SAN FRANCISCO ESTUARY & WATERSHED SCIENCE
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Title:
Hydrologic Variability of the Cosumnes River Floodplain

Journal Issue:
San Francisco Estuary and Watershed Science, 4(2)

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Publication Date:
2006

Publication Info:
San Francisco Estuary and Watershed Science, John Muir Institute of the Environment, UC Davis

Permalink:
http://escholarship.org/uc/item/71j628tv

Keywords:
Cosumnes River, environmental flow, flood regime, floodplains, floods, hydrologic analysis, instream flow, restoration, watershed

Abstract:

Natural floodplain ecosystems are adapted to highly variable hydrologic regimes, which include periodic droughts, infrequent large floods, and relatively frequent periods of inundation. To more effectively manage water resources and maintain ecosystem services provided by floodplains – and associated aquatic, riparian, and wetland habitats – requires an understanding of seasonal and inter-annual hydrologic variability of floodplains. The Cosumnes River, the largest river on the west-slope Sierra Nevada mountains without a major dam, provides a pertinent test case to develop a systematic classification of hydrologic variability. By examining the dynamics of its relatively natural flow regime, and a 98-year streamflow record (1908 – 2005), we identified 12 potential flood types. We identified four duration thresholds, defined as short (S), medium (M), long (L), and very long (V). We then intersected the flood duration division by three magnitude classes, defined as small-medium (1), large (2), and very large (3). Of the 12 possible flood types created by this classification matrix, the Cosumnes River streamflow record populated 10 such classes. To assess the robustness of our classification, we employed discriminant analysis to test class fidelity based on independent measures of flood capability, such as start date. Lastly, we used hierarchical divisive clustering to classify water years by flood type composition resulting in 8 water year types. The results of this work highlight the significant seasonal and inter-annual variability in natural flood regimes in Central Valley rivers. The construction of water impoundment and flood control structures has significantly altered all aspects of the flood pulse. Restoring floodplain ecosystem services will require re-establishing key elements of these historic flood regimes in order to achieve regional restoration goals and objectives.

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Published by the California Bay-Delta Authority Science Program and the John Muir Institute of the Environment

Hydrologic Variability of the Cosumnes River Floodplain

(This paper is one in a series of interdisciplinary papers dedicated to documenting the restoration of the lower Cosumnes River, a tributary to the San Francisco Bay-Delta. These papers represent the findings of several California Bay-Delta Authority projects funded through the Ecosystem Restoration Program that focus on linked hydrogeomorphic and ecological processes in order to evaluate and guide ecosystem conservation and restoration efforts throughout the region.)

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ABSTRACT

Natural floodplain ecosystems are adapted to highly variable hydrologic regimes, which include periodic droughts, infrequent large floods, and relatively frequent periods of inundation. Effectively managing water resources and maintaining ecosystem services provided by floodplains—and associated aquatic, riparian, and wetland habitats—requires an understanding of seasonal and inter-annual hydrologic variability of floodplains. The Cosumnes River, the largest river on the west-slope Sierra Nevada mountains without a major dam, provides a pertinent test case to develop a systematic classification of hydrologic variability. By examining the dynamics of its relatively natural flow regime, and a 98-year streamflow record (1908 – 2005), we identified 12 potential flood types. We identified four duration thresholds, defined as short (S), medium (M), long (L), and very long (V). We then intersected the flood duration division by three magnitude classes, defined as small-medium (1), large (2), and very large (3). Of the 12 possible flood types created by this classification matrix, the Cosumnes River streamflow record populated 10 such classes. To assess the robustness of our classification, we employed discriminant analysis to test class fidelity based on independent measures of flood capability, such as start date. Lastly, we used hierarchical divisive clustering to classify water years by flood type composition resulting in eight water year types. The results of this work highlight the significant seasonal and inter-annual variability in natural flood regimes in Central Valley rivers. The construction of water impoundment and flood control structures has significantly altered all aspects of the flood pulse. Restoring floodplain ecosystem services will require re-establishing key elements of these historic flood regimes in order to achieve regional restoration goals and objectives.

KEYWORDS

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SUGGESTED CITATION

Booth, Eric, Jeffrey Mount, and Joshua Viers. Hydrologic Variability of the Cosumnes River Floodplain. San Francisco Estuary and Watershed Science. Vol. 4, Issue 2 [September 2006]. Article 2.

http://repositories.cdlib.org/jmie/sfews/vol4/iss2/art2

INTRODUCTION

Background

Floodplains are among the most productive and diverse ecosystems on Earth; they are also some of the most impacted and at risk ecosystems globally (Tockner and Stanford 2002), affected by myriad anthropogenic stressors and consumptive demands. Natural floodplain ecosystems are adapted to highly variable hydrologic regimes, which include periodic droughts, infrequent catastrophic floods, and relatively frequent periods of inundation (Lytle and Poff 2004). Hydrologic variability acts to disturb and/or reset various biotic populations within aquatic, riparian, and wetland ecosystems, acting as an essential complement to ecological processes (e.g., nutrient cycling) in maintaining complex ecosystem pathways, which in turn promote high biodiversity and biological integrity (Power et al. 1995; Ward and Stanford 1995). Furthermore, the connectivity of floodplains to river systems is a critical linkage that creates and maintains a mosaic of habitats for primary productivity (Ahearn et al. in review), the reproductive cycle of fishes (Ribeiro et al. 2004; Sommer et al. 2004), nesting and foraging of birds (Saab 1999), and regeneration of riparian vegetation (Tabacchi et al. 1998).

Effective long-term maintenance of floodplain ecosystem services—especially large ecosystem recovery efforts, such as those undertaken by the California Bay-Delta Authority—requires an improved understanding of the spatiotemporal variability within a flow regime including the types and frequencies of floods within the regime. The 'natural flow' paradigm (Poff et al. 1997; Bunn and Arthington 2002), a synthetic approach to better reconciling competing demands between environment and society, emphasizes the importance of natural intra-annual and inter-annual variability in river flows. This paradigm maintains that hydrologic variability is essential for maintaining ecological integrity, which includes the self-sustaining products and processes of ecosystems that provide social and economic services to humans. The goal of maintaining ecological integrity of river ecosystems has led to research that attempts to characterize flow regimes using available streamflow data and to apply these characterizations to river management activities.

The most traditional method for characterizing the hydrologic variability of a river is flood frequency analysis. Flood frequency analysis produces discharge recurrence intervals to calculate an exceedance probability distribution based on an observed streamflow record. While these types of analyses are critical for engineering flood control infrastructure, they do not accurately distinguish different flood events based on duration or timing. Important ecosystem services, such as primary productivity and juvenile fish rearing, are often more dependent upon the duration and timing of floodplain inundation than the magnitude or frequency of the event. In other words, ecological complexity is reliant upon the strength of biotic-abiotic interactions, which are time-dependent processes.

The discharge-duration-frequency method (Javelle et al. 2002; Javelle et al. 2003) attempts to include duration in flood frequency analysis but, as with all flood frequency analyses, only the largest events of the year are considered. By ignoring the smaller, more frequent flooding events many critical aspects of the flood regime are left out of the analysis.

Recent attempts to characterize flow regimes have developed a suite of hydrologic indices, primarily aimed at quantifying variability. For example, the Indicators of Hydrologic Alteration (IHA) method (Richter et al. 1996) combined with the Range of Variability Approach (RVA) (Richter et al. 1997) calculates 32 ecologically significant hydrologic indices for each year of record and recommends a range of variability for each index to set as a goal for water managers. In addition to the 32 IHA parameters, 34 Environmental Flow Components (EFCs) parameters are calculated based on statistics for five distinct flow types: low flows, extreme low flows, high flow pulses, small floods, and large floods (Postel and Richter 2003). This method has been used extensively by resource agencies throughout the world (TNC 2005).

Other examples include a study by Olden and Poff (2003), who highlight patterns of redundancy for 171 hydrologic indices (including the IHA parameters) and recommend a condensed, non-redundant set of hydrologic indices that characterize different aspects of the flow regime for different river systems. To similar ends, Harris et al. (2000) present a method to classify water years by the shape and size of the annual hydrograph for several British rivers, using four shape classes, timing of the peak flow(s), and four magnitude classes. Finally, Stewardson and Gippel (2003) introduce the Flow Events Method (FEM), which emphasizes the importance of temporal variability within the functional relationship between hydrology and ecology. After identifying important ecological processes, the FEM characterizes specific flow events and their distribution in time. All of these methods build on the understanding of the 'natural flow' paradigm and are usually applied as functional analysis tools when establishing environmental river flow requirements (Acreman and Dunbar 2004).

Specifically related to floodplains, Benke et al. (2000) quantified the inundation dynamics of a floodplain in the southeastern U.S. coastal plain over a 58-year time period. Although important hydrologic indices were calculated for each year of record, no specific typology of floods or years was given to characterize the inter-annual variability of floodplain hydrology.

Objectives

The objectives of this study are to integrate elements of these previous studies and to characterize the hydrologic variability of the lower Cosumnes River by analyzing a 98-year streamflow record (1908 – 2005). Located in central California on the west slope of the Sierra Nevada, this river is unique in that it possesses a relatively undisturbed hydrograph. Our work expands on the concept introduced by Harris et al. (2000) by defining individual flood types as one of four duration and three magnitude class combinations, which are based on significant geomorphic and hydrologic thresholds for the Cosumnes River system. We calculate frequency of occurrence for each flood type and then employ discriminant analysis to test type fidelity based on independent measures of flood capability, such as a flood's start date. Lastly, we used hierarchical divisive clustering to classify water years by flood type composition (i.e., frequency of flood types within the water year).

Our methodology also expands on the IHA method by looking within the ranges of variability for flood events and quantifying how often certain types of floods and water years occur. This knowledge of the natural frequency of certain flood events should aid water managers in the future. If the goal of management is to sustain ecosystem services of floodplains, the frequency of certain flood and water year types in the future should be roughly similar to what has been quantified in the previous 98 years. The described methodology, however, is limited to characterizing the hydrologic variability once the river connects with its floodplain and not during flows that remain in-channel. Finally, while similar techniques could be used on other rivers, this specific method only typifies one lowland segment of river in central California.

Study Area

The Cosumnes River watershed (Figure 1), located southeast of Sacramento, drains a 1989 km2 area starting at 2,300 m in the Sierra Nevada mountain range and draining into the Mokelumne River at an elevation of 2 m above sea level. Water from the Cosumnes River ultimately flows into the San Francisco Bay–Delta. It is one of the few unimpounded rivers flowing from the Sierra Nevada Range into the Central Valley. With the exception of loss of base flow in the summer and fall (Fleckenstein et al. in press), the Cosumnes maintains a relatively unimpaired hydrograph. Average annual precipitation in the upper watershed (based on data from a meteorological station at Fiddletown, CA from 1939-2004) is 926 mm and in the lowlands (based on data from a meteorological station at Elliott, CA from 1927-1992) 447 mm, with the majority of precipitation occurring between December and March (NCDC 2006). This winter precipitation is typically in the form of snow above 1,500 m; however, only 16% of the watershed is above 1,500 m; thus, winter rainfall plays a much

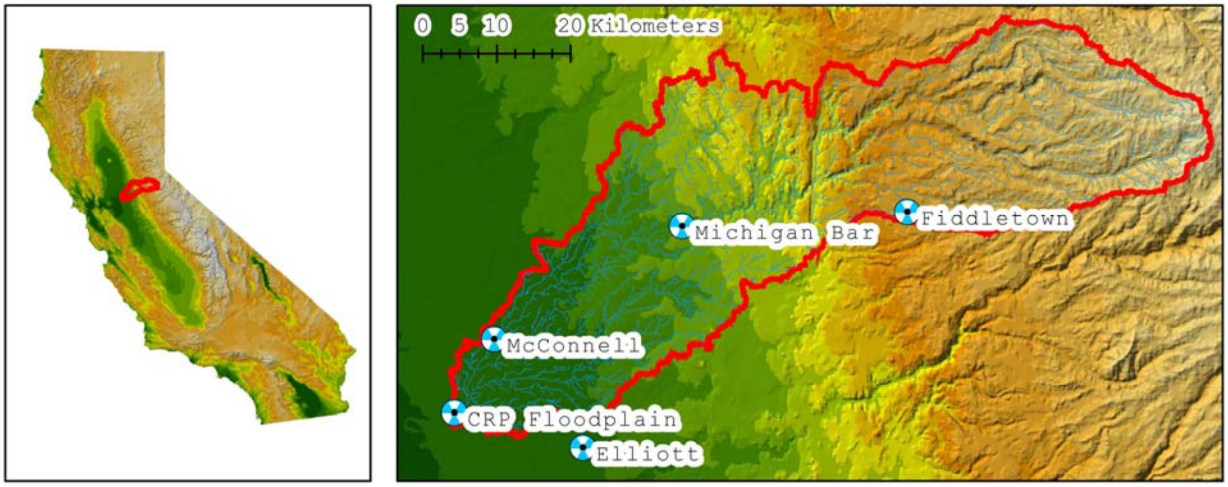


Figure 1. Map of Cosumnes River watershed showing locations of Cosumnes River Preserve (CRP) floodplain, Michigan Bar streamflow gage, McConnell streamflow gage, Fiddletown precipitation gage, and Elliott precipitation gage.

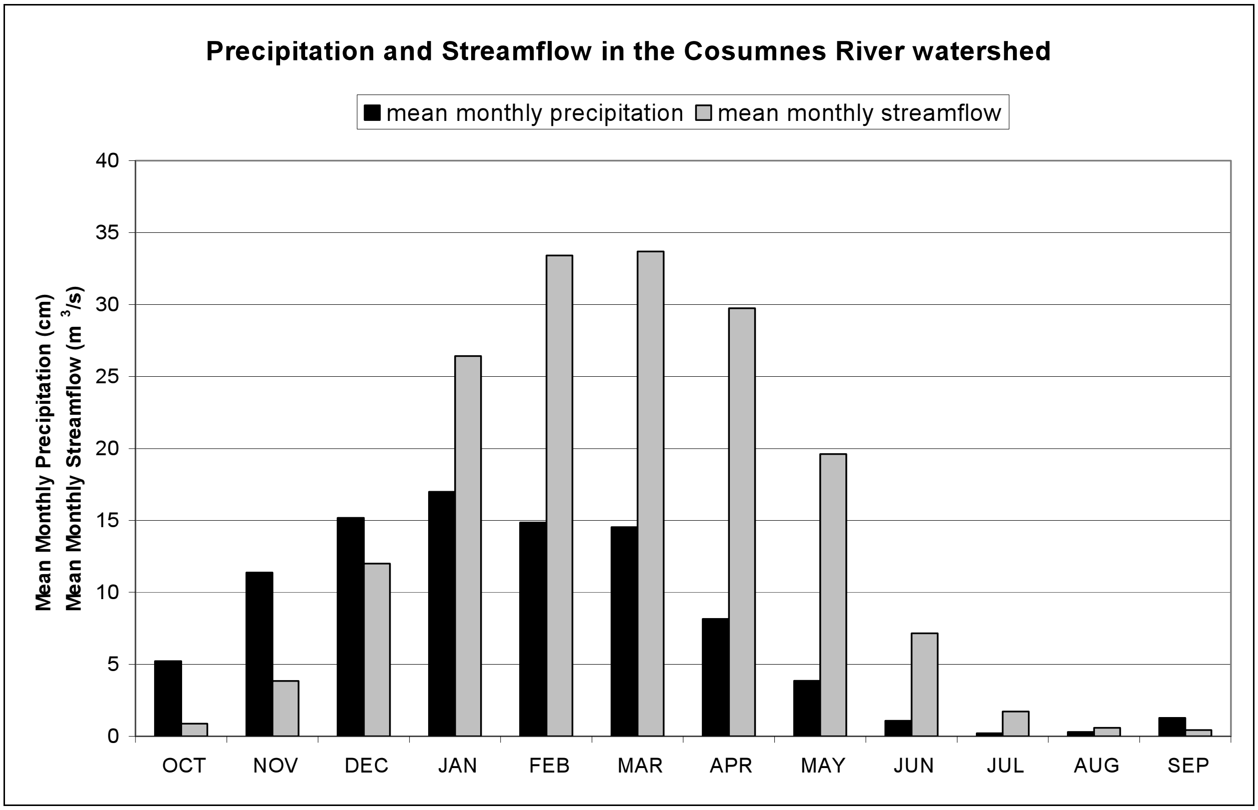


Figure 2. Mean monthly precipitation (from meteorological station at Fiddletown, CA) and mean monthly streamflow at Cosumnes River at Michigan Bar.

more significant role in runoff compared to other rivers draining the western Sierra Nevada mountains with higher elevation watersheds (USACE 1965). Figure 2 shows the mean monthly precipitation (from the Fiddletown station) and the mean monthly streamflow (at Michigan Bar) for the watershed.

Overall, temperature plays an important role in Sierra Nevada flood regimes by determining whether storm precipitation will contribute more runoff or more snowpack (Dettinger 2005). This temperature is driven by orographic effects as well as by the geographic origin and direction of the storm system. For example, circulations that transport exceptionally warm and moist air from the subtropics and tropics into the central Sierra Nevada mountains are often responsible for warm storms with intense precipitation that lead to large floods.

Historically, the lower Cosumnes River was a dynamic, low-gradient, multi-channel anastomosing system dominated by frequent avulsions and regular inundation of the floodplain during winter and spring (Florsheim and Mount 2002). This floodplain can be classified as a low-energy cohesive floodplain (C2) according to the genetic floodplain classification presented by Nanson and Croke (1992). For the last 200 years, the Cosumnes River has been impacted by a range of land use activities. Hydraulic mining and grazing increased erosion throughout the upper watershed and provided a source of sediment to the downstream channel and floodplain. Once the hydraulic mining sediment source was eliminated in the early 1900s, channel incision, initiated due to levee construction, occurred throughout the previously aggraded bed (Vick et al. 1997). This incision has occurred in all alluvial reaches of the river except the farthest downstream section near its tributary junction with the Mokelumne River (Florsheim and Mount 2003). Widespread conversion of the floodplain forests and wetlands of the lower Cosumnes to agricultural fields took place during the early 1900s, although some patches of remnant riparian forest remain. Today, the river is confined to a single channel and remains almost entirely disconnected from its floodplain except during high flows when levees are breached.

The lowland river-floodplain reference site is a restored floodplain located on the Cosumnes River Preserve (CRP), which is managed by a coalition of state, federal, and non-profit organizations, such as The Nature Conservancy California. Restoration of the agricultural fields along the river was achieved through breaching of levees during the 1990s. Since restoration of connectivity, the channel and the floodplain have undergone considerable topographic change due to localized deposition and scour during flood events (Florsheim and Mount 2002). This restoration effort has increased habitat heterogeneity due to the colonization of tree and herbaceous vegetation on floodplain sand deposits.

METHODS

Streamflow Record

A continuous daily record of discharge data (Figure 3) for the Cosumnes River at Michigan Bar from 1908 – 2005 was acquired from the U.S. Geological Survey's National Water Information System (USGS 2005). Although the gage at Michigan Bar (MHB) is located approximately 50 km upstream of the floodplain reference site on the Cosumnes River Preserve, it accurately predicts flood conditions on the floodplain due to very little streamflow being added downstream of Michigan Bar. This point is illustrated by comparing annual streamflow volumes at MHB with the Cosumnes River at McConnell gage (MCC) that was rated by the USGS for discharge from 1941 – 1982 (USGS 2005). MCC is located approximately 11 km upstream of the CRP floodplain and is a very good predictor of streamflow at the CRP because there are no tributaries in between the two sites. Excluding three drought years (1961, 1976, and 1977), the mean of the ratio of November – June streamflow volume between MHB and MCC is 0.94. Therefore, on average, 94% of the streamflow volume during the flood season that passes MCC also passed MHB. This 6% difference is acceptable for our analysis since MHB data are used only as a proxy for flooding on the CRP floodplain.

The MHB streamflow record was also analyzed for stationarity because many surrounding basins in the Sierra Nevada exhibit trends in variables such as cen-

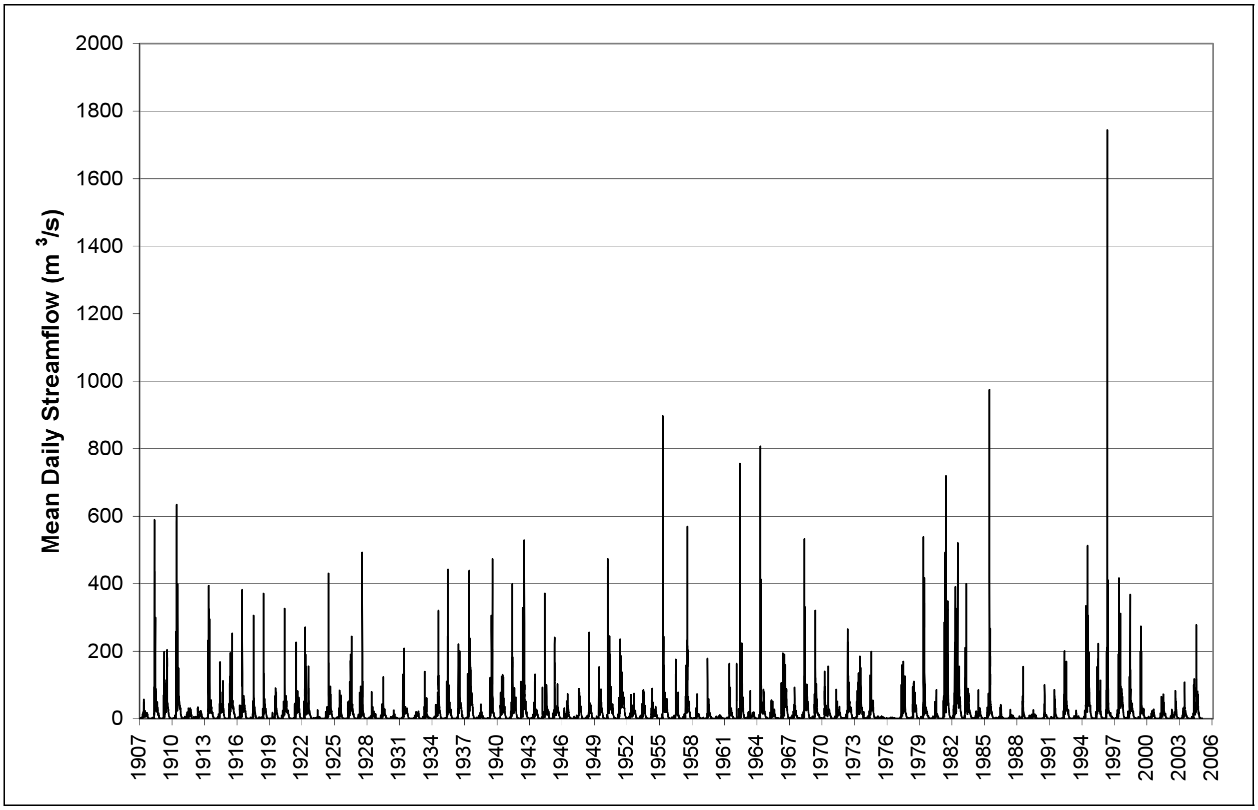


Figure 3. Hydrograph of daily discharge data of Cosumnes River at Michigan Bar (WY1908-2005)

ter of mass of annual flow and maximum annual flow due to changes in climatic conditions since 1950. Stewart et al. (2005) found that the center of mass of annual flow has come earlier since 1948 for snowmelt-dominated watersheds throughout the western U.S. They attributed this trend to warmer winter and spring air temperatures. Similarly, the National Research Council (NRC) (1999) found that larger flood events were concentrated after 1950 in each of the streamflow records for the American, Feather, Merced, Mokelumne, Stanislaus, Tuolumne, and Yuba rivers. For the Cosumnes River, we found no trend for the center of mass of annual flow, which is most likely because the Cosumnes River is a lower elevation watershed with less snowpack compared to most west-slope Sierran rivers; snowmelt is therefore not as large of a contributor to the annual streamflow volume. However, we performed a 51-year moving window analysis of the MHB streamflow record, which revealed an increasing trend related to maximum annual flow. As in surrounding basins, the larger flood events have occurred post-1950 in the Cosumnes River basin. To determine this change in stationarity, we first calculated the moving mean (MM) and moving standard deviation (MSD) of the annual maximum daily flow time series. Subsequently, we applied maximum likelihood estimation, using a log-normal distribution, to determine the moving 100-year annual maximum daily flow event (Q100) (Figure 4). To test for significant differences in trend, the series was bisected and the differences in means of the MM, MSD, and Q100 for each half were tested using the two-sample t-test with unequal variances. The first and second half means for each parameter were significantly different ($p = 0.01$) from each other (Table 1). We believe that the observed increasing trend in the moving mean, moving standard deviation, and moving 100-year daily flood in the Cosumnes River streamflow record is noteworthy and one that is considered throughout this analysis.

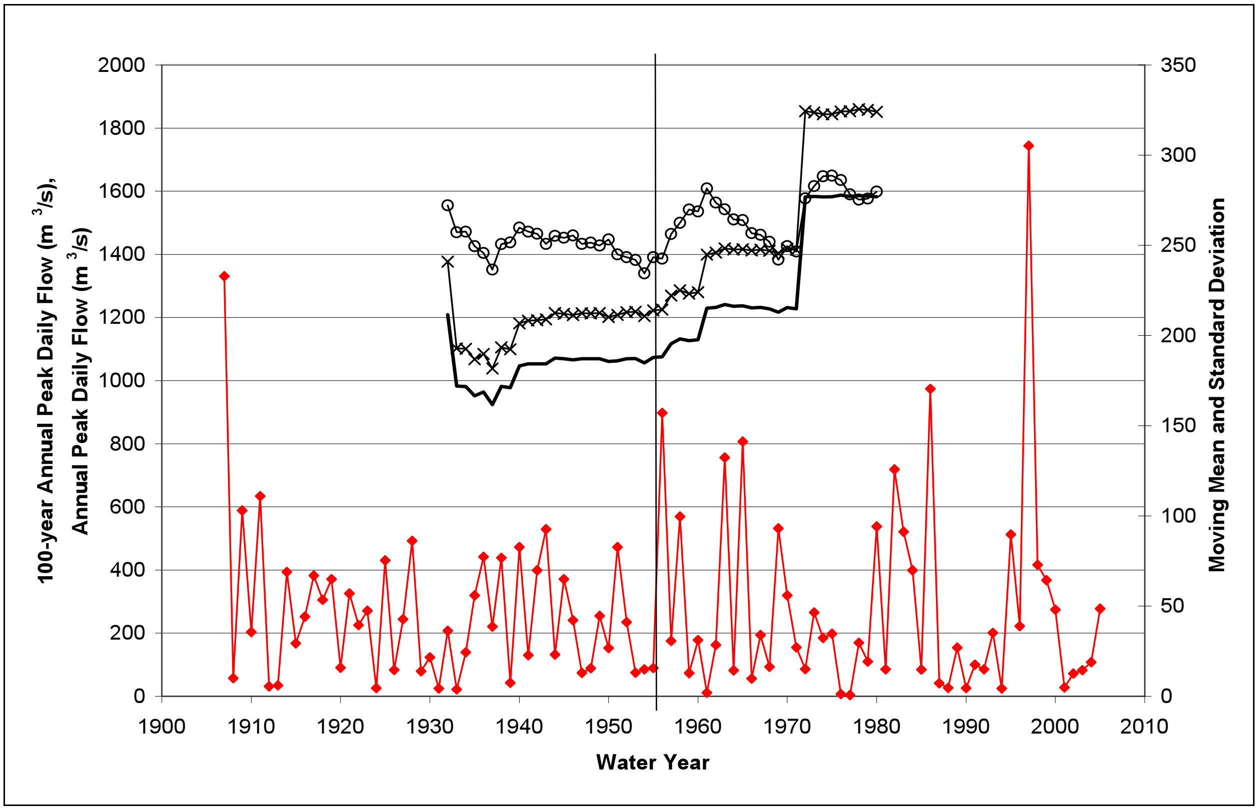


Figure 4. Plot showing the annual peak daily flow time series (red line) and trends in the moving mean (black line with circle markers), standard deviation (black line with x-markers), and 100-year annual maximum daily flow (black line with no markers) of the Cosumnes River at Michigan Bar (WY 1907 - 2005) that was calculated by fitting the log-normal distribution using maximum likelihood estimation. Vertical line shows the mid-point of the record.

Water Year range	MM mean	MSD mean	Q_{100} mean
1907 – 1955 (*N* = 24)	251.0 m^3/s	206.2 m^3/s	1041.2 m^3/s
1956 – 2005 (*N* = 25)	267.5 m^3/s	269.7 m^3/s	1335.2 m^3/s
Degrees of Freedom	38.1	28.3	28.5
$t_{0.01}$	2.712	2.763	2.763
t*	5.014	7.124	7.187

Table 1. Means of the 51-year moving-window mean (MM), standard deviation (MSD), and 100-year annual maximum daily flow for the first and second halves of the annual maximum daily flow record and results from a two-sample t-test with unequal variances showing the means to be significantly different (p = 0.01) for each parameter.

In a similar concern, the streamflow record was analyzed for alteration using the Indicators of Hydrologic Alteration (IHA) analysis (Richter et al. 1996). The IHA analysis yielded medians and coefficients of dispersion for 68 hydrologic parameters for a period before and after a “disturbance,” which in this case was defined as the middle of the record. The only significant (95% confidence interval) changes related to floods on the Cosumnes were for the coefficients of dispersion for January, April, May, and June monthly discharge and 30-day and 90-day annual maximum discharges. For each of these five parameters, coefficients of dispersion were larger post-1956. The idea that discharges were more variable in the period after 1956 is important and could be related to climate changes. However, other pertinent characteristics of the streamflow record do not show a similar trend and can be considered consistent with a stationary time series.

Flood Typing

Field observations of the floodplain at the Cosumnes River Preserve since 1998 suggest a floodplain connectivity threshold of 25 m3/s at MHB (Florsheim et al. in press). This threshold corresponds to approxi-

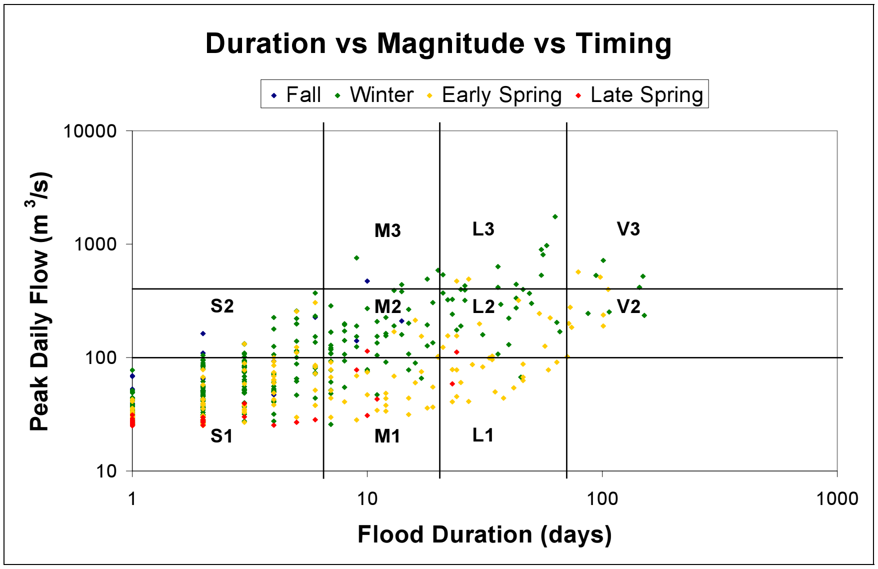


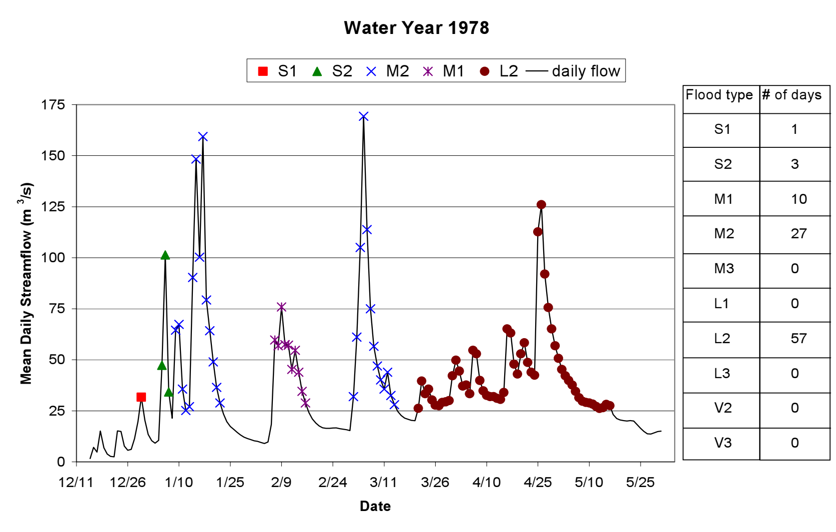
Figure 5. Plot of 479 events on Cosumnes River at Michigan Bar (WY1908-2005) separated into nine flood types. Fall = OCT, NOV; Winter = DEC, JAN, FEB; Early Spring = MAR, APR; Late Spring = MAY, JUN

mately the one-year flood using the methodology described in Bulletin 17B (IACWD 1982) on daily streamflow data at MHB from 1907-2004. For the purposes of this analysis, a flood event—a flow that connects the lower Cosumnes River channel to the floodplain through overland flow—was defined to be any period when the flow at MHB is above 25 m3/s. Disconnection is defined as the day when flow at MHB reaches 25 m3/s following a flood event. Since levee breaches currently control connectivity between the channel and floodplain, this threshold does not describe actual historical flood conditions. Rather, this threshold only describes how the current floodplain would function if subjected to the range of discharge conditions experienced over the past 98 years. Since the Cosumnes floodplain is highly altered, this threshold provides only an approximation of historic conditions and is not intended to be used to simulate flow conditions prior to land conversion. This study provides an analysis of flood patterns, rather than a simulation of historic conditions.

Using the 98-year discharge record observed from the continuous flow gage at MHB, we separated 479 flood events (using the 25 m3/s threshold) and calculated the following statistics for each event: start date, end date, flood duration, peak daily discharge, mean daily discharge, disconnection period before flood, disconnection period after flood, antecedent floodplain volume, total flood volume, and number of flood peaks. We plotted flood duration versus peak daily discharge for each flood event (Figure 5), displaying the corresponding season in color. Using the empirical hydrogeomorphic thresholds described below, we delineated four duration classes, which were defined as short (S) (<7 days), medium (M) (7-20 days), long (L) (21-70 days), and very long (V) (>70 days). We then superimposed three magnitude classes, defined as small-medium (1) (<100 m3/s), large (2) (100-400 m3/s), and very large (3) (>400 m3/s), creating 12 possible flood types. The ten flood types shown in Figure 5 indicate where observed gage data met our typing criteria—two types were absent in the period of record.

Boundary thresholds for each flood type were defined based on hydrologic and geomorphic characteristics of the floodplain-channel interface and the watershed. Floods with durations greater than 71 days dominated the entire flood season and had peak daily discharges greater than 100 m3/s (approximately the 1.5-year flood). This magnitude threshold corresponds to observations from floodplain monitoring, in which peak daily discharges above 100 m3/s transport new sediment (i.e., sand) onto the floodplain (Florsheim et al. in press). These empirical observations also guided the definition of an upper magnitude threshold; flood events with a peak daily discharge above 400 m3/s (slightly less than the 5-year flood) inundate and fill the entire floodplain and create substantial geomorphic disturbance.

A majority (63%) of the floods less than seven days in duration were formed with one peak and most likely corresponded with one significant precipitation event. A majority (75%) of the floods with a duration greater than seven days were composite events (more than one peak) and most likely corresponded with more than one precipitation event. Floods lasting less than 21 days did not occupy a large fraction of the flood season but differed considerably from the single-event floods.



Flood type	# of days
S1	1
S2	3
M1	10
M2	27
M3	0
L1	0
L2	57
L3	0
V2	0
V3	0

Figure 6. Mean daily streamflow (cm) on the Cosumnes River at Michigan Bar for water year 1978 shown with flood types and number of days each flood type is present.

Flood Frequency & Flood Type Fidelity

In order to quantify the frequency of occurrence of each flood type, the flood event record was separated into water years (October 1 – September 30). The number of occurrences of each flood type during the period of record and the empirical frequency of a flood type occurring in any given year were calculated.

Discriminant analysis was used to validate the statistical uniqueness of each flood type. This technique predicts whether or not a particular flood event belongs within its assigned flood type by looking at independent variables aside from the ones that were used for classification (e.g., peak daily discharge and flood duration). Three variables (start date, mean daily discharge, and number of peaks) were used to evaluate how rigorously the classification distinguished flood events. The stepwise method of discriminant analysis was used with prior probabilities proportional to the number of floods in each flood type.

Water Year Classification

Finally, to classify water year types, hierarchical cluster analysis was used to differentiate years based on the number of days each flood type occurred during each water year. Hierarchical cluster analysis groups similar observations into clusters based on their distance apart from one another. In other words, the closer two observations are to each other the more likely they will be clustered together. This analysis can be performed using N number of variables (i.e., distance is calculated in N-dimensions). In this case, each observation was a water year, and the number of variables coincided with ten flood types (N = 10). The value given to each variable was the number of days each flood type was present in the water year. For example, in water year 1978 an M2 flood event was present for 27 days (Figure 6). Using the number of days each flood type was present in a given water year instead of only the number of floods corresponding with each type allowed us to separate out the longer events from the shorter events and give more credence to flood duration. Ward's minimum variance method was used to calculate distance between objects. This method uses the distance between two clusters as the ANOVA sum of squares between the two clusters added over all the variables.

Flood Type	Duration	Duration (days)	Magnitude	Peak Flow (m^3/s)	Start Season	# of occur.	emp freq 1 or more	emp freq 2 or more	emp freq 3 or more
S1	short	< 7	small to med	< 100	All seasons	278	0.91	0.72	0.54
S2	short	< 7	large	100-400	Fall to Early Spring	31	0.29	0.03	0.00
M1	medium	7-20	small to med	< 100	Winter to Late Spring	42	0.33	0.09	0.01
M2	medium	7-20	large	100-400	Winter	44	0.36	0.07	0.02
M3	medium	7-20	very large	> 400	Fall to Winter	5	0.05	0.00	0.00
L1	long	21-70	small to med	< 100	Early Spring	20	0.18	0.02	0.00
L2	long	21-70	large	100-400	Winter to Early Spring	31	0.28	0.04	0.00
L3	long	21-70	very large	> 400	Winter	12	0.11	0.01	0.00
V2	very long	> 70	large	100-400	Winter to Early Spring	10	0.10	0.00	0.00
V3	very long	> 70	very large	> 400	Winter to Early Spring	6	0.06	0.00	0.00
2 or 3			large-very large	> 100		139	0.66	0.47	0.22
3			very large	> 400		23	0.21	0.02	0.00
L or V	long-very long	> 20				79	0.58	0.22	0.00
V	very long	>70				16	0.16	0.00	0.00
ALL						479	0.94	0.88	0.83

Table 2. Nine flood types of the Cosumnes River and each respective duration, magnitude, timing, and empirical frequency in any given year.

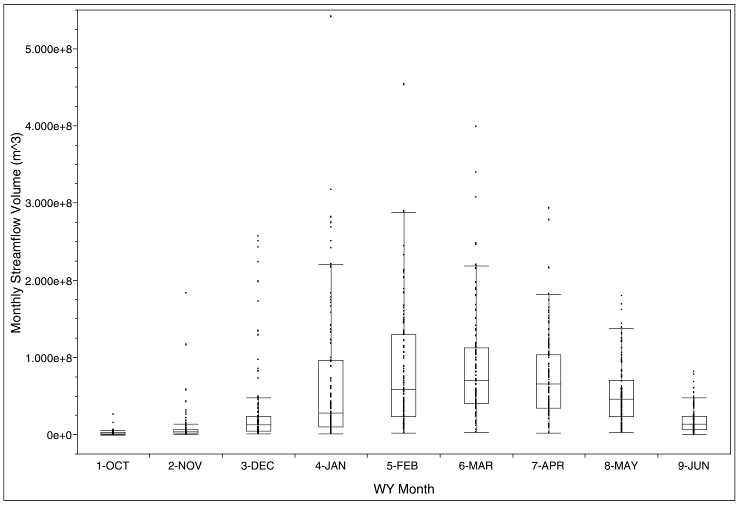


Figure 7. Monthly water volumes for 98-year streamflow record for Cosumnes River at Michigan Bar.

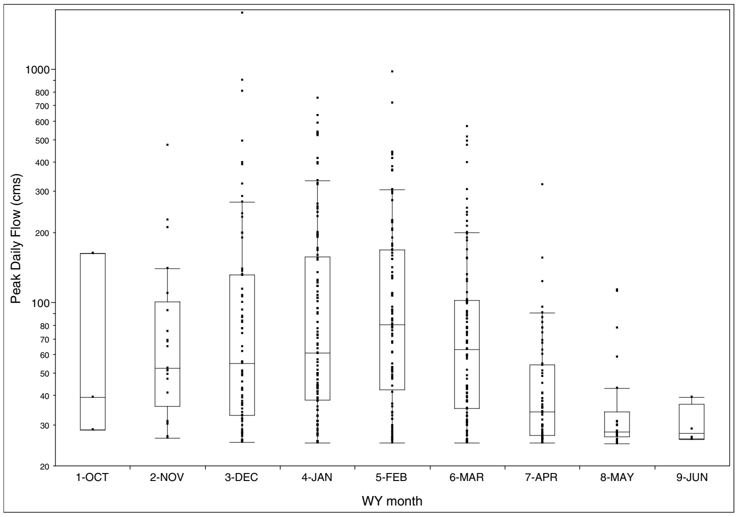


Figure 8. Peak daily flow versus starting month with box plots for all 479 flood events.

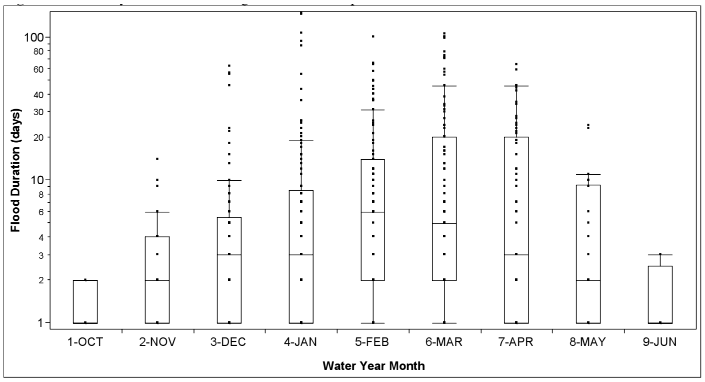


Figure 9. Flood duration versus starting month with box plots for all 479 flood events.

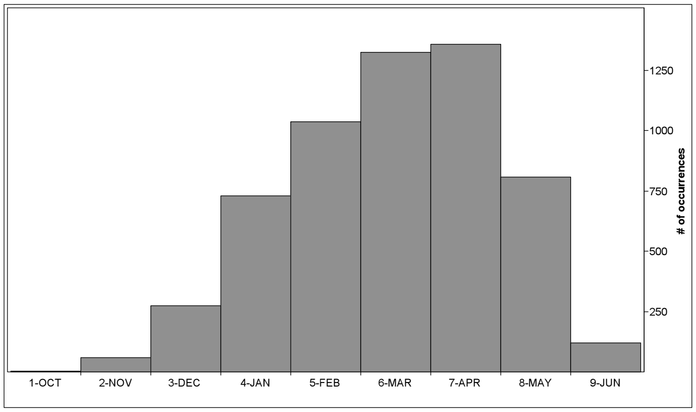


Figure 10. Frequency distribution of days of flooding per water year month.

RESULTS

Flood Typing

We created a generalized framework for hydrologic characterization of the Cosumnes River using a combination of flood duration and magnitude. Using empirical hydrogeomorphic thresholds, we typed 479 floods into 10 classes, of the possible 12, for all observed events in the 98-year streamflow record—Table 2 describes each of the 10 flood types. The relationship between magnitude (peak flow), duration, and timing (season) for all events is shown by respective classes in Figure 5. No flood events occupied the short duration, very large magnitude type and the very long duration, small-medium magnitude type classes, as was expected due to the positive relationship between flood magnitude and duration. An example of how the flood types are defined in a given year is shown in Figure 6.

On average, the first flood of the season occurs in early January (mean and median of all years with floods is January 6). Subsequent winter floods have larger peak to duration ratios due to higher intensity rainfall inputs compared with spring floods, which have smaller peak to duration ratios due most likely to higher snowmelt contributions (Figure 5). The wettest month of the year based on total streamflow volume is March (median = 7.0 x 107 m3), with April and February slightly drier (Figure 7). However, peak daily

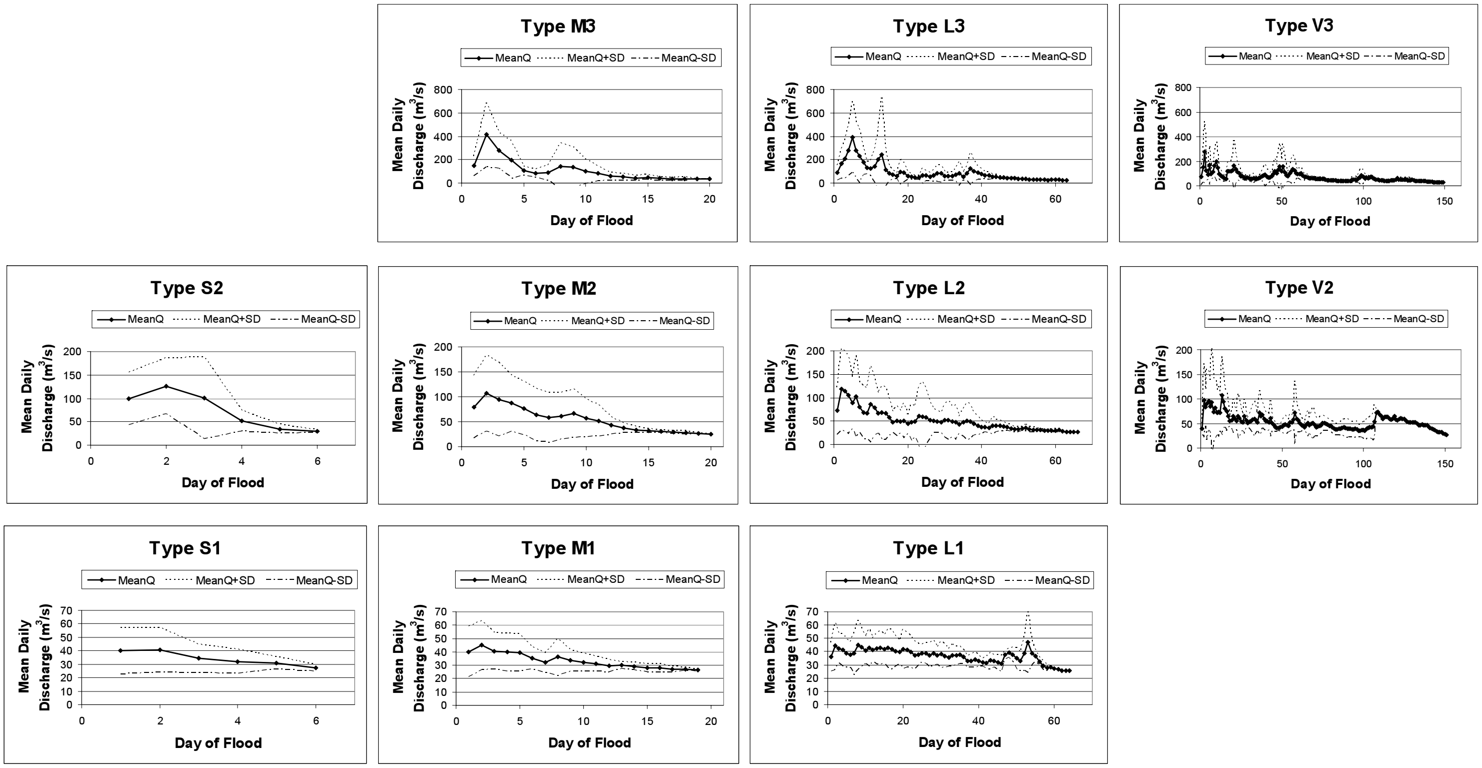


Figure 11. Average hydrographs representing each flood type.

flows of the separated flood events are highest in February (median = 81 m3/s), with March and January approximately 20 m3/s lower (Figure 8). Flood durations, as shown in Figure 9, are longest when flooding starts in February (median = 6 days), with March just slightly shorter. Figure 10 shows the frequency distribution of all days of flooding over the 98-year record; occurrences steadily increase until the peak in April. Since precipitation declines substantially in April, this peak in the number of flood days is most likely due to snowmelt. Finally, nearly two-thirds of all floods in the period of record started in January, February, or March.

Since each flood event within a flood type is different, average hydrographs were determined for each flood type to show the general shape of the flood hydrograph. Figure 11 shows each average hydrograph with plus or minus one standard deviation from the mean to show variability for each day of flooding. Each average hydrograph shows a peak within several days of the start date and then gradually decreases over time. The peaks are more noticeable in the flood types with higher peak discharges relative to duration such as types S2, M2, M3, L2, L3, and V3. The flood types with smaller magnitudes relative to duration (S1, M1, L1, and V2) tend to have a more sustained and constant discharge over the flood period. Variability tends to decrease with duration within each flood type because of the decrease in sample size (n) of floods with longer durations (e.g., for L1, n = 20 at 23 days, but n = 2 at 47 days).

Several of the same flood statistics used to describe individual flood events were also used to describe each flood type, including the following variables: number of peaks, start date, duration, peak flow, mean flow, and flow volume (Figure 12). Start dates show roughly the same temporal trend observed in Figure 5 (i.e., timing) but with specific start dates for each flood type. The general trend is that floods with higher peak flows and shorter durations tend to be earlier in the season as compared to floods with smaller peak flows and longer durations that occur later in the season. The differences in early season versus late season flood types is exemplified by type M3, which only occurs in fall and winter, and type L1, which primarily occurs in spring due to snowmelt. Types L and V tend to start later in the season while types S and M can begin at any time throughout the flood season.

Discriminant Analysis

Discriminant analysis is an eigenvector technique that quantifies the degree of association between independent variables, maximally separating a fixed number of classes (McCune and Grace 2002). Our objective was to maximize among class variation, in this case across flood types, relative to within class variation, or within flood types. As a statistical technique, discriminant analysis is focused on multivariate structure and misclassifications of *a priori* classes (McCune and Grace 2002), allowing us to gauge the efficacy of our typing thresholds.

We used three independent measures of flood composition in discriminant analysis to objectively quantify the strength of association of floods within our *a priori* thresholds. Using flood start date, mean daily discharge during the flood, and number of peaks within a flood as independent, multivariate classifiers and with class odds proportional to observed, discriminant analysis showed that 27.6% of the flood events were misclassified. However, 57% of misclassified events were predicted to be S1 flood types (n = 75), which is the most highly populated flood type. Of these misclassified events—ones predicted to be S1—over 50% (n = 41) were initially defined as M1 events.

This relatively high misclassification rate is most likely due to the descriptive nature of the original classification; the misclassification rate was also quite high (23%) when using dependent variables (i.e., peak flow and duration) instead of the independent variables (i.e., start date, average daily discharge, and number of

		D	S	M	L	V	*M*
Magnitude	> 400 m^3/s	↑		M3	L3	V3	3
	100 m^3/s < 400 m^3/s		S2	M2	L2	V2	2
	25 m^3/s <= 100 m^3/s		S1	M1	L1		1
	Type Code		0 < 7 days	7 < 21 days	21 < 71	> = 71 days →	
			Duration				

		D	S	M	L	V	*M*
Magnitude	> 400 m^3/s	↑		14.2	41.7	110.8	3
	100 m^3/s < 400 m^3/s		4.4	11.6	36.5	94.3	2
	25 m^3/s <= 100 m^3/s		2.1	10.9	35.8		1
	Mean Flood Duration (days)		0 < 7 days	7 < 21 days	21 < 71	> = 71 days →	
			Duration				

		D	S	M	L	V	*M*
Magnitude	> 400 m^3/s	↑		5	12	6	3
	100 m^3/s < 400 m^3/s		31	44	31	10	2
	25 m^3/s <= 100 m^3/s		278	42	20		1
	# of Occurrences		0 < 7 days	7 < 21 days	21 < 71	> = 71 days →	
			Duration				

		D	S	M	L	V	*M*
Magnitude	> 400 m^3/s	↑		549.9	698.5	544.6	3
	100 m^3/s < 400 m^3/s		163.9	174.6	240.7	232.4	2
	25 m^3/s <= 100 m^3/s		42.9	57.3	68.4		1
	Mean Peak Flow (m^3/s)		0 < 7 days	7 < 21 days	21 < 71	> = 71 days →	
			Duration				

		D	S	M	L	V	*M*
Magnitude	> 400 m^3/s	↑		2.20	5.67	15.33	3
	100 m^3/s < 400 m^3/s		1.10	2.20	5.58	14.80	2
	25 m^3/s <= 100 m^3/s		1.07	2.05	5.35		1
	Mean # of Peaks		0 < 7 days	7 < 21 days	21 < 71	> = 71 days →	
			Duration				

		D	S	M	L	V	*M*
Magnitude	> 400 m^3/s	↑		140.1	105.6	80.3	3
	100 m^3/s < 400 m^3/s		85.8	68.6	64.0	54.7	2
	25 m^3/s <= 100 m^3/s		36.3	37.1	38.8		1
	Mean Average Flow (m^3/s)		0 < 7 days	7 < 21 days	21 < 71	> = 71 days →	
			Duration				

		D	S	M	L	V	*M*
Magnitude	> 400 m^3/s	↑		0.27 ~ (JAN 7)	0.33 ~ (JAN 29)	0.37 ~ (FEB 12)	3
	100 m^3/s < 400 m^3/s		0.30 ~ (JAN 18)	0.33 ~ (JAN 29)	0.38 ~ (FEB 16)	0.40 ~ (FEB 23)	2
	25 m^3/s <= 100 m^3/s		0.37 ~ (FEB 12)	0.45 ~ (MAR 14)	0.51 ~ (APR 4)		1
	Mean Start Date		0 < 7 days	7 < 21 days	21 < 71	> = 71 days →	
			Duration				

		D	S	M	L	V	*M*
Magnitude	> 400 m^3/s	↑		1.64E+08	3.90E+08	7.66E+08	3
	100 m^3/s < 400 m^3/s		3.27E+07	6.86E+07	1.93E+08	4.55E+08	2
	25 m^3/s <= 100 m^3/s		7.09E+06	3.42E+07	1.21E+08		1
	Mean Storm Volume (m^3)		0 < 7 days	7 < 21 days	21 < 71	> = 71 days →	
			Duration				

Figure 12. Flood type statistics (flood type code, # of occurrences, mean # of peaks, mean start date (WY fraction and date), mean flood duration, mean peak flow, mean average flow, mean storm volume.

peaks) within the discriminant analysis. In other words, rigid vertical and horizontal thresholds (Figure 5) were needed to describe the magnitude and duration boundaries for each flood type. However, statistically-based techniques (e.g., discriminant analysis) do not use such rigid boundaries to group similar data points but instead use n-dimensional multivariate space for determining class separation. The results of our discriminant analysis suggested that of all *a priori* thresholds for flood typing, the demarcation between S1 and M1 events (seven-day duration) does not possess high discriminatory power. Furthermore, work by Gallo et al. (in review) suggests that complete floodplain mixing of waterborne constituents happens in floods greater than five days in duration. Therefore, our results, while useful and indicative of hydrological processes, should be viewed in the context of our intent: to provide a meaningful composite of flood types throughout the streamflow record and their prevalence within water years.

Water Year Typing & Cluster Analysis

Using the classified flood types, we performed a hierarchical cluster analysis to yield eight distinct water year types (Figure 13). Water year types were named numerically based on increasing median annual streamflow volumes (Figure 14). Of the 98 water years typed, WYT-1 possessed the greatest number (n = 32), representing 33% of the record. WYT-7 was the least populated water year type (n = 4) using this method, with 4% of the years on record. The number of occurrences and empirical frequencies of the different water year types is given in Table 3.

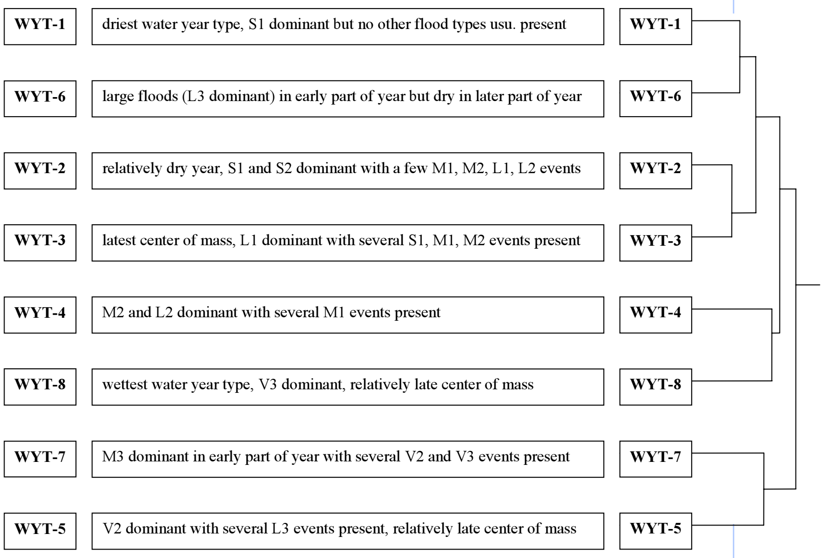


Figure 13. Hierarchical clustering of similar water years and general descriptions of each water year type.

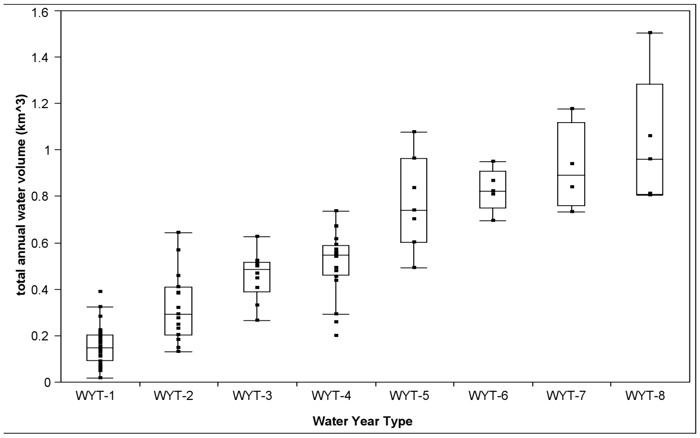


Figure 14. Total annual water volume (km^3) for each water year type.

Water Year Type	# of occurrences	empirical frequency
WYT-1	32	0.33
WYT-2	15	0.15
WYT-3	10	0.10
WYT-4	20	0.20
WYT-5	7	0.07
WYT-6	5	0.05
WYT-7	4	0.04
WYT-8	5	0.05

Table 3. Water Year Types with number of occurrences and empirical frequency based on 98-year streamflow record.

The primary flood type in WYT-1, the driest water year type, is S1 with very few other types. S1 and S2 floods are the only dominant types in WYT-2. L1 flood types are the major constituent in WYT-3; whereas M2 and L2 events dominate WYT-4, but with several M1 floods also present. WYT-5 consists of mostly V2 floods in combination with L3 floods, in contrast to WYT-6, which primarily consists of L3 floods. WYT-7 is primarily M3 floods; but several V2 and V3 events are present as well. The wettest water year type, WYT-8, is largely dominated by the very large magnitude, very long duration V3 floods.

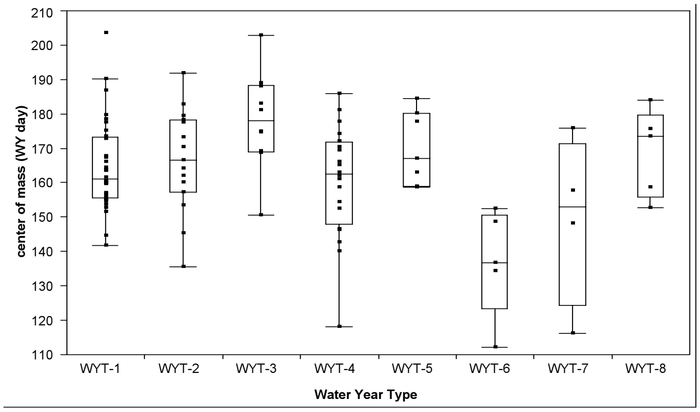


Figure 15. Day of water year that corresponds with the center of flow mass for each water year type.

We also calculated the center of flow mass for each water year type in addition to generating average hydrographs. The center of flow mass for each water year is shown in Figure 15 and shows a wide range of values associated with each water year type. The type with the earliest center of mass is WYT-6, which is largely dominated by early-season L3 floods. WYT-3 has the latest center of mass because of the large influence of the late-season L1 floods and relatively few floods in the early season. Average hydrographs for each water year type are shown in Figure 16. Changes in the center of flow mass, total streamflow volume, and overall magnitude for each water year type are visually apparent.

DISCUSSION AND SUMMARY

Based on the general hydrologic characteristics given by separating flood types, the lowland Cosumnes River

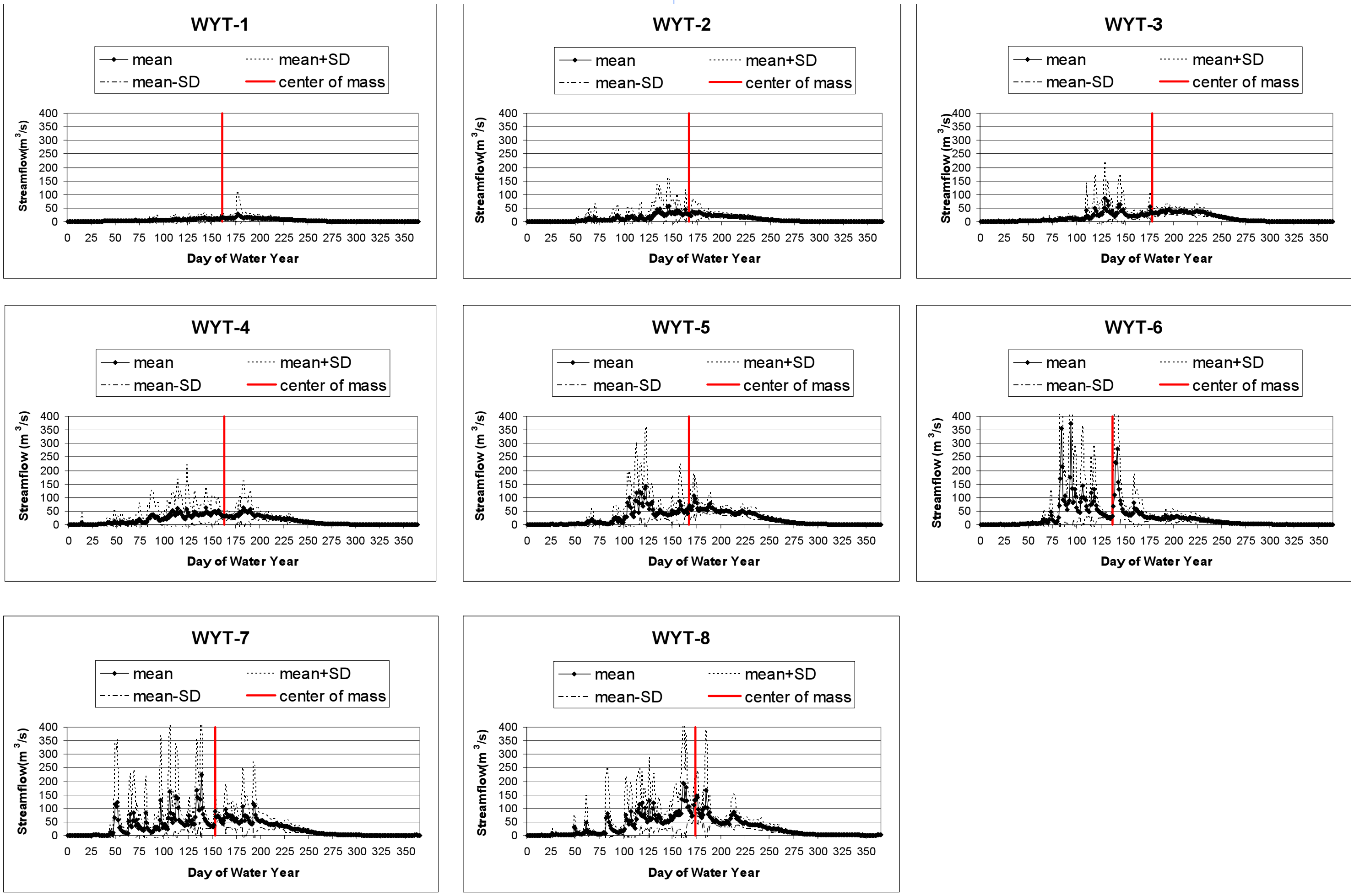


Figure 16. Average annual hydrographs for each water year type.

floodplain experiences two distinct periods of flooding. The first period, occurring roughly from November to February, is comprised of floods that tend to be flashier and have larger peak flows (Figure 8), but sustained flooding is not as common during this period as in the second period. This early period also yields smaller monthly streamflow volumes (Figure 7) based on less days of flooding (Figure 10). The second period, occurring roughly from March to May, contains smaller peak flows (Figure 8) compared to the first period, but days of flooding are more abundant (Figure 10). Therefore, the second period yields a much larger amount of streamflow volume (Figure 7). These two distinct periods of the flood season are most likely due to later-season snowmelt contributions and larger shallow groundwater inputs in the second period from sources earlier in the season.

This bi-seasonal effect is also reflected in the difference in mean start date for types M1 and L1 versus types M2, M3, L2, and L3 (Figure 12). For the former group, the combined mean start date is March 24, and for the latter group, the combined mean start date is January 28. This nearly two month difference between these groups of flood types shows the bi-seasonal effect and supports the effectiveness of this methodology at recognizing certain hydrologic phenomena specific to this watershed.

Empirical frequencies over the period of record were also calculated for each flood type and several flood type combinations (Table 2) to see how often certain floods occurred in the historical record. Types 2 and 3, which consist of the floods that can transport sand onto the floodplain, occur at least once in approximately two out of every three years and twice in half of the years. The very large magnitude type 3 floods occur at least once in one out of every five years on average. The long duration flood types (L and V) occur at least once in roughly six out of every ten years.

The flood type classification along with the flood statistics determined for each of the 479 flood events on record can also be used to test the potential long-term frequency of certain biological phenomena observed on the lowland Cosumnes River floodplain. Ahearn et al. (in review) examined the importance of flood pulse interaction on the floodplain and its influence on energy and nutrient subsidies between the floodplain and the river. They showed that floodplain waters that have intermediate residence times yield high levels of primary productivity, principally as algal biomass. Flood pulses displace this residual floodplain water from the floodplain back into the river, feeding river food webs. Ahearn et al. (in review) defined “productivity pumps” as floods that optimize algal subsidies from the floodplain to the river channel. Productivity pumps occur when floods are separated by periods of floodplain draining (no inflow) that last 5-25 days.

The five-day lower draining period boundary is based on sampling that shows significantly increased Chlorophyll-*a* concentrations (a proxy for algal productivity) after at least five days of draining; the 25-day upper disconnection period boundary is based on the floodplain being too empty for significant production subsidies to occur. These conditions are typically associated with S and M-type floods. Based on historical data, at least one productivity pump flood occurred, on average, in two out of every three years, and at least two effective floods occurred in roughly half of the years. The relatively high frequency of productivity pumping floods may reflect how much of a role floodplains play in providing a source of productive water to downstream areas such as the San Francisco Bay-Delta. Tributaries to the Delta, such as the Cosumnes River, are the largest source of organic carbon (Jassby and Cloern 2000) and represent an important research topic for management of this complex ecosystem.

The water year type classification also has the ability to analyze the frequency of certain ecological phenomena but on an annual time-scale. While the classification adequately distinguishes different water years and results in relative frequencies of these different water year types, more research is needed to more accurately describe the ecological differences between water year types. Continued collection of field-based observations that have been going on since 2001 will strengthen our approach by allowing for explicit linkage to temporal variability in ecological processes. As an example of this connection, WYT-7 contains at least one M3 flood, which will most likely create new bare ground in the form of sand deposits, and substantial late-season flooding. Using the Recruitment

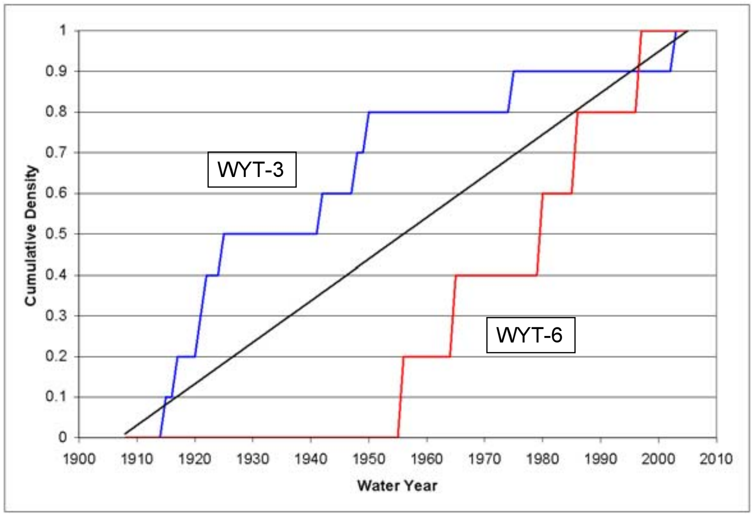


Figure 17. Cumulative frequency of water year types for WYT-3 (blue line) & WYT-6 (red line) for entire period of record. Black line shows a constant cumulative frequency.

Box Model (Amlin and Rood 2002), the combination of new bare ground and late-season flooding provides a very favorable condition for the recruitment of cottonwood trees. Conversely, WYT-6, while containing several large early-season floods (the four highest annual maximum daily flows on record all occur in WYT-6), has a relatively dry spring period and therefore is likely responsible for poor fish recruitment (Crain et al. 2004) as they cannot access the floodplain for spawning and rearing.

The distribution of certain water year types throughout the period of record also illuminated the previously mentioned observation of the inconsistency of certain aspects of the streamflow record with a stationary time series. Two water year types with very different characteristics showed opposite patterns in distribution over the period of record. WYT-3 describes a year with a relatively dry winter but a relatively wet spring. Intuitively, this water year type would occur when winter rainfall does not generate large flood events but enough snowmelt and/or abundant spring precipitation leads to inundation of the floodplain into the late spring. This water year type was much more prevalent in the first half of the period of record as compared to the second half (Figure 17). By 1950, 80% of WYT-3 years had occurred. Conversely, the opposite trend is shown for WYT-6. This water year type consists of a year with a very wet winter (four of the highest daily flows in the record occur in this water year type) but a relatively dry spring that does not lead to inundation of the floodplain into the late spring. WYT-6 is much more prevalent in the latter half of the record—it did not occur until water year 1956. These two opposite trends are consistent with the hypothesis of a rising snow-rainfall transition line, leading to larger winter floods and diminishing the later snowmelt-dominated part of the hydrograph due to increased winter and spring air temperatures since the mid-twentieth century (Stewart et al. 2005).

While restoration of aquatic ecosystems continues to rise in popularity and importance due to the recognition of the valuable services they provide, the question of how much water individual ecosystems need remains largely unanswered (Richter et al. 2003). Concurrently, the demand for water continues to increase as human populations grow, which compels water managers to increase regulation of rivers and streams. Therefore, as more complex water resources issues surface, managers need to be informed about the degree of variability that these systems critically need to continue to provide ecosystem services to humans. The promotion of natural variability is now recognized as a central theme in the implementation of successful river restoration projects (Wohl et al. 2005).

Organizing flood events and water years into similar types will allow managers to visualize this variability more effectively. While climate will ultimately drive the frequency at which these important floods occur, as a watershed becomes more regulated, the water managers will increasingly become more responsible for maintaining the natural frequencies of specific flood types and water year types. For example, the natural frequency of very large magnitude and long duration events (e.g., greater than 25-year recurrence interval) will still occur in modestly regulated systems, but the frequency of smaller events will often be controlled by water regulators. A wide range of hydrologic events is responsible for maintaining the ecological integrity of aquatic ecosystems by resetting ecological succession during large floods, providing ecological cues, and discouraging the persistence of non-native species that are not adapted to natural conditions (Stewardson and Gippel 2003). By knowing roughly the natural frequencies of specific flood types and water year types in the recent past, water managers will be able to more accurately provide these aquatic ecosystems with the variability they require to exist.

Flow or flood regimes of any river, stream, or floodplain could be characterized using this methodology as long as interaction between hydrologic, geomorphic, and ecological processes is well understood for the system under analysis. Inputs to the method are the daily streamflow record and a number of hydrogeomorphic thresholds in terms of magnitude and duration of flooding. Huh et al. (2005) suggest that at least 40 years of streamflow record are necessary to effectively characterize hydrologic variability. Given sufficient input data, outputs to the method (i.e., a given number of flood types and water year types along with corresponding frequencies) will aid in characterizing the historical hydrologic variability and planning for future sustainable ecosystem management. Similar to the IHA method (Richter et al. 1996; Richter et al. 1997; Postel and Richter 2003), separate analyses could be performed before and after a large-scale hydrologic modification is introduced to the system (e.g., a large dam) to determine how the frequencies of certain flood types and water year types have responded to this disturbance.

Although this method has potential for helping water managers provide a more naturally variable hydrologic regime, several limitations exist. The implicit assumption of constant flood magnitude thresholds (i.e., the 25 m3/s, 100 m3/s, and 400 m3/s values) over the period of record may not be able to adequately handle the effects of a changing riverine system. River and floodplain systems are inherently dynamic and hydrogeomorphic thresholds (e.g., floodplain connectivity) are constantly changing. Future research will determine whether or not the floodplain connectivity threshold has changed substantially since 1908 due to the construction of levees along the river.

The assumption made when recommending that the natural frequencies of hydrologic phenomena in the future should be similar to those in the recent past (i.e., the last 100 years) is that the ecosystem adapted under historic conditions will also exist in the near future. Changes in climatic conditions will undoubtedly alter these frequencies, and the question of whether or not these ecosystems can adapt to these changes in hydrologic variability will need to be examined. However, the true value of the methodology presented is the idea that substantial hydrologic variability must be present to preserve the integrity of such aquatic ecosystems. The question of how similar this variability is to historical variability will need to continue to be examined.

ACKNOWLEDGEMENTS

Research on the Cosumnes River floodplain was made possible by a grant from the CALFED Bay Delta Environmental Restoration Program (Award # ERP-01-NO1) and a fellowship awarded to Jeffrey Opperman from the CALFED Bay Delta Science Program. The authors are grateful for cooperation with the Cosumnes River Preserve, The Nature Conservancy – California, and the Cosumnes Research Group. We would also like to acknowledge Erika Gallo, Bill Rainey, Dylan Ahearn, and Ken Potter for providing insightful comments and information throughout our analysis.

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