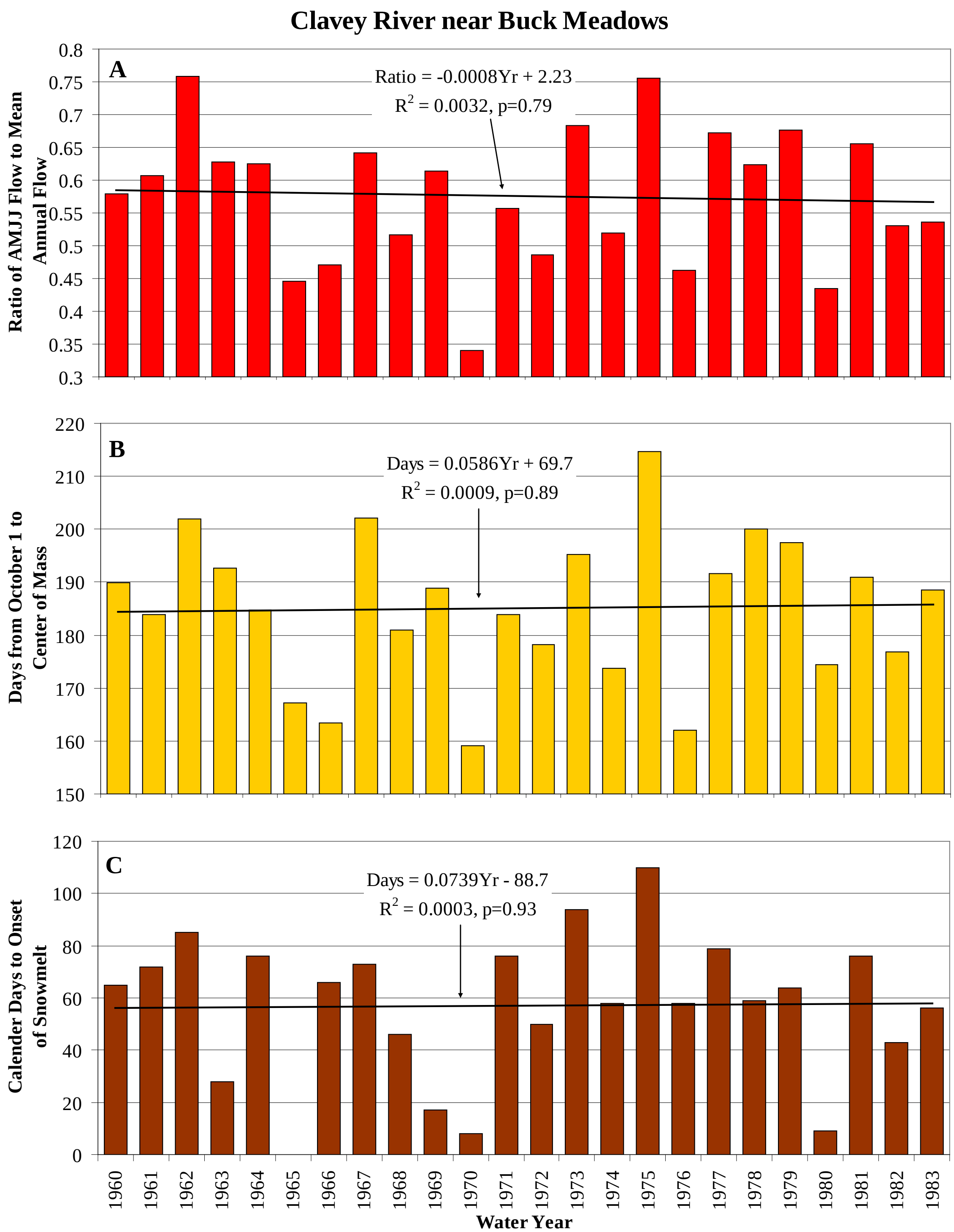


Figure B12. Graphs showing the observed sequence of (a) the ratio of AMJJ/annual runoff, (b) the number of water years/days to the runoff center of mass, and (c) number of calendar days to the onset of snowmelt runoff in the Clavey River near Buck Meadows.

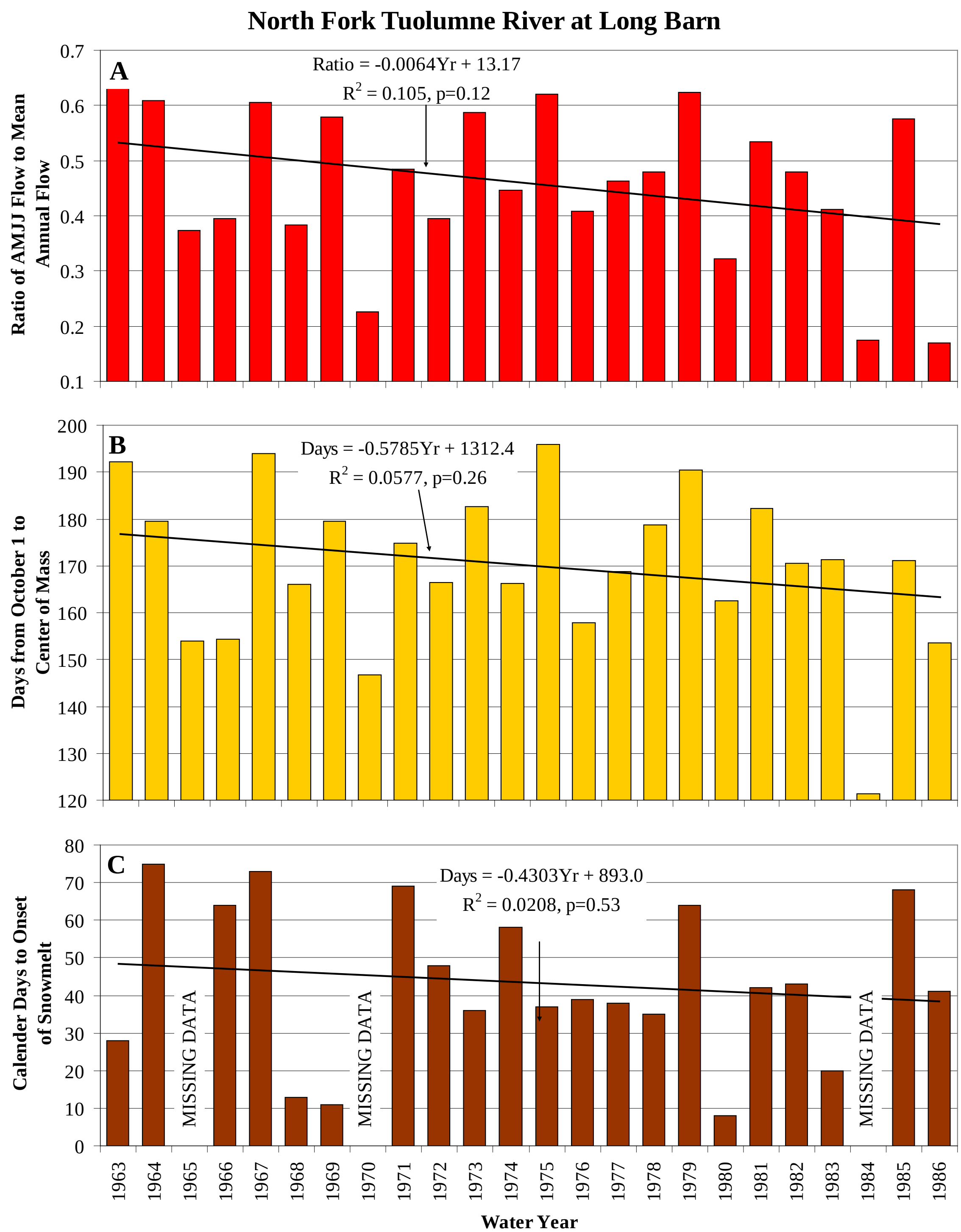


Figure B13. Graphs showing the observed sequence of (a) the ratio of AMJJ/annual runoff, (b) the number of water years/days to the runoff center of mass, and (c) number of calendar days to the onset of snowmelt runoff in the North Fork Tuolumne River at Long Barn.

Appendix C. Flows at Gaging Stations.

Magnitudes of 3-, 7-, 10-, and 14-day High Flows and 3-, 7-, and 14-day Winter and Summer Low Flows Equaled or Exceeded From 98 to 2 Percent at the Time

	Exceedance Probability																	
	0.950	0.900	0.800	0.070	0.060	0.500	0.330	0.200	0.143	0.100	0.067	0.050	0.040	0.033	0.029	0.025	0.022	0.020
Station 11264500 Merced River at Happy Isles Bridge near Yosemite																		
3-Day High Flow	992	1195	1440	1838	2047	2272	2559	3033	3498	3857	4114	4293	4541	4641	4825	5013	5159	5300
7-Day High Flow	879	1050	1323	1671	1871	2089	2395	2699	3033	3319	3472	3610	3621	3651	3742	3841	3918	3972
10-Day High Flow	860	971	1214	1548	1776	1996	2261	2570	2771	3140	3337	3454	3523	3525	3595	3678	3742	3776
14-Day High Flow	829	898	1181	1471	1703	1826	2069	2446	2685	2993	3211	3361	3418	3471	3520	3562	3595	3615
3-Day Winter Low Flow	100	71	53	42	30	21	14	11	7	6	5	5	5	4	4	4	4	4
7-Day Winter Low Flow	107	75	54	41	32	22	15	11	8	6	5	5	5	5	5	5	4	4
14-Day Winter Low Flow	115	81	58	40	35	21	16	11	8	7	6	5	5	5	5	5	5	5
3-Day Summer Low Flow	60	43	26	18	13	11	7	5	4	3	3	3	2	2	2	2	2	2
7-Day Summer Low Flow	69	51	27	20	14	12	7	5	4	4	3	3	3	3	2	2	2	2
14-Day Summer Low Flow	79	60	31	24	16	13	8	6	5	4	4	3	3	3	3	3	3	3

Appendix C. Flows at Gaging Stations (continued).

	Exceedance Probability																	
	0.950	0.900	0.800	0.070	0.060	0.500	0.330	0.200	0.143	0.100	0.067	0.050	0.040	0.033	0.029	0.025	0.022	0.020
Station 11266500 Merced River at Pohono Bridge near Yosemite																		
3-Day High Flow	1542	1767	2399	2943	3438	3897	4581	5713	5995	6457	7945	8638	9101	9365	9489	9563	9620	9975
7-Day High Flow	1359	1592	2240	2661	3197	3616	4166	5085	5470	5709	6250	6788	6979	7021	7188	7357	7488	7543
10-Day High Flow	1282	1541	2102	2557	3027	3479	3830	4751	5264	5456	5713	6285	6592	6723	6782	6816	6843	6880
14-Day High Flow	1232	1439	1997	2409	2867	3255	3560	4453	4877	5268	5458	6039	6384	6448	6570	6686	6776	6811
3-Day Winter Low Flow	222	151	102	89	67	49	34	25	20	18	16	16	14	14	14	14	13	13
7-Day Winter Low Flow	246	154	104	90	69	50	34	25	20	18	16	16	15	15	14	14	14	14
14-Day Winter Low Flow	268	157	111	88	68	49	33	25	21	18	17	16	16	15	15	14	14	14
3-Day Summer Low Flow	94	67	45	34	29	26	20	16	15	14	11	11	10	10	10	9	9	8
7-Day Summer Low Flow	104	73	47	37	30	27	21	17	16	14	12	11	11	11	10	10	9	9
14-Day Summer Low Flow	119	85	55	40	32	29	22	18	17	15	13	12	11	11	10	10	10	9
Station 11230500 Bear Creek near Lake Thomas A. Edison																		
3-Day High Flow	267	291	350	441	490	578	647	726	858	907	1033	1060	1130	1211	1238	1258	1292	1380
7-Day High Flow	242	265	330	399	464	543	602	679	755	836	907	920	958	993	1000	1004	1010	1023
10-Day High Flow	236	248	310	388	431	511	576	648	670	777	854	877	914	940	954	964	971	973
14-Day High Flow	211	237	298	366	406	477	555	620	649	743	778	841	877	882	903	919	930	935

Appendix C. Flows at Gaging Stations (continued).

	Exceedance Probability																	
	0.950	0.900	0.800	0.070	0.060	0.500	0.330	0.200	0.143	0.100	0.067	0.050	0.040	0.033	0.029	0.025	0.022	0.020
3-Day Winter Low Flow	24	20	16	13	11	10	7	5	5	4	4	4	4	3	3	3	3	3
7-Day Winter Low Flow	23	21	16	13	12	10	7	5	5	4	4	4	4	3	3	3	3	3
14-Day Winter Low Flow	24	21	17	14	12	10	8	6	5	5	4	4	4	3	3	3	3	3
3-Day Summer Low Flow	36	29	19	16	11	9	6	5	4	4	4	4	4	3	3	3	3	3
7-Day Summer Low Flow	39	30	21	17	12	9	6	5	4	4	4	4	4	4	3	3	3	3
14-Day Summer Low Flow	50	35	25	18	14	10	7	5	5	4	4	4	4	4	4	3	3	3
Station 11237500 Pitman Creek below Tamarack Creek																		
3-Day High Flow	105	119	164	201	257	301	420	605	700	762	830	838	842	853	865	875	940	999
7-Day High Flow	96	114	155	185	234	273	378	524	565	638	672	674	677	700	728	750	755	758
10-Day High Flow	89	109	143	173	214	266	355	495	524	595	648	649	649	673	704	727	736	743
14-Day High Flow	81	104	132	166	207	246	332	450	504	558	615	621	642	669	693	712	721	727
3-Day Winter Low Flow	18	8	4	3	2	1	1	0	0	0	0	0	0	0	0	0	0	0
7-Day Winter Low Flow	19	8	4	3	2	1	1	0	0	0	0	0	0	0	0	0	0	0
14-Day Winter Low Flow	22	8	5	3	2	1	1	0	0	0	0	0	0	0	0	0	0	0
3-Day Summer Low Flow	2	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-Day Summer Low Flow	2	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Appendix C. Flows at Gaging Stations (continued).

	Exceedance Probability																	
	0.950	0.900	0.800	0.070	0.060	0.500	0.330	0.200	0.143	0.100	0.067	0.050	0.040	0.033	0.029	0.025	0.022	0.020
14-Day Summer Low Flow	3	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Station 11186000 Kern River near Kernville																		
3-Day High Flow	935	1085	1690	1928	2525	2993	3531	4876	5924	6643	7352	8381	9034	9871	11162	12670	13844	14715
7-Day High Flow	841	1011	1575	1755	2338	2858	3339	4504	4887	5710	6526	6776	7927	8321	8568	8733	8861	8988
10-Day High Flow	803	967	1490	1693	2269	2710	3219	4163	4787	5544	6150	6392	6454	6616	7000	7495	7879	8190
14-Day High Flow	762	923	1430	1637	2150	2493	3060	3909	4745	5158	5909	6030	6160	6271	6654	7176	7582	7903
3-Day Winter Low Flow	349	304	268	230	214	196	167	144	136	129	122	119	118	118	118	117	117	115
7-Day Winter Low Flow	347	312	273	235	220	200	175	149	145	136	131	128	125	122	120	120	119	118
14-Day Winter Low Flow	359	316	271	240	223	198	178	153	147	138	130	129	127	123	121	121	121	120
3-Day Summer Low Flow	444	364	278	237	208	177	147	119	115	110	104	98	97	93	90	87	85	83
7-Day Summer Low Flow	452	380	287	239	210	182	148	122	116	111	106	103	100	96	92	89	86	84
14-Day Summer Low Flow	477	397	307	245	218	188	153	126	117	113	111	108	105	101	97	92	88	86
Station10296000 West Walker River below Little Walker River near Coleville																		
3-Day High Flow	645	709	927	1147	1409	1563	1787	2133	2407	2663	3004	3012	3040	3120	3177	3494	3802	4047
7-Day High Flow	591	646	857	1058	1265	1456	1626	1914	2131	2463	2569	2680	2685	2698	2707	2742	2775	2802
10-Day High Flow	561	617	846	1013	1208	1392	1584	1770	2057	2308	2418	2508	2535	2560	2578	2613	2645	2670

Appendix C. Flows at Gaging Stations (continued).

	Exceedance Probability																	
	0.950	0.900	0.800	0.070	0.060	0.500	0.330	0.200	0.143	0.100	0.067	0.050	0.040	0.033	0.029	0.025	0.022	0.020
14-Day High Flow	544	590	790	958	1149	1280	1500	1694	1942	2117	2290	2363	2479	2545	2592	2601	2601	2602
3-Day Winter Low Flow	82	63	51	46	40	35	29	26	24	22	20	18	16	15	14	14	13	13
7-Day Winter Low Flow	90	69	54	49	41	38	32	27	25	23	21	20	19	17	15	15	14	14
14-Day Winter Low Flow	97	74	55	50	44	41	34	29	25	24	22	21	19	17	16	15	15	15
3-Day Summer Low Flow	109	100	71	58	53	40	33	26	25	19	18	18	18	16	15	14	13	12
7-Day Summer Low Flow	116	104	77	62	56	43	36	27	26	20	19	18	18	17	16	15	13	13
14-Day Summer Low Flow	128	112	85	68	59	46	38	29	28	21	19	19	19	18	18	16	15	14

Station 11282000
Middle Fork Tuolumne River near Oakland Recreation Camp

	0.950	0.900	0.800	0.070	0.060	0.500	0.330	0.200	0.143	0.100	0.067	0.050	0.040	0.033	0.029	0.025	0.022	0.020
3-Day High Flow	129	137	263	300	373	433	623	801	869	967	1028	1218	1341	1408	1409	1410	1452	1543
7-Day High Flow	120	131	247	276	342	403	513	648	763	837	911	941	951	971	1010	1039	1062	1081
10-Day High Flow	111	126	233	262	323	374	486	615	718	765	821	859	876	888	907	922	934	945
14-Day High Flow	106	123	219	255	312	350	464	574	664	690	753	807	844	873	895	913	926	936
3-Day Winter Low Flow	28	22	13	11	8	6	4	3	2	2	2	1	1	1	1	1	1	1
7-Day Winter Low Flow	29	23	14	11	9	7	5	3	2	2	2	1	1	1	1	1	1	1
14-Day Winter Low Flow	29	24	14	12	9	7	5	3	3	2	2	1	1	1	1	1	1	1
3-Day Summer Low Flow	7	6	3	2	2	2	1	0	0	0	0	0	0	0	0	0	0	0

Appendix C. Flows at Gaging Stations (continued).

	Exceedance Probability																	
	0.950	0.900	0.800	0.070	0.060	0.500	0.330	0.200	0.143	0.100	0.067	0.050	0.040	0.033	0.029	0.025	0.022	0.020
7-Day Summer Low Flow	8	6	3	3	2	2	1	0	0	0	0	0	0	0	0	0	0	0
14-Day Summer Low Flow	8	7	4	3	2	2	1	0	0	0	0	0	0	0	0	0	0	0
Station 11281000 South Fork Tuolumne River near Oakland Recreation Camp																		
3-Day High Flow	106	137	218	294	368	515	698	1063	1597	2206	2422	2560	2821	2990	3109	3194	3224	3249
7-Day High Flow	89	108	199	234	296	400	570	697	970	1210	1464	1655	1808	1894	1949	1991	2022	2046
10-Day High Flow	85	101	185	218	273	347	525	636	855	958	1163	1335	1461	1561	1637	1689	1691	1693
14-Day High Flow	83	98	165	212	260	334	466	606	681	831	1027	1114	1120	1194	1268	1319	1321	1323
3-Day Winter Low Flow	47	38	28	21	18	15	12	9	7	6	5	4	4	4	4	4	4	4
7-Day Winter Low Flow	49	39	27	21	18	16	13	10	7	7	6	5	5	4	4	4	4	4
14-Day Winter Low Flow	51	40	29	22	19	16	13	10	8	7	6	6	5	4	4	4	4	4
3-Day Summer Low Flow	21	17	13	10	8	7	4	3	2	2	1	1	1	1	0	0	0	0
7-Day Summer Low Flow	22	17	13	10	8	7	5	3	3	2	1	1	1	1	1	1	1	1
14-Day Summer Low Flow	22	18	14	11	9	7	5	4	3	2	2	1	1	1	1	1	1	1
Station 11206500 Middle Fork Kaweah river near Potwisha Camp																		
3-Day High Flow	296	317	423	515	578	743	1016	1343	1851	2869	3396	3541	3692	4031	4403	4684	4902	5077
7-Day High Flow	263	287	391	492	528	638	856	1237	1488	1736	1808	1848	1863	2006	2182	2315	2418	2501

Appendix C. Flows at Gaging Stations (continued).

	Exceedance Probability																	
	0.950	0.900	0.800	0.070	0.060	0.500	0.330	0.200	0.143	0.100	0.067	0.050	0.040	0.033	0.029	0.025	0.022	0.020
10-Day High Flow	241	278	377	477	512	611	835	1162	1316	1368	1480	1610	1643	1699	1758	1802	1836	1864
14-Day High Flow	237	269	358	458	508	591	807	1039	1112	1160	1364	1435	1453	1490	1530	1560	1584	1602
3-Day Winter Low Flow	124	81	56	44	37	29	23	19	17	14	12	10	10	10	10	10	10	10
7-Day Winter Low Flow	124	88	56	47	39	30	24	19	17	14	12	12	11	11	11	10	10	10
14-Day Winter Low Flow	116	91	60	51	38	31	25	20	18	15	13	12	12	11	11	11	11	11
3-Day Summer Low Flow	68	49	30	25	18	16	13	11	10	10	9	8	8	8	8	7	7	7
7-Day Summer Low Flow	71	51	33	25	19	16	14	11	10	10	9	8	8	8	8	8	7	7
14-Day Summer Low Flow	76	55	36	25	20	17	14	12	11	10	10	9	9	8	8	8	8	7
Station 11208000 Marble Fork Kaweah River at Potwisha Camp																		
3-Day High Flow	183	206	263	332	379	514	707	1024	1291	1494	1830	2088	2380	2528	2615	2680	2731	2772
7-Day High Flow	160	195	228	292	343	463	661	849	964	1017	1107	1211	1233	1301	1368	1419	1458	1490
10-Day High Flow	147	182	220	290	333	454	600	758	826	939	964	1023	1105	1131	1139	1145	1150	1154
14-Day High Flow	148	172	216	278	321	415	548	688	814	843	916	941	950	994	1038	1072	1098	1119
3-Day Winter Low Flow	66	33	21	18	15	13	10	7	6	6	4	3	3	3	3	2	2	2
7-Day Winter Low Flow	69	39	22	19	16	13	10	8	7	6	5	3	3	3	3	2	2	2
14-Day Winter Low Flow	72	47	24	20	17	14	11	7	7	7	5	4	3	3	3	2	2	2

Appendix C. Flows at Gaging Stations (continued).

	Exceedance Probability																	
	0.950	0.900	0.800	0.070	0.060	0.500	0.330	0.200	0.143	0.100	0.067	0.050	0.040	0.033	0.029	0.025	0.022	0.020
3-Day Summer Low Flow	27	18	10	8	6	5	4	3	2	2	2	2	2	1	1	1	1	1
7-Day Summer Low Flow	29	18	11	9	6	5	4	3	2	2	2	2	2	2	1	1	1	1
14-Day Summer Low Flow	32	20	12	9	7	5	4	3	3	2	2	2	2	2	1	1	1	1
Station11208730 East Fork Kaweah River near Three Rivers																		
3-Day High Flow	152	172	302	376	427	511	729	1054	1311	1558	2769	3477	3845	4091				
7-Day High Flow	137	153	275	358	393	474	681	922	1274	1381	1633	1806	1923	2002				
10-Day High Flow	126	148	267	348	385	458	640	891	1226	1289	1367	1428	1471	1501				
14-Day High Flow	119	146	252	332	374	436	626	875	1042	1188	1244	1282	1306	1321				
3-Day Winter Low Flow	40	13	10	7	4	2	1	0	0	0	0	0	0	0				
7-Day Winter Low Flow	46	14	11	7	5	2	1	0	0	0	0	0	0	0				
14-Day Winter Low Flow	38	16	12	8	5	3	1	1	0	0	0	0	0	0				
3-Day Summer Low Flow	29	17	7	6	3	1	1	0	0	0	0	0	0	0				
7-Day Summer Low Flow	31	18	7	6	3	1	1	0	0	0	0	0	0	0				
14-Day Summer Low Flow	33	21	7	6	4	1	1	1	0	0	0	0	0	0				
Station 11214000 North Fork Kings River below Meadow Brook																		
3-Day High Flow	242	264	365	423	468	508	644	743	782	917	950	1025	1097	1235	1332	1406	1463	

Appendix C. Flows at Gaging Stations (continued).

	Exceedance Probability																	
	0.950	0.900	0.800	0.070	0.060	0.500	0.330	0.200	0.143	0.100	0.067	0.050	0.040	0.033	0.029	0.025	0.022	0.020
7-Day High Flow	216	245	334	391	433	469	605	696	746	788	857	937	1014	1139	1227	1293	1345	
10-Day High Flow	210	221	320	376	413	467	601	647	724	753	815	888	960	1075	1157	1218	1266	
14-Day High Flow	191	207	304	353	376	433	563	630	689	735	775	846	909	1017	1092	1149	1194	
3-Day Winter Low Flow	16	12	10	8	6	4	3	2	1	1	0	0	0	0	0	0	0	
7-Day Winter Low Flow	16	12	10	8	6	4	3	2	1	1	0	0	0	0	0	0	0	
14-Day Winter Low Flow	15	13	10	9	6	5	3	2	1	1	1	0	0	0	0	0	0	
3-Day Summer Low Flow	11	6	2	2	2	1	1	1	0	0	0	0	0	0	0	0	0	
7-Day Summer Low Flow	12	6	3	2	2	1	1	1	0	0	0	0	0	0	0	0	0	
14-Day Summer Low Flow	14	8	3	2	2	2	1	1	0	0	0	0	0	0	0	0	0	
Station 11209500 North Fork Kaweah River at Kaweah																		
3-Day High Flow	167	183	311	390	510	579	955	1523	1996	2182	2384	2769	3054	3808	4392	4834	5177	5452
7-Day High Flow	137	168	255	310	371	427	689	1019	1085	1181	1291	1428	1578	2001	2330	2578	2771	2926
10-Day High Flow	117	152	239	289	327	364	617	829	903	1185	1213	1226	1240	1538	1775	1955	2094	2205
14-Day High Flow	99	142	221	257	294	347	541	689	821	997	1068	1110	1147	1308	1434	1530	1604	1663
3-Day Winter Low Flow	42	30	23	16	12	11	9	7	7	6	6	5	5	4	4	4	3	3
7-Day Winter Low Flow	43	28	22	17	13	12	9	7	7	6	5	5	5	4	4	4	3	3

Appendix C. Flows at Gaging Stations (continued).

	Exceedance Probability																	
	0.950	0.900	0.800	0.070	0.060	0.500	0.330	0.200	0.143	0.100	0.067	0.050	0.040	0.033	0.029	0.025	0.022	0.020
14-Day Winter Low Flow	45	29	23	18	13	12	10	8	7	7	5	5	5	4	4	3	3	3
3-Day Summer Low Flow	12	9	5	5	4	3	2	1	1	0	0	0	0	0	0	0	0	0
7-Day Summer Low Flow	13	9	6	5	4	3	2	1	1	0	0	0	0	0	0	0	0	0
14-Day Summer Low Flow	14	9	6	5	5	4	2	1	1	0	0	0	0	0	0	0	0	0
Station 11275000 Falls Creek near Hetch Hetchy																		
3-Day High Flow	430	541	688	784	882	944	1014	1135	1222	1373	2388	2577	2807	3005	3145	3253	3337	3404
7-Day High Flow	378	466	627	696	756	844	947	1011	1102	1217	1275	1516	1652	1665	1691	1745	1788	1821
10-Day High Flow	366	437	591	687	740	809	913	972	1036	1114	1209	1239	1250	1257	1270	1299	1322	1340
14-Day High Flow	352	404	542	647	708	760	840	917	946	1007	1042	1116	1158	1177	1190	1198	1205	1210
3-Day Winter Low Flow	41	38	31	22	15	10	6	2	1	1	0	0	0	0	0	0	0	0
7-Day Winter Low Flow	43	41	31	23	16	11	6	2	1	1	0	0	0	0	0	0	0	0
14-Day Winter Low Flow	47	44	34	26	16	11	7	2	1	1	0	0	0	0	0	0	0	0
3-Day Summer Low Flow	6	5	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-Day Summer Low Flow	7	5	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14-Day Summer Low Flow	8	7	3	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0

Appendix C. Flows at Gaging Stations (continued).

	Exceedance Probability																	
	0.950	0.900	0.800	0.070	0.060	0.500	0.330	0.200	0.143	0.100	0.067	0.050	0.040	0.033	0.029	0.025	0.022	0.020
Station 11213500 Kings River above North Fork near Trimmer																		
3-Day High Flow	2660	3286	4668	5277	6604	7633	8720	10887	11854	14043	15969	16899	17388	18706	20190	21310	22182	22879
7-Day High Flow	2501	3000	4476	4653	5919	6914	8202	8932	9902	11099	12800	13394	13873	14513	15144	15621	15992	16288
10-Day High Flow	2424	2897	4115	4507	5709	6556	7660	8673	9142	10298	11661	12873	13148	13763	14437	14946	15342	15659
14-Day High Flow	2219	2715	3965	4294	5604	6303	7244	8319	8782	10001	11236	12284	12291	12894	13655	14229	14676	15033
3-Day Winter Low Flow	484	369	297	251	227	199	150	127	120	111	94	93	92	89	85	82	80	78
7-Day Winter Low Flow	504	379	301	265	227	210	157	131	122	117	96	95	93	91	88	86	84	83
14-Day Winter Low Flow	504	394	316	268	239	209	158	134	126	121	98	97	96	94	92	90	89	88
3-Day Summer Low Flow	503	388	285	225	197	160	134	116	113	109	99	93	90	87	83	81	79	77
7-Day Summer Low Flow	549	417	298	232	204	164	139	118	116	112	102	95	93	90	86	83	81	79
14-Day Summer Low Flow	647	455	317	240	213	173	148	127	121	115	108	102	99	94	90	87	85	83
Station 11265000 Tenaya Creek near Yosemite Village																		
3-Day High Flow	280	450	578	654	726	742	817	959	1102	1127	1609	1750	1832	1948	2030	2092	2140	
7-Day High Flow	260	395	515	612	656	700	775	880	995	1043	1065	1105	1159	1246	1308	1355	1391	
10-Day High Flow	250	376	492	554	607	680	743	835	921	1002	1035	1042	1054	1075	1091	1102	1111	
14-Day High Flow	239	370	469	520	576	652	692	785	841	953	972	991	1011	1041	1063	1079	1091	

Appendix C. Flows at Gaging Stations (continued).

	Exceedance Probability																	
	0.950	0.900	0.800	0.070	0.060	0.500	0.330	0.200	0.143	0.100	0.067	0.050	0.040	0.033	0.029	0.025	0.022	0.020
3-Day Winter Low Flow	33	22	17	15	7	3	2	2	1	1	1	1	1	1	1	1	1	
7-Day Winter Low Flow	34	23	17	15	7	4	2	2	1	1	1	1	1	1	1	1	1	
14-Day Winter Low Flow	36	23	19	13	7	5	2	2	1	1	1	1	1	1	1	1	1	
3-Day Summer Low Flow	3	2	2	2	2	2	1	1	1	1	1	1	1	1	1	1	1	
7-Day Summer Low Flow	3	3	2	2	2	2	1	1	1	1	1	1	1	1	1	1	1	
14-Day Summer Low Flow	4	3	2	2	2	2	2	1	1	1	1	1	1	1	1	1	1	
Station 11210100 South Fork Kaweah River at Three Rivers																		
3-Day High Flow	83	115	164	198	244	333	541	890	1045	1530	1848	2505	3069	3448				
7-Day High Flow	79	102	143	187	223	305	445	618	805	879	1128	1385	1575	1702				
10-Day High Flow	76	98	133	180	206	290	416	581	682	728	1015	1151	1215	1258				
14-Day High Flow	71	97	126	171	204	276	416	543	581	668	817	881	913	935				
3-Day Winter Low Flow	51	27	18	14	11	10	8	5	4	3	2	2	2	2				
7-Day Winter Low Flow	52	29	19	14	11	10	9	5	4	3	3	2	2	2				
14-Day Winter Low Flow	57	24	21	14	12	10	9	5	4	3	3	2	2	2				
3-Day Summer Low Flow	10	7	3	2	1	0	0	0	0	0	0	0	0	0				
7-Day Summer Low Flow	11	8	3	2	1	0	0	0	0	0	0	0	0	0				

Appendix C. Flows at Gaging Stations (continued).

	Exceedance Probability																	
	0.950	0.900	0.800	0.070	0.060	0.500	0.330	0.200	0.143	0.100	0.067	0.050	0.040	0.033	0.029	0.025	0.022	0.020
14-Day Summer Low Flow	12	8	3	2	1	1	0	0	0	0	0	0	0	0				
Station 11226500 San Joaquin River Miller Crossing																		
3-Day High Flow	1355	1490	1849	2283	2617	3133	4060	4613	5224	5635	6010	6095	6143	6304	6418	6503	6570	
7-Day High Flow	1173	1356	1736	2083	2454	2777	3676	4254	4511	4873	5605	5696	5750	5901	6007	6088	6150	
10-Day High Flow	1129	1247	1659	1987	2399	2681	3453	4017	4500	4724	5400	5499	5540	5681	5780	5855	5914	
14-Day High Flow	1099	1155	1525	1925	2224	2500	3414	3866	4377	4511	5208	5370	5409	5531	5616	5681	5731	
3-Day Winter Low Flow	198	170	129	106	91	81	67	54	47	39	29	28	27	26	25	25	24	
7-Day Winter Low Flow	200	150	127	109	93	84	71	59	48	40	30	28	27	26	26	25	25	
14-Day Winter Low Flow	205	155	133	111	100	84	73	60	49	42	30	29	28	28	27	26	26	
3-Day Summer Low Flow	209	145	129	104	75	67	55	45	41	40	36	33	31	29	28	27	26	
7-Day Summer Low Flow	216	159	136	112	79	71	56	47	42	41	37	34	32	30	29	28	27	
14-Day Summer Low Flow	245	181	151	127	89	77	60	50	47	43	41	38	36	34	32	31	30	
Station 11283500 Clavey River near Buck Meadows																		
3-Day High Flow	231	377	631	737	1362	1446	2635	5223	6184	6773	7434	7682						
7-Day High Flow	193	313	597	617	1092	1317	2426	3081	3702	3983	4392	4609						
10-Day High Flow	176	291	557	612	973	1283	2114	2834	3069	3285	3511	3721						

Appendix C. Flows at Gaging Stations (continued).

	Exceedance Probability																	
	0.950	0.900	0.800	0.070	0.060	0.500	0.330	0.200	0.143	0.100	0.067	0.050	0.040	0.033	0.029	0.025	0.022	0.020
14-Day High Flow	171	275	516	585	892	1203	1733	2285	2558	2666	2884	3118						
3-Day Winter Low Flow	232	135	98	59	45	33	27	17	14	13	11	9						
7-Day Winter Low Flow	240	141	102	64	48	37	28	17	15	13	11	9						
14-Day Winter Low Flow	260	144	105	58	50	39	30	19	15	13	11	10						
3-Day Summer Low Flow	34	24	20	18	13	12	8	6	6	5	3	2						
7-Day Summer Low Flow	36	25	21	19	14	12	8	6	6	5	3	2						
14-Day Summer Low Flow	37	27	22	21	15	13	8	7	6	5	3	2						
Station 11284700 North Fork Tuolumne River Long Barn																		
3-Day High Flow	12	36	76	92	150	243	461	616	746	811	1048	1279						
7-Day High Flow	12	34	64	80	137	180	300	406	459	479	625	797						
10-Day High Flow	12	32	61	78	138	158	272	351	372	398	516	639						
14-Day High Flow	11	30	56	77	124	141	225	297	324	339	421	509						
3-Day Winter Low Flow	34	22	10	7	6	4	3	3	2	1	1	1						
7-Day Winter Low Flow	36	22	10	8	7	5	3	3	2	1	1	1						
14-Day Winter Low Flow	40	23	10	8	5	4	3	3	2	1	1	1						
3-Day Summer Low Flow	2	2	1	1	1	1	0	0	0	0	0	0						

Appendix C. Flows at Gaging Stations (continued).

	Exceedance Probability																	
	0.950	0.900	0.800	0.070	0.060	0.500	0.330	0.200	0.143	0.100	0.067	0.050	0.040	0.033	0.029	0.025	0.022	0.020
7-Day Summer Low Flow	3	2	1	1	1	1	0	0	0	0	0	0						
14-Day Summer Low Flow	3	2	2	1	1	1	0	0	0	0	0	0						

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