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Authors

Whipple, Alison A
Viers, Joshua H
Dahlke, Helen E

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Flood regime typology for floodplain ecosystem management as applied to the unregulated Cosumnes River of California, United States

Alison A. Whipple[1] | Joshua H. Viers[2] | Helen E. Dahlke[3]

[1] Center for Watershed Sciences, University of California Davis, CA, USA
[2] School of Engineering, University of California Merced, CA, USA
[3] Land, Air and Water Resources, University of California Davis, CA, USA

Correspondence
Alison A. Whipple, Center for Watershed Sciences, University of California Davis, CA, USA.
Email: aawhipple@ucdavis.edu

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Abstract
Floods, with their inherent spatiotemporal variability, drive floodplain physical and ecological processes. This research identifies a flood regime typology and approach for flood regime characterization, using unsupervised cluster analysis of flood events defined by ecologically meaningful metrics, including magnitude, timing, duration, and rate of change as applied to the unregulated lowland alluvial Cosumnes River of California, United States. Flood events, isolated from the 107-year daily flow record, account for approximately two-thirds of the annual flow volume. Our analysis suggests six flood types best capture the range of flood event variability. Two types are distinguished primarily by high peak flows, another by later season timing and long duration, two by small magnitudes separated by timing, and the last by later peak flow within the flood event. The flood regime was also evaluated through inter- and intra-annual frequency of the identified flood types, their relationship to water year conditions, and their long-term trends. This revealed, for example, year-to-year variability in flood types, associations between wet years and high peak magnitude types and between dry years and the low magnitude, late season flood type, and increasing and decreasing contribution to total annual flow in the highest two peak magnitude classes, respectively. This research focuses needed attention on floodplains, flood hydrology, ecological implications, and the utility of extending flow regime classification typically used for environmental flow targets. The approach is broadly applicable and extensible to other systems, where findings can be used to understand physical processes, assess change, and improve management strategies.

KEYWORDS
classification, cluster analysis, flood regime, floodplain, flow regime, river management, variability

1 | INTRODUCTION

A river's flood regime, defined as the prevailing characteristics and distribution of flood pulses and variability within and across years, is controlled by geography, geology, climate, and human modifications and drives physical and ecological processes within floodplain ecosystems, affecting the diversity, abundance, and communities of species (Poff, 2002). Floods drive geomorphic processes, such as sediment deposition and erosion, as well as a host of biogeochemical processes, including nutrient cycling, primary and secondary productivity, and a wide range of biotic interactions. Flood pulses and their variable characteristics support a spatially and temporally heterogeneous and dynamic mosaic of habitats to which species are adapted (Junk, Bayley, & Sparks, 1989; Poff et al., 1997; Tockner, Malard, & Ward, 2000; Ward & Stanford, 1995). Flooding serves as a disturbance mechanism and generates complex hydrologic and geomorphic interactions that support ecological diversity and drive ecosystem structure and function (Resh et al., 1988; Richards, Brasington, & Hughes, 2002). Different types of floods constituting a flood regime are associated with particular ecological functions (Opperman, Luster, McKenney, Roberts, & Meadows, 2010), extensively demonstrated in the literature, including research specific to the system of focus here, the Cosumnes River of California, United States. These include infrequent large-magnitude floods causing avulsion and initiating riparian forest successional processes (Florsheim & Mount, 2002; Trush, McBain, & Leopold, 2000), snowmelt floods associated with predictable prolonged flooding and low recession rates supporting seed germination (Mahoney & Rood, 1998) and cuing reproduction of fish and amphibians (Yarnell, Viers, & Mount, 2010), or high frequency but low-magnitude spring flood pulses generating high levels of primary and secondary productivity and creating high-quality fish spawning and rearing habitat (Ahearn, Viers, Mount, & Dahlgren, 2006; Jeffres, Opperman, & Moyle, 2008; Sommer et al., 2001). The flow and flood regime components, including magnitude, timing, duration, rate of change, and frequency, that drive these and other ecological functions have been well-documented for their ecological relevance (Naiman, Latterell, Pettit, & Olden, 2008; Poff, 2002; Poff et al., 1997). Effectively characterizing the floods of a flood regime is therefore fundamental to understanding and managing processes driving floodplain functions.

Floodplains, with their flood-driven heterogeneous landscapes, support some of the most diverse and productive ecosystems globally (Naiman & Décamps, 1997; Tockner & Stanford, 2002). However, these systems are also some of the most degraded because of anthropogenic hydrologic alteration and land use change (Naiman et al., 2002; Nilsson & Dynesius, 1994). Within most large lowland alluvial rivers, fully natural flow regimes and restored landscapes are rarely achievable. Consequently, a central challenge is managing for greater function within such heavily modified riverine landscapes (Acreman et al., 2014; Palmer & Bernhardt, 2006; Sparks, Nelson, & Yin, 1998). Improving the reconciliation of human and ecosystem needs requires more precise water management (Harris, Gurnell, Hannah, & Petts, 2000), where water is used to provide ecological function in the most strategic manner (Poff & Schmidt, 2016; Yarnell et al., 2015). Doing so demands refined understanding of variability and the processes and functions driven by it, as well as temporally consistent features, such as snowmelt recession rates and other functional flow components (Yarnell et al., 2010).

A clear consensus on the need to improve water management for riverine ecosystems has led to numerous management strategies that typically involve flow regime characterization to set targets based on selected metrics (Petts, 2009). Over the last several decades, the natural flow regime concept of Poff et al. (1997) has encouraged the inclusion of variability in flow conditions in setting environmental flow standards (Poff et al., 2010). However, although flooding is recognized as an essential component of the natural flow regime, assessing variability in flood characteristics is often not a focus of management despite ecological outcomes. Furthermore, environmental flow science rarely considers how the surrounding landscape—often highly modified environments—can influence the ecological performance of a managed flow regime (Arthington, Bunn, Poff, & Naiman, 2006; Yarnell et al., 2015). This is exemplified in Jacobson and Faust (2014), who showed that although flood frequency and duration followed expected patterns on the Missouri River, floods that should have inundated floodplains did not due to channelization and incision. As land and water management decisions are often interdependent, analysis of altered flood regimes should be examined jointly with modification of the physical landscape (Kondolf et al., 2006).

Restoring riverine ecosystem functions depends on understanding the flows that produce natural floodplain inundation patterns (Benke, 2001). Although common flood frequency analyses that determine return period flows from the annual peak flow time series may be adequate in many engineering contexts, they are insufficient for interpreting ecosystem process and function. Assessment of inter- and intra-annual variability adds critical insight because although several floods may occur within a year, floods with particular ecologically relevant characteristics may occur far less frequently. Thus, more detailed and systematic characterization of flood regimes is needed to better target ecological needs within floodplains. Despite studies that quantify floodplain inundation dynamics (Benke, 2001), relate specific ecological functions to flood characteristics (Agostinho, Gomes, Veríssimo, & Okada, 2004), identify thresholds to guide management (Richter & Richter, 2000), and assess climate change impacts (Hall et al., 2014), there have yet to be systematic classifications of flood characteristics into a coherent flood regime typology to inform ecological management objectives.

Classification allows simplification of flood complexity and variability for describing and interpreting the prevailing flood regime of a river and its floodplain. Classification is applied in many fields including hydrology, where it is used to generate fundamental knowledge of river form and process, to assess variability at different spatial and temporal scales, to provide clear and easily interpretable class definitions, and to develop management guidelines (Olden, Kennard, & Pusey, 2012; Tadaki, Brierley, & Cullum, 2014). It can be applied at multiple scales, from the flow regime scale to the flow pulse or event scale (Olden et al., 2012). Most hydrologic classification studies group streams based on their flow regimes for regionalization and for predicting characteristics of ungaged basins (e.g., Haines, Finlayson, & McMahon, 1988; Toth, 2013). Flow regime classification is also used to establish connections between flow and ecology (e.g., McManamay, Bevelhimer, & Frimpong, 2015), evaluate climate change impacts on flow regime characteristics of ecological relevance (e.g., Dhungel, Tarboton, Jin, & Hawkins, 2016), and inform environmental flow standards (e.g., Kennard et al., 2010). Methods typically involve some form of unsupervised classification, or cluster analysis, which provides more objective and reproducible definitions of classes than classification using predetermined classes (e.g., Hannah, Smith, Gurnell, & McGregor, 2000; McManamay, Bevelhimer, & Kao, 2014; Poff, 1996; Sanborn & Bledsoe, 2006). In one of the earliest of such studies, Burn (1989) applied cluster analysis to group stations based on watershed characteristics for purposes of regional flood frequency analysis. Both partitional (e.g., k-means) and hierarchical clustering methods are used, although hierarchical clustering with either divisive or agglomerative approaches is most common for streamflow classification (Olden et al., 2012).

Classification applied at the flood-event level is far less common. In one example, Aubert et al. (2013) classified flood events to compare clustering methods, as applied to examining relationships to water quality. Through a supervised classification approach, a recent study used fuzzy decision trees to classify floods into types to identify dominant flood processes across watersheds (Sikorska, Viviroli, & Seibert, 2015). Merz and Blöschl (2003) also explored flood mechanisms using predefined classes, or process types, with annual peak floods of Austrian catchments that were assigned using process indicators, such as timing, storm duration, and rainfall depth. For the same system studied here, Booth, Mount, and Viers (2006) defined flood types based on a priori classification, using predefined thresholds of magnitude and duration to form combinations of flood types with differential frequency. To our knowledge, the methods and objectives common to flow regime classification within the field of environmental flows have not been extended to flood type classification for floodplain management applications.

With an emphasis on ecological relevance and the use of existing data classification techniques, the objectives of this paper are (a) to establish a flood regime typology and delineation approach that captures a river's flood regime relevant for floodplain ecosystems, (b) to demonstrate its effectiveness in identifying dominant flood types through application to the Cosumnes River of California, United States, and (c) to relate flood types to driving mechanisms and ecological and management implications. Our flood regime typology offers a novel and systematic approach for simplifying complex information to describe a floodplain's flood regime, provides insights into climate and watershed processes, and generates needed information for water management and restoration of floodplain ecosystems.

2 | METHODS

2.1 | Overview

As a means for flood regime characterization, we establish flood types via k-means cluster analysis using individual flood events identified from the historical streamflow record and described by ecologically relevant metrics representing flood event magnitude, timing, duration, rate of change, and hydrograph shape. After clusters are assessed for stability and validated, the most distinguishing characteristics of flood types are described, as is their frequency, relationship to water year conditions, and trend. Finally, we link flood types to watershed processes and floodplain ecological functions and discuss management applications.

2.2 | Study site

The Cosumnes River watershed, the case study for this analysis, is located along the west slope of the central Sierra Nevada mountain range in California, United States (Figure 1). It drains approximately 2460 km^2 with elevation ranging from 2300 m at its headwaters to near sea level at its confluence with the Mokelumne River. The Cosumnes River is the only large river of the Sierra Nevada without a major dam, and its resulting unregulated hydrograph, as well as a 107-year continuous daily streamflow record, is greatly beneficial to this study in the capacity to examine largely natural inter- and intra-annual variability in flood characteristics. Although the majority of the watershed consists of forested headwater regions, the lower watershed has been altered substantially over the last century and a half through leveeing, channelization, groundwater abstraction, and other land uses, which has profoundly altered how the still largely unregulated flood regime is expressed spatially within the floodplain. Over the last three decades, process-based restoration involving levee breaching has reconnected some of the floodplain to the river in the lower reaches, including the site used in this study. Associated scientific research and monitoring has linked this increased hydrologic connectivity to sediment deposition, increases in topographic complexity, hydrochorus dispersal of native seeds within the floodplain, riparian forest establishment and succession, primary and secondary productivity, and greater provision of spawning and rearing habitat for native fish, including juvenile Chinook salmon and the endemic minnow, Sacramento splittail (Ahearn et al., 2006; Andrews, 1999; Florsheim & Mount, 2002; Jeffres et al., 2008; Moyle, Crain, & Whitener, 2007; Swenson, Whitener, & Eaton, 2003; Trowbridge, 2002).

The climate consists of cold wet winters and warm dry summers with high interannual precipitation variability due to its predominately Mediterranean-montane climate. Recent research has highlighted that river systems in California such as the Cosumnes River depend upon just a few storms to produce the majority of annual runoff, accounting for extreme interannual variability (Dettinger, Ralph, Das, Neiman, & Cayan, 2011). Mean annual precipitation (1971–2000) ranges from 1460 mm in the upper elevations to 430 mm in the lower elevations, with a spatially weighted average of 855 mm (PRISM Climate Group, 2006). Precipitation occurs primarily between the months of November and March with the majority of runoff occurring between

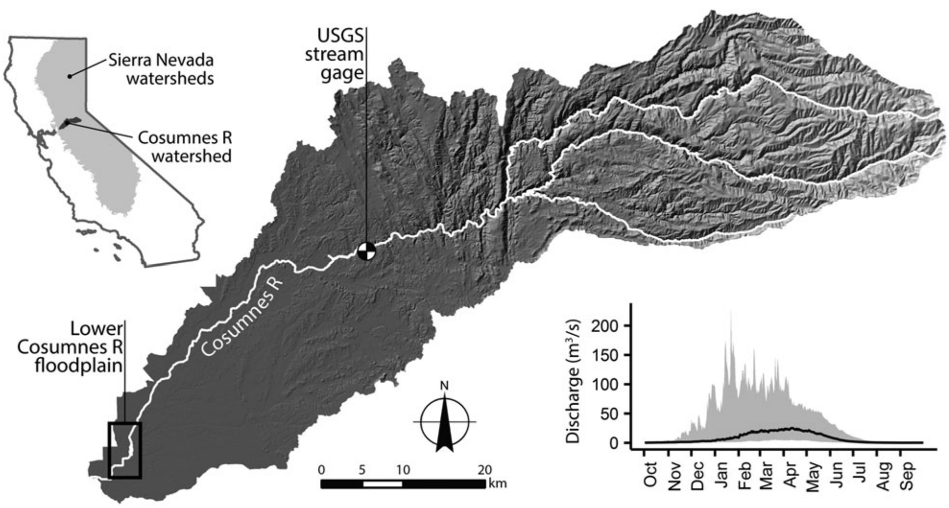

FIGURE 1 Map depicting the Cosumnes River watershed, located along the west slope of California's Sierra Nevada. The location of the USGS stream gage used in the study and the reference floodplain approximately 45 km downstream are illustrated. The inset graph shows median daily flow with shading representing the 5th to 95th percentile at the gage

December and May. The resulting hydrograph is rain dominated, as much of the watershed area lies below the snow line (~90% below 1500 m; see inset of Figure 1), although a spring snowmelt signature is present. Following precipitation variability, streamflow is highly variable. The flood of record in 1997 resulted in a peak daily flow of 2630 m^3/s in contrast to the mean annual daily flow approximating 14 m^3/s. In dry years, flow ceases by the end of the summer in the lower river reaches, exacerbated by severe declines in regional groundwater levels (Fleckenstein, Anderson, Fogg, & Mount, 2004).

2.3 | Hydrologic data

The primary dataset used in this analysis is the daily streamflow record for the time period 1908 to 2014 (MHB, #11335000; U.S. Geological Survey, 2015). The river at Michigan Bar, California drains 57% of the watershed, from which the majority of streamflow originates. Although tributary inflows and other gains and losses affect flows at the floodplain site considered here (located 45 km downstream), these are understood to be minor for purposes of examining flood characteristics (Andrews, 1999). Analyses were performed using the water year, beginning October 1. Daily precipitation data were obtained from the National Climatic Data Center COOP weather station (Fiddletown Ranch #043038) located within the upper watershed and date back to 1948 (Western Regional Climate Center, 2015). Atmospheric river and "pineapple-express" events in California have been studied and summarized by Dettinger et al. (2011) for 1948 to 2008.

2.4 | Flood event identification and metrics

We identified individual flood events from the daily flow record using a previously determined floodplain inundation threshold of 23 m^3/s at MHB, flows at which lowest lying floodplain areas connect to the river (Figure 2; Florsheim, Mount, & Constantine, 2006; personal observation). This flow approximates a 95% exceedance probability for the annual peak flow series (U.S. Interagency Advisory Committee on Water Data, 1982). Although floodplains are typically defined using the 1.5-year return period flow to represent bankfull (Leopold & Wolman, 1964), this is not consistent for all river reaches. Using the 1.5-year return period flow (107 m^3/s) would exclude many ecologically relevant lower flow flood events from the analysis. The methodology applied here captures frequent, annual floods on the floodplain as well as peak annual storms. Using a flow threshold to identify flood events contrasts with common flood analyses based on the annual peak flow time series.

Flood events were isolated and numerically characterized in *R* (R Core Team, 2013). We established eight metrics derived from flow and flood regime components of magnitude, duration, timing, and rate of change, defined and described by Poff et al. (1997) and Poff (2002) as driving various ecological processes in riverine systems (Table 1). These factors affect both abiotic and biotic processes. The magnitude of floods affects sediment erosion and deposition, maintaining habitat mosaics and heterogeneity. For example, flood disturbance and variability along the Cosumnes River create complex floodplain topography and initiate riparian forest successional processes (Florsheim &

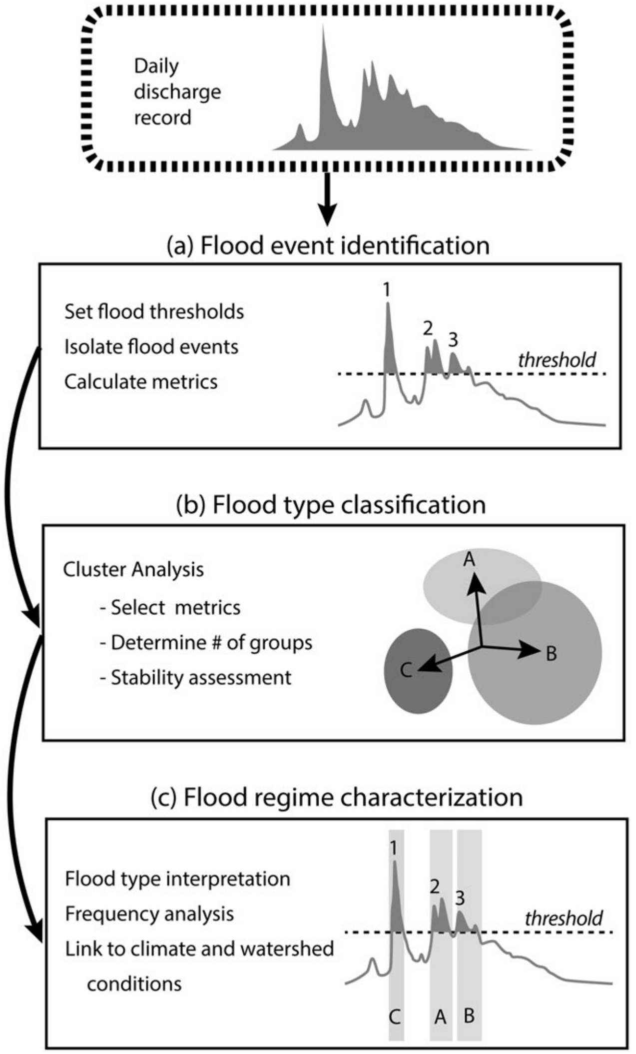

FIGURE 2 Flood typology and characterization approach. Flood events from the daily flow record input are separated using a floodplain activation threshold and characterized using selected metrics (a). Subsequently, classification is performed using cluster analysis (b). Identified flood types are then interpreted and assessed for frequency, relationship to climate factors, and (c) trends to describe the flood regime

Mount, 2002). Floods occurring at different times of the season serve different ecological functions, whether it be winter floods that cue fish migration or spring floods that provide rearing habitat for juvenile fish and promote primary and secondary productivity (Moyle et al., 2007). Research on the Cosumnes River has also linked flood duration (residence time) and connectivity dynamics to productivity (Ahearn et al., 2006; Grosholz & Gallo, 2006). Rate of change, another flow and flood regime component, affects the temporal variability in habitat conditions and availability as well as seed germination and survivorship (Yarnell et al., 2010). Frequency, also identified by Poff et al. (1997), was irrelevant as a metric for summarizing the sequence of daily flows that make up individual flood events but was assessed in other stages of the analysis after floods were isolated and described. Three metrics related to the shape of the hydrograph (e.g., position of peak within the event) were included because the timing of peak flows within an event can have hydraulic, geomorphic, and ecological implications (Tockner et al., 2000). The isolated flood events were summarized on annual

TABLE 1 Flood regime components with the metrics representing these components used for characterizing individual flood events of the Cosumnes River. Metrics annotated with ([a]) were used in the final cluster analysis for establishing flood types. Examples of related ecological functions and references, as discussed in Poff et al. (1997) and Poff (2002), are listed for each of the main flood regime components

Flood regime component	Metric	Description	Ecological functions affected	References
Magnitude	Peak discharge[a]	Peak daily discharge (m^3/s) within flood event	Channel avulsion, sediment erosion and deposition, reset successional processes, maintenance of habitat mosaic and heterogeneity, habitat availability, and reduce competition	Resh et al. (1988), Ward and Stanford (1995), Florsheim and Mount (2002), Opperman et al. (2010)
	Mean discharge	Mean daily discharge (m^3/s) across flood event		
	Volume[a]	Total volume of flood event (km^3)		
Timing	Start day	Water year day of the flood event beginning	Species migration cue, spawning and rearing habitat availability, and primary and secondary productivity	Robertson et al. (2001), Lytle and Poff (2004), Moyle et al. (2007), Bailly et al. (2008), Jeffres et al. (2008)
	Centroid day[a]	Water year day of centroid volume of flood event		
	End day	Water year day of the flood event ending		
	Cumulative flow	Total water year flow volume to date of flood beginning		
Duration	Days[a]	Total number of flood days	Primary and secondary productivity and spawning and rearing habitat availability	Sommer et al. (1997), Sommer et al. (2004), Grosholz and Gallo (2006), Bailly et al. (2008)
Rate of change	Rising rate	Maximum flow (m^3/s) difference between days on the rising limb(s) of flood event	Seed germination and habitat availability	Mahoney and Rood (1998), Stella et al. (2006), Yarnell et al. (2010)
	Recession rate[a]	Maximum flow (m^3/s) difference between days on the falling limb(s) of flood event		
Shape	Peak location[a]	Fraction of flood-event duration before the day of peak flow	Nutrient cycling and primary and secondary productivity, sediment erosion and deposition patterns and export of organic and inorganic material	Tockner et al. (2000), Florsheim and Mount (2002)
	Centroid volume location	Fraction of flood event duration before the day of flood event centroid volume		
	Number of peaks	Number of hydrograph peaks within flood event		

and monthly bases to quantitatively characterize the flood regime prior to flood type classification.

2.5 | Statistical methods for flood typing

The flood type classification methods described here addresses core classification objectives identified by Jain (2010); these include understanding data structure and developing insights into the range of conditions, as well as simplification and organization of complex multivariate data. The goal of our flood regime typology is to simplify highly variable flood events into basic types for describing essential characteristics of floods that inundate floodplains and provide information useful for managing riverine ecosystems.

We established flood type classes from the characterized flood events using k-means cluster analysis from the *R* package *fpc* (R Core Team, 2013, Hennig, 2014). K-means clustering is a common clustering method for a wide range of applications, including hydrologic classification and regionalization (e.g., Burn, 1989; Chinnayakanahalli, Hawkins, Tarboton, & Hill, 2011; Dettinger & Diaz, 2000; Parajka et al., 2010; Poff, 1996; Sanborn & Bledsoe, 2006). As a partitional nonhierarchical clustering algorithm, it iteratively adjusts cluster centers and assigns individual points to classes based on the nearest center (Euclidian distance), and centers are adjusted to minimize the sum of distances between points and the associated centroid within a cluster (Jain, 2010). Although hydrologic applications often use divisive hierarchical clustering methods, such as Ward's linkage, we chose the partitional k-means approach following Hartigan and Wong (1979) because it is known to handle large datasets well, individual points are allowed to move from one cluster to another over the series of iterations, hierarchy was not relevant to interpretation, and more stable clusters were found in comparison to complementary hierarchical methods (Olden et al., 2012). All data were normalized (subtracting the mean and dividing by the standard deviation) prior to analysis.

To perform k-means clustering, we first specified the distinguishing variables and number of classes. Because of their ecological relevance (Poff, 2002), we included at least one metric from each of the flood regime components as variables in the analysis (see Table 1). We conducted principal components analysis to examine redundancy and the relative strength of different metrics in explaining the variance in the data. On the basis of this analysis, metrics with higher explanatory power were prioritized for inclusion. For final metric selection, we used clustering strength and stability, as discussed later. In addition to metric selection, the location of cluster centers and choice of the number of classes can impact clustering results. To address potential subjectivity, we used randomized cluster seed locations and several common statistical criteria, including within cluster sum of squared errors and silhouette width (Olden et al., 2012; Rousseeuw, 1987), to determine the optimal number of classes.

Stability of resulting flood types was assessed via the *clusterboot* function in the *fpc* package for *R* (Hennig, 2014). We used this function to apply 1000 sampling runs using a nonparametric bootstrap scheme, where new flood datasets were sampled with replacement from the original set of floods (Hennig, 2007). Such stability assessments have been used in previous hydrologic classification applications (Mackay, Arthington, & James, 2014; McManamay et al., 2014). The more stable clusters are those that maintain cluster membership despite minor changes to the original dataset in each resample. To measure cluster stability, we calculated the Jaccard stability index (i.e., the proportion of the intersection and union of two sets) between each resampled cluster and the most similar cluster in the original set, which were then averaged to produce a stability measure for each cluster (Hennig, 2007). Clusters with indices above 0.75 are thought to form valid stable clusters, while those below 0.5 are indicative of dissolved clusters (Hennig, 2014). The Jaccard similarity index was also used to determine which set of metrics and number (i.e., k-value) of clusters produced the most stable clusters. Instead of comparing the highest average score across all clusters from each combination of metrics and number of clusters, we selected those with the highest minimum cluster score (i.e., comparing the lowest scoring cluster of each set). Because stability alone cannot guarantee valid clusters, we complemented this with visual validation of the cluster separation to assess how well classes were distinguished. In this analysis, highly isolated flood types are not expected because floods result from many interacting environmental variables and processes, causing many floods to lie between the predominant flood types.

2.6 | Flood regime characterization

Post-classification, the identified flood types were assessed and compared and then examined with regard to frequency, relationship to water year conditions (e.g., wet vs. dry), and trend. Where applicable, the analysis was performed for both the number of events and the number of days for a given flood type. Frequency, a natural flow-regime component, was calculated empirically for the flood types both inter- and intra-annually. Flood types were also examined for their association with other types within years. We compared flood types in relation to the water year conditions (defined by annual flow quantiles), which revealed clear distinctions between flood types, but also provided an independent measure of the strength of the classification, as floods in wet years are expected to have different characteristics from those in dry years. We explored whether a change in the frequency or dominance of different flood types had occurred over the period of record with trend analysis on the number of events, number of days, and volume of each flood type using five and 10 water year block averages of each variable. Block averages helped to provide data independence and address the fact that some years had no events of particular types. We estimated and tested trends by fitting a generalized least squares model with the method of maximum likelihood using the *nlme* package in *R* (Chatfield, 1989, Dahlke, Lyon, Stedinger, Rosqvist, & Jansson, 2012, Pinheiro et al., 2013, R Core Team, 2013). To address autocorrelation, we fit autoregressive moving average correlation structures to the residuals (Fox, 2002). Finally, we linked flood types to relevant climatic and watershed processes and to ecological functions and discussed floodplain management implications.

3 | RESULTS

3.1 | Flood event summary

Using a flow threshold of 23 m^3/s, we identified a total of 532 individual floods from the 107-year record spanning water years 1908 to 2014. Flood event summary statistics revealed that the number of flood events ranged from 0 to 13 per year, with a median of five events and 68 days of flooding (Table 2). Event volumes summed within a water year accounted for a median of over two-thirds (66.9%) of the annual flow volume. More flood events occurred in January through March, although March and April had the highest number of flood days. A median 46.3 m^3/s discharge was recorded for the peak daily flow. Total flood volumes were most variable, with a median of 0.010 km^3. The median flood duration was 3 days. For flood timing, mean date of flood center of mass (Stewart, Cayan, & Dettinger, 2004) was February 18, ranging from October 14 to June 30.

TABLE 2 Summary of 532 flood events identified from the 107 years of the historical daily flow record. Annual and monthly summary statistics, including median, mean, standard deviation (SD), and coefficient of variation (CV), are provided along with the metrics used in the cluster analysis

Type	Parameter	Median	Mean	SD	CV
Annual	#events/yr	5	5.0	2.6	52%
	#days/yr	65	63.9	51.5	81%
	Total % of annual volume	66.9	54.9	30.9	56%
Monthly	#events October	0	0.0	0.2	628%
	#events November	0	0.2	0.6	289%
	#events December	0	0.7	1.1	148%
	#events January	1	1.1	1.2	107%
	#events February	1	1.0	1.0	93%
	#events march	1	0.9	1.0	104%
	#events April	0	0.6	0.8	145%
	#events may	0	0.3	0.5	195%
	#events June	0	0.1	0.3	434%
	#days October	0	0.0	0.3	615%
	#days November	0	0.7	2.4	360%
	#days December	0	3.2	5.8	184%
	#days January	3	7.9	9.6	122%
	#days February	8	10.9	10.1	92%
	#days march	10	14.5	12.2	84%
	#days April	17	15.2	13.1	86%
	#days may	4	9.7	11.8	122%
	#days June	0	1.8	5.1	279%
Metrics	Peak flow (m^3/s)	46.3	101.5	149.8	148%
	Volume (km^3)	0.010	0.064	0.1	223%
	Duration (days)	3	12.8	23.9	186%
	Centroid day (water year day)	141	141.1	50.0	35%
	Recession rate (m^3/s)	18.0	47.4	90.0	190%
	Peak location	0.02	0.2	0.2	130%

Recession rate, quantified as the maximum decline over a day within a flood event, had a median of −18 m^3/s. Most flood peaks occurred toward the beginning of the flood event. All flood event metrics were highly variable, requiring subsequent classification to distinguish characteristic flood types.

3.2 | Classification of flood types

3.2.1 | Metric selection and cluster stability

Examination of statistical redundancy aided the selection of metrics within each flood regime component, because we decided to use at least one metric related to each component in the cluster analysis for purposes of ecological relevance. As expected, most metrics within each component were highly correlated. Magnitude, duration, and rate of change metrics were also highly correlated. Principal components analysis revealed that over 95% of the variance in the data was explained by the first five principal components. The peak flow, centroid date, peak location, and flood event volume had the highest absolute loadings associated with these components. Duration and recession rate—each included for their previously discussed ecological relevance—were associated with higher loadings in the first principal component (along with peak flow).

Final metric selection and cluster number were based on the cluster stability results (Jaccard similarity index) from multiple bootstrapped (B = 1000) cluster analysis runs using permutations of cluster numbers (within cluster sum of squared error supported using six to eight clusters) and the sets of metrics meeting criteria. In comparing the lowest scoring cluster of each combination, the highest consisted of six classes and the six metrics summarized above (peak flow, flood event volume, duration [log transformed], centroid timing, recession rate, and peak location). The average cluster stability for this combination was 0.80, and all clusters had values above or close to the suggested threshold of 0.75 for stable clusters (Hennig, 2014). The flood types are primarily separated by magnitude (peak flow and flood volume) as well as duration and recession rate along the first component axis, while timing dominates the second axis (Figure 3). A single possible outlier is the flood of record (1997), but its removal did not substantially affect cluster results, so it was retained in the analysis.

3.2.2 | Flood type description

The six classified flood types are easily discerned from the metrics (Figure 4). Referred to here as *Very Large* events, the floods with the highest peak flows (median = 598 m^3/s) were clustered together and also associated with high volumes (median = 0.69 km^3), long durations (median = 90 days), and steep recessions (median = −319 m^3/s per day). Only 17 of the total 532 events (3.2%) were classified as this type, including the largest flood on record. The second highest peak-flow magnitude class is distinguished both for its high peak flows and volumes (median = 300 m^3/s, 0.26 km^3) and long duration (median = 35 days), referred to as *Large and Long* events. This class included 46 flood events (8.6%). The long duration of these two classes is attributed to the high-peak flows but also the multiple storms that occur over the period of the flood, which maintains flow above the floodplain inundation threshold. The flood type with the latest seasonal timing centroid, the *Long and Late* type, also has the third longest

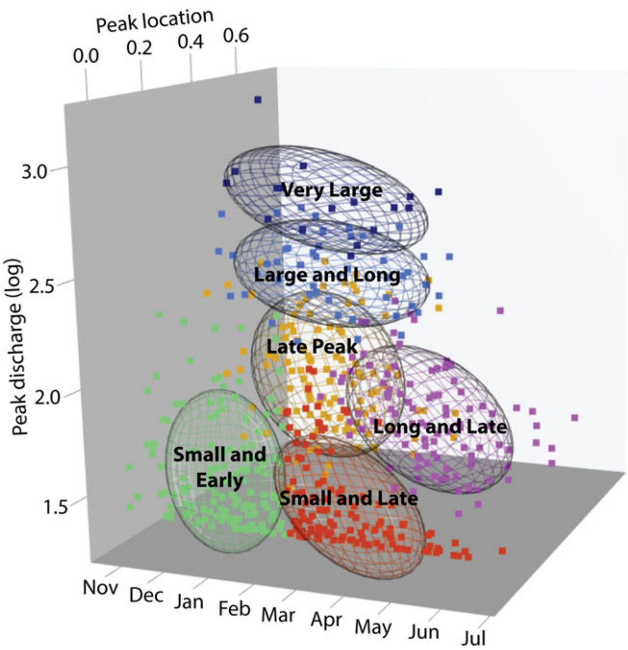

FIGURE 3 Clustered flood events along three metrics used in analysis: magnitude of peak discharge (log transformed), centroid date, and location of hydrograph peak (fraction of flood-event duration before the day of peak flow). Ellipses cover the 50% confidence region for each type. The color scheme is consistent across figures

duration. One flood type is predominantly characterized by its late peak within the flood hydrograph; referred to as the *Late Peak* flood type. Its other metrics are mid-range compared to other flood types. Two types are distinguished by their very low magnitudes and short durations (often only a day or two long). They are separated by timing, with the *Small and Late* events occurring late in the season and the *Small and Early* occurring earliest of all the types. These last four types are larger classes, with membership ranging from 101 to 139 events (19–26%). Substantial differences in the range of metric values within each of the flood types can be found. For example, the *Very Large* and *Large and Long* classes have the greatest magnitude range. Both *Small and Late* and *Small and Early* types are fairly tight across the metrics, except for centroid day, which is the primary metric distinguishing the two classes.

3.3 | Flood type frequency

Understanding the inter- and intra-annual frequency of different flood types allows for improved interpretation of ecological implications of flood events. As shown in Table 3, interannual frequency of the *Very Large* type is just 15%, and in only one year did two of these events occur. The *Late Peak* type is the most frequent, occurring in 64% of the years. However, *Long and Late*, *Small and Late*, and *Small and Early* types have a greater percentage of years with two or more events, and *Small and Late* and *Small and Early* types each have over 5% of years with four or more events. The *Small and Early* type has the greatest mean intra-annual frequency of 2.2 events per year (assessed only for those years containing the flood type). Although *Very Large* events are usually over 90 days long, *Large and Long* and *Long and Late* events are also long (means of 47 and 19 days, respectively), but occur much

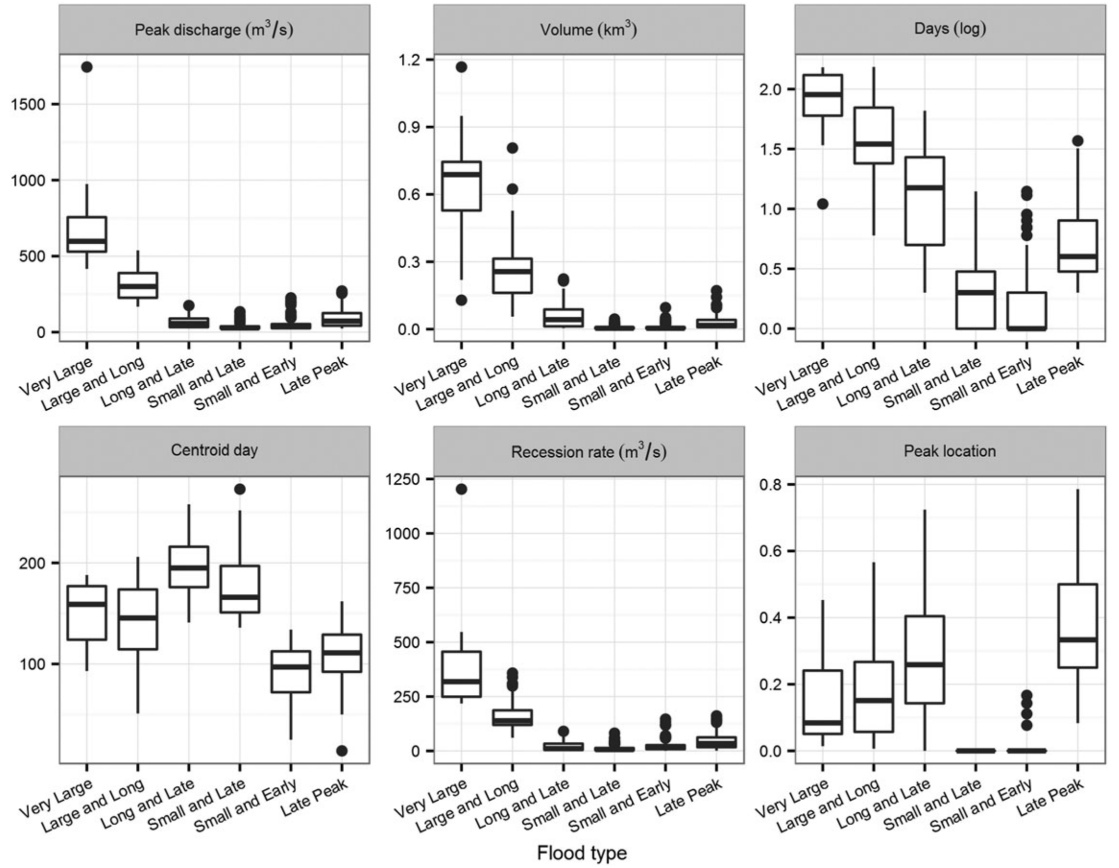

FIGURE 4 Box plots for each metric used in the analysis by flood type. Unscaled metrics are shown for purposes of interpretation. Median is shown with the first and third quartiles. Whiskers extend to the highest and lowest values within 150% of the inter-quartile range. For metric descriptions, refer to Table 1

TABLE 3 Frequencies of events for each flood type showing (a) interannual and (b) intra-annual empirical frequency. Interannual includes frequencies for at least 1, 2, 3 and 4 events within a year for each flood type. Both number of events as well as number of days is assessed for intra-annual frequencies. Intra-annual frequencies were calculated only for those years containing flood types

	(a) Interannual				(b) Intra-annual			
	≥1 event	≥2 events	≥3 events	≥4 events	# events (mean)	# events (sd)	# days (mean)	# days (sd)
Very large	15%	1%	0%	0%	1.1	0.3	91.2	41.7
Large and long	36%	7%	1%	0%	1.2	0.5	47.2	33.4
Long and late	53%	31%	8%	1%	1.8	0.8	18.6	16.0
Small and late	60%	35%	14%	6%	1.9	1.0	2.2	2.0
Small and early	60%	40%	18%	7%	2.2	1.2	2.2	2.1
Late peak	64%	24%	8%	2%	1.5	0.8	6.2	5.8

more frequently. Understanding this difference is useful for evaluating the relative importance of the flood types in the provision of flooded habitat, for example.

Given that multiple events of different flood types usually occur within a given flood season, knowing flood type associations is also valuable for understanding flood type frequency (Table 4). We found that years with *Very Large* events were often associated with *Small and Early* or *Late Peak* events, while years with *Long and Late* or *Small and Late* events rarely had a *Very Large* event. Years with *Large and Long* events were associated with a wider range of flood types and occurred with *Small and Early* events over 80% of the time. All other percentages of association within years were below 70%. This analysis also showed that *Small and Late*, *Small and Early*, and *Late Peak* events all occurred with each other over 50% of the time. Lastly, Figure 5 provides a visual depiction of the occurrence, duration, frequency, as well as high degree of inter- and intra-annual variability, of flood types across the streamflow record. Most years begin with short events of usually *Small and Early* or *Late Peak* flood types. Years with *Very Large* events clearly lack *Large and Long* or *Long and Late* events. In years where few long duration events occur, *Small and Late* events are more prevalent.

3.4 | Relationship to water year

Although climate-related metrics were not used for classification purposes, we found distinct relationships between flood types or sets of

TABLE 4 Associations of flood types within flood seasons. The diagonal shows the percent of years with that flood type. Co-occurrence values are calculated as the percent of years including the flood types in the rows with those in the columns (e.g., 25% of the years that have *Very Large* also have *Large and Long* and 11% of the years that have *Large and Long* also have *Very Large*)

	Very large	Large and long	Long and late	Small and late	Small and early	Late peak
Very large	15	25	25	19	69	63
Large and long	11	36	63	63	82	68
Long and late	7	42	53	68	56	67
Small and late	5	38	61	60	53	61
Small and early	17	48	50	53	60	69
Late peak	14	38	55	57	64	65

flood types and the water year conditions. We defined five water year types using flow quantiles: very wet (0.8–1 quantile), wet (0.6–0.8 quantile), normal (0.4–0.6 quantile), dry (0.2–0.4 quantile), and critically dry (0–0.2 quantile). The clearest association between flood types and water year type was between *Very Large* events and very wet years, where all except for one *Very Large* event occur in this water year type (Figure 6). Similarly, *Large and Long* floods are also associated with wetter year types. No *Large and Long* events occur in dry and critically dry water years. Other flood types are more evenly spread across the different water year types, although the *Long and Late* and *Small and Late* types are least associated with wetter years.

In examining the flood type composition of different water year types, we found that only 2.1 events and a total of 4.6 days of flooding occurred on average in critically dry years, predominantly composed of *Small and Late* events. Comparing events and days illustrates the relative substantial contribution of *Late Peak* events to flood days. For the dry water year type, the *Small and Late* type had the greatest percentage of events within a year, while the *Long and Late* type had the greatest percent of days. In normal water years, the number of events was fairly well distributed across the flood types (except for the lack of *Very Large* events), with *Large and Long* and *Long and Late* types contributing disproportionately to the percent of flood days. The wet water year class had the highest number of events on average (>7) and was similar to the normal water year save for the larger contribution of *Large and Long* and *Late Peak* events. For very wet years, the average number of events dropped below five, but they had the highest average number of flood days (130). The flood type distribution shows that the *Small and Early* type tended to have the greatest number of events, while by far the greatest proportion of flooding days was attributable to *Very Large* and *Large and Long* events.

3.5 | Trend analysis

Two flood types show evidence of statistical trends, which were analyzed using 5-year block averages of each flood type's contribution to the annual flow volume starting in 1910 through 2014 (Figure 7). All years during this period were used, including those periods where no floods occurred. On the basis of AIC values and plots of the autocorrelation function and partial autocorrelation function, we selected appropriate generalized least squares models and fit them to the data. A significant ($p < 0.01$) increasing trend in the percent of annual volume of *Very Large* events was found. On the basis of the regression analysis, this trend amounted to an increase of 14% in the percent volume that *Very Large* events contribute to the annual total flow volume.

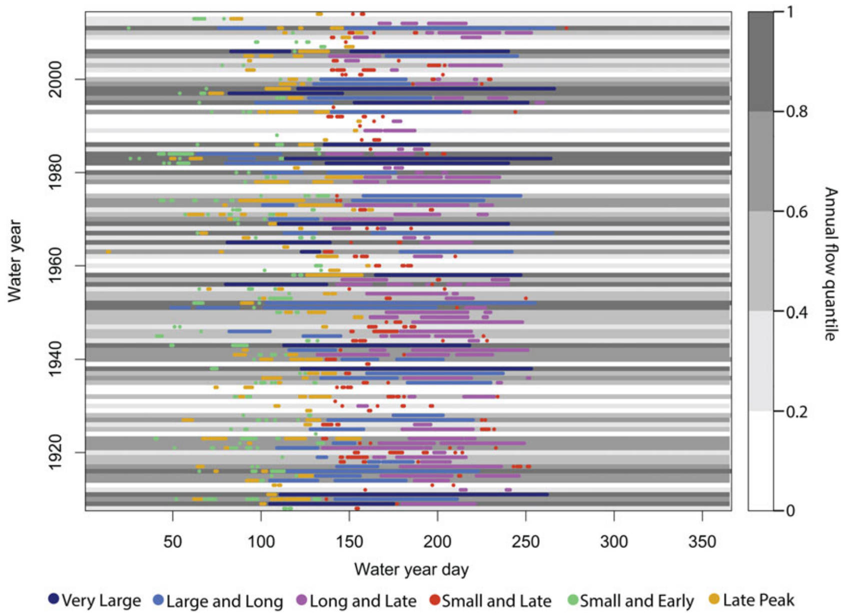

FIGURE 5 Each day of the 532 individual flood events is shown over the period of record, colored by their flood type classification. To relate the events and their frequencies to climate conditions, the water year types based on annual flow quantiles are shown in the right part of the plot (wetter years are the darker shades)

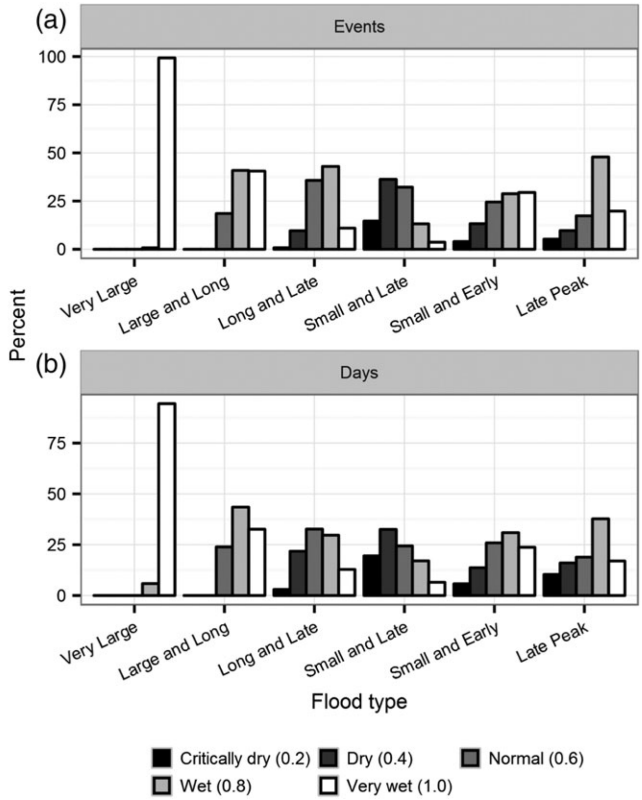

FIGURE 6 The percent of flood types associated with each water year type for the percent of (a) events and (b) days. Water year types are defined by annual flow quantile (in parentheses) from the daily flow record at the Cosumnes River gage. Darker shading is associated with wetter year types. Each flood type grouping sums to 100%

The trend for the *Large and Long* type was also significant ($p < 0.01$), suggesting decreases of 10% in the percent volume *Large and Long* events contribute to annual volume. Thus, the flood type associated with the very largest magnitude floods show an increasing dominance within the annual total flow, while the second largest magnitude type is declining in dominance. Although not significant, the other four flood types also showed declining trends.

4 | DISCUSSION

Flow regime classification has been used extensively over the last several decades to better understand and manage riverine ecosystems (Kennard et al., 2010; Olden et al., 2012; Poff & Ward, 1989). The flood event classification proposed here presents an extension of these methods by providing more systematic and higher resolution characterization of the range of flood types and their inter- and intra-annual variability within flood regimes that generate the dynamic yet predictable habitat conditions to which species are adapted. The typology elucidates driving mechanisms and related ecological functions of floods, thereby improving our ability to understand and manage riverine ecosystems.

4.1 | Flood regime typology

The primary metrics used to characterize flood events are derived from flow and flood regime components of magnitude, duration, timing, and rate of change, which are well established in the literature for their ecological significance (e.g., Lytle & Poff, 2004; Poff, 2002; Poff et al., 1997; Rood et al., 2005; Sparks et al., 1998), and are commonly applied in classification studies linking hydrology and ecology (e.g., Belmar, Velasco, & Martinez-Capel, 2011; Kennard et al., 2010; Mackay et al., 2014). The metrics identified for the cluster analysis were associated with the principal components explaining the majority of the variance across the identified flood events and resulted in the most stable clusters. Metrics related to magnitude and timing appear to be the best for classifying floods given their correlation with the first two principal components, and visual separation between the identified flood types. These findings are similar to the principal flow-regime elements of magnitude and temporal variability identified by Belmar et al. (2011).

Our flood regime typology approach established six flood types from historical daily streamflow data, reducing the highly variable Cosumnes River flood regime into manageable elements. The *Very Large* flood type with the highest peak flows occurred in only 15% of the years on record, but this type dominates the flood season when it occurs. The second highest magnitude class (*Large and Long*) is more common (36% of years). The volume centroids for both of these high-magnitude classes define the peak of the flood season in late February and early March, with the events typically beginning in late January or early February. The *Long and Late* flood type is present in over half of the years and occurs most frequently with *Small and Late* and *Late Peak* events. The *Small and Early* and *Small and Late* events usually occur twice within the same season and in roughly two-thirds of the years on record, with both types in about half of the years. The *Late Peak* type is the most common: all other flood types are associated with this type in roughly two-thirds of the years in which they occur. The variability shown in the frequency and co-occurrence of the different flood types illustrates the complexity of the river's flood regime. At the annual scale, no single set of flood types or number of floods defines the flood regime, reflecting the highly variable regional climate. However, general expectations for a given year's composition of flood types based on the water year type can be made.

Previous research on the Cosumnes River established 10 flood types based on predefined class boundaries for flood peak flow and duration (Booth et al., 2006). Using a similar floodplain connectivity threshold (25 m^3/s) to isolate flood events, three flood magnitude and four flood duration classes were used to classify flood events. Booth et al. (2006) found that their long (21–70 days) and small to medium magnitude (<100 m^3/s) flood type (L1) was associated with early spring timing, similar to this study's longer and later flood type (*Long and Late*). Although the 10 types of Booth et al. (2006) offer more classes defined by peak magnitude and duration (selected to capture large differences applicable for management), these may be less meaningful than the class distinctions in this analysis defined by a wider array of metrics. For example, their short- and low-magnitude class (S1) included events classified into three different types identified here (*Small and Early*, *Small and Late*, and *Late Peak*). This comparison suggests that the six types defined by this study distill flood event variability into fewer classes while also accounting for a larger number of distinguishing and ecologically relevant characteristics.

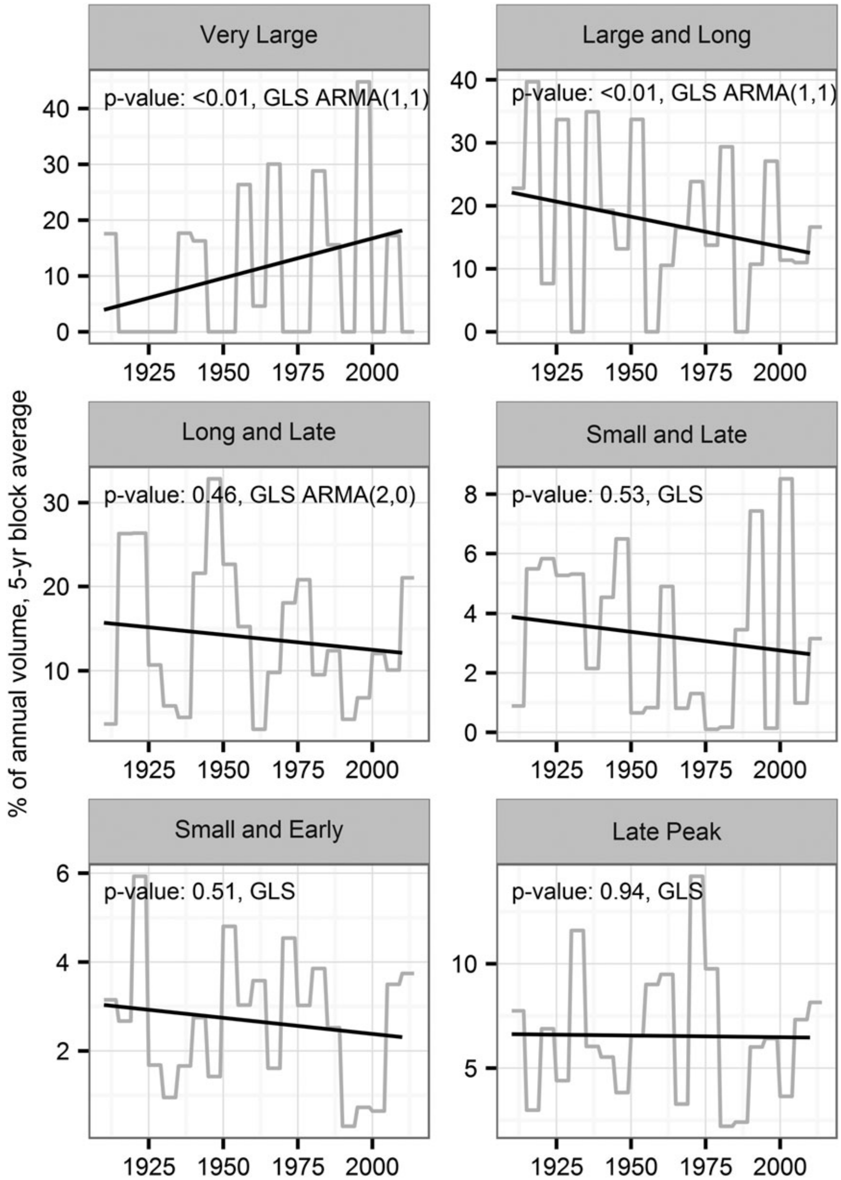

FIGURE 7 Time series of 5-year block averages of the percent of annual volume for each flood type over the Cosumnes River gage period beginning in 1910. The linear regression fits are shown as lines, with the slope, *p* value, and GLS model used included as text within each plot. ARMA = autoregressive moving average; GLS = generalized least squares

There are potential limitations to the approach presented here. The daily flow record should cover a sufficiently long period to capture climatic variability. Given the dependence upon the underlying time series, awareness of the potential of nonstationarity to affect results is also necessary. In addition, effectively separating floods from the daily flow record requires that the flow at which the floodplain of interested is inundated be known, which can be difficult to determine particularly in highly modified systems. A selected discharge value that is lower than the floodplain inundation threshold will include events of minimal ecological relevance, as these floods would not activate the floodplain (sensu Williams, Andrews, Opperman, Bozkurt, & Moyle, 2009). Similarly, a selected discharge threshold that is too high will omit some floods from classification that inundate the floodplain and affect ecosystem processes and functions. Relatively small variation in the threshold may alter the metric criteria and number and stability of clusters, but the basic flood type characteristics would likely persist. To explore this idea, we determined mean metric values for flood thresholds representing exceedance probabilities between 90% and 99% and found they deviated from mean metrics of the selected threshold by less than 25% (except for the 99% exceedance probability flood volume metric, which deviated by 40%). As the threshold selection affects the lower flood flow days, flood volume and low peak magnitudes are expected to respond the most, which may either expand membership of the low magnitude flood classes or potentially even cause the elimination of these classes if the threshold is set much higher. The addition of new years of data also may affect flood types, potentially as a result of nonstationarity in longer term trends (Null & Viers, 2013), although these are likely to be relatively small changes to the class membership. In addition, although there may be a strong ecological rationale for the selected metrics for aiding interpretation, it must be balanced by statistical measures for determining cluster analysis parameters (Mackay et al., 2014). Finally, the benefits and drawbacks to available clustering techniques and algorithms should be taken into consideration when applying this typological approach to other systems.

The flood type classification approach as developed here can be applied to other river floodplain systems where flood conditions vary inter- and intra-annually. Although hydrologic regimes and associated flood regimes vary widely across the globe, from highly seasonal tropical systems (Junk et al., 1989) to sporadic arid systems (Hughes & James, 1989), metrics relating to magnitude, duration, and timing are expected to be universally applicable for interpreting ecological function (Agostinho et al., 2004; Hughes, 1990; Poff et al., 1997). Because climatic and watershed drivers vary widely across systems, flood types are expected to be quite different from those established in this study.

4.2 | Relating flood types to watershed conditions

The flood types identified in this study reflect the physical state of the watershed, including climate and antecedent conditions. Other flood classification studies such as Merz and Blöschl (2003) have focused on such processes to define classes a priori (e.g., long-rainfall, short-rainfall, rain-on-snow, etc.). Hydrologic responses to climatic forcing vary across watersheds because of interacting factors including topography and geology (Wagener, Sivapalan, Troch, & Woods, 2007), making it useful to explore watershed-specific relationships to typical storm types while seeking to understand commonalities across watersheds. Examining the flood types of events known to be associated with particular conditions, which here include rain-on-snow, multiple storm events, atmospheric river events, snowmelt recession, first flood, and water year type, can help connect these types—not predefined by processes—to possible driving physical mechanisms of different flood types. These relationships are illustrated conceptually in Figure 8, where for each watershed or climate process, an arrow was drawn across the 90% ellipse to intersect the centroid of the associated floods identified from various existing datasets, described in the following text.

First, the largest floods on record for California's Central Valley are rain-on-snow events (Kattelmann, Berg, & McGurk, 1991). We found that, of 15 such events documented (Fissekis, 2008; Kattelmann et al., 1991; Leavesley, 1997), 10 aligned with the *Very Large* flood type and three with *Large and Long* events. Second, *Very Large*, *Large and Long*, and *Long and Late* events were associated with multiple storm events occurring close together (identified as >1 set of continuous days of precipitation over the course of a flood; Western Regional Climate Center, 2015). Third, using atmospheric river events summarized in Dettinger et al. (2011), we found that all of the *Very Large* events were associated with such storms within the period of available data (post-1948). The remaining events were classified as *Large and Long*, *Small and Early*, or *Late Peak*. Fourth, the flood events with volume centroids after the start of the spring snowmelt recession on the Cosumnes River—defined as April 13 by Epke (2011)—are shown to overlap predominantly with *Long and Late* and *Small and Late* events. Fifth, nearly all of the first floods of the season are either *Small and Early* or *Late Peak* events. This is likely associated with antecedent moisture conditions, where the watershed is still dry, producing short, but relatively higher magnitude events. Finally, events associated with very wet years span a range of flood types, but *Very Large* events occurred almost exclusively in these years. The dispersed nature of these events suggests that very wet years include a range of

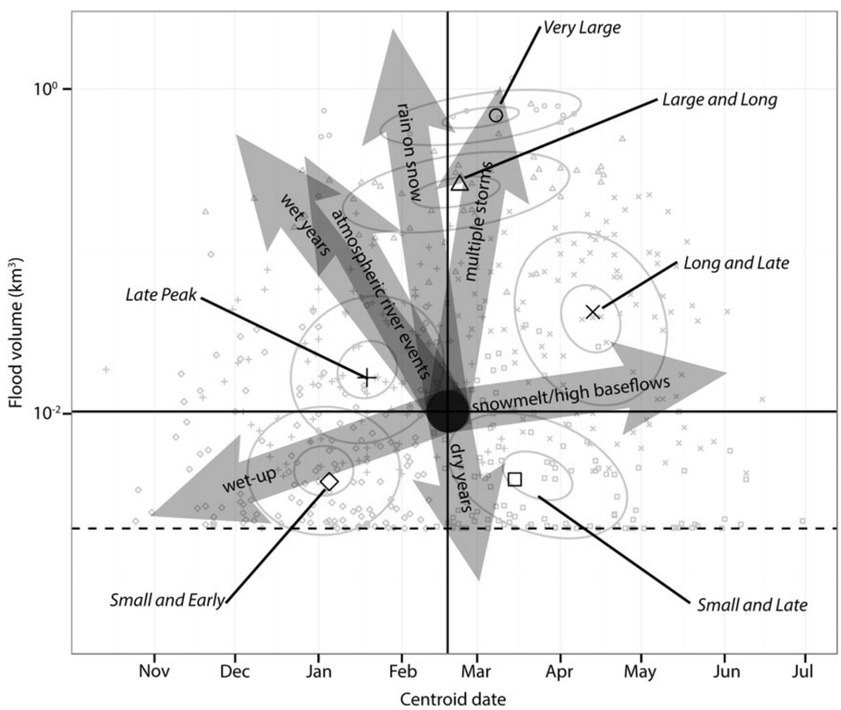

FIGURE 8 Association of flood types with climate and watershed conditions. Flood events of known conditions are represented by the arrows (drawn across the 90% ellipse to intersect the centroid), which overlay flood events (gray points) grouped by flood types (gray ellipses for 10% and 50% of the data)

precipitation and watershed conditions that allow for this diversity of flood types. In contrast, events occurring in critically dry years are much more concentrated within the domain of *Small and Late* events, which occur at times of the year when larger events would otherwise be occurring. These associations suggest a physical basis to the identified flood types, which supports the validity of the types. They also demonstrate that the types are not completely explained or separated by the watershed and climate factors explored here and thus support the classification performed.

4.3 | Flood type interpretation for ecosystem functions

Aligning the characteristics of the resulting flood types from this analysis with ecological processes and functions facilitates the interpretation of the flood types for their ecological relevance (Figure 9). Floods of different magnitude serve different physical and ecological functions and affect species differently. Infrequent high peak magnitude flows—associated with the representative *Very Large* and *Large and Long* flood types shown in Figure 9—are associated with sediment erosion and deposition producing high levels of disturbance that supports heterogeneous habitat mosaics, resets successional processes, and reorganizes ecosystem structure (Florsheim & Mount, 2002; Resh et al., 1988; Ward, Tockner, Arscott, & Claret, 2002). On the Cosumnes River, two levee breaching events in the 1980s and 1990s reconnected the floodplain to flood disturbance processes, resulting in sediment deposition and recruitment of large wood and initiating riparian forest successional processes (Andrews, 1999). Linking floods to their associated disturbance mechanisms at this site, Florsheim and Mount (2002) studied the sand-splay complex formation and evolution, which generated local physical variability that affected the patterns of riparian vegetation establishment. Their conceptual model of sand-splay generation links lower magnitude flood flows to reworking of sediment within the floodplain, while high magnitude events transport sediment onto the floodplain, creating new formations. The extent to which the sediment is moved within the floodplain is also affected by the event duration. Therefore, although the flood types with high-peak flows (*Very Large*, *Large and Long*) serve critical functions of creating new floodplain landforms, lower magnitude flood types of sufficient duration that occur frequently (*Long and Late* and *Late Peak*) provide the regular addition of new substrate material and reworking of sediment to shift the habitat mosaic without resetting the landscape (Opperman et al., 2010).

Floodplain vegetation community composition is also affected by floods through hydrochory, for which the magnitude (via processes similar to sediment deposition) and timing (which is species dependent) of flood events are governing factors (Nilsson, Brown, Jansson, & Merritt, 2010). Subsequent successful recruitment of the dispersed seeds is dependent upon flood timing and recession rates, as addressed by the "recruitment box model" of Mahoney and Rood (1998), establishing a recession rate of 2.5 cm/day during the spring-growth period for cottonwood seedlings. For the snowmelt dominated Tuolumne River in California, cottonwood seed dispersal aligned with the season's peak flow period while willows were more associated with the later spring snowmelt flows (Stella, Battles, Orr, & McBride, 2006). Mapping Cosumnes River flood types on these functions, the earlier

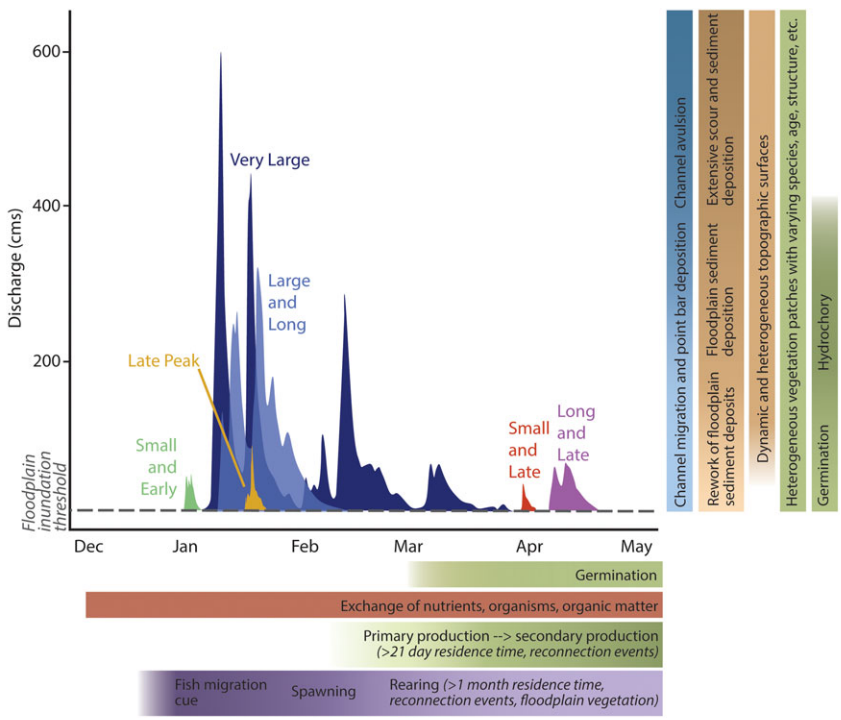

FIGURE 9 Floodplain physical and ecological processes and functions in California's Central Valley derived from available literature connected to the timing and magnitude of flood types (Ahearn et al., 2006; Andrews, 1999; Crain et al., 2004; Florsheim & Mount, 2002; Grosholz & Gallo, 2006; Jeffres et al., 2008; Opperman et al., 2010; Stella et al., 2006). Six flood events from the historical record, each most representative of the identified flood type, are shown. The selected processes and functions are shown along the axis (or axes) representing the driver(s) of relevance, with shading representing shifts in the processes. Characteristics of specific events, their antecedent conditions, spatial attributes of the floodplain, and other abiotic and biotic conditions will also affect ecological outcomes

season high flows of *Very Large* and *Large and Long* events can be expected to serve seed dispersal functions through hydrochory for cottonwood, while *Long and Late* and *Late Peak* events may also serve dispersal functions for willow species. Flooding later in the season that provides long-duration lower-recession rate receding hydrograph limbs with the capacity to promote seed germination and growth align with *Long and Late* as well as the end of *Very Large* and *Large and Long* events. Multiple flood types therefore support different riparian forest successional processes.

Regular floodplain connectivity via frequent lower peak flows creates dynamic and heterogeneous habitat conditions in space and time (Junk et al., 1989; Tockner et al., 2000). Such flood events can substantially reconfigure floodplain habitat mosaics spatially without necessarily changing the overall composition (Ward et al., 2002). The frequent low-magnitude pulses promote nutrient exchange and the movement and transformation of organic matter (Robertson, Bunn, Boon, & Walker, 1999), as well as serve species' life history requirements such as providing fish spawning and rearing habitat (Welcomme, 1979). Inundation timing, duration, and connectivity control fish habitat conditions as well as primary and secondary productivity, which generates needed food for rearing juvenile fish and for export downstream (Sommer, Harrell, Solger, Tom, & Kimmerer, 2004). For example, fish with different reproductive strategies in the Upper Pantanal, Brazil, have been shown to be highly correlated with the duration, timing, and magnitude of flows (Bailly, Agostinho, & Suzuki, 2008). Zooplankton productivity and community composition within a Danube River floodplain to be particularly correlated with water age, representing hydrologic and connectivity conditions (Baranyi, Hein, Holarek, Keckeis, and Schiemer 2002). Within a floodplain restoration site along the Cosumnes River, Ahearn et al. (2006) demonstrated periods of disconnection and reconnection could maximize primary productivity and export, and Grosholz and Gallo (2006) found that zooplankton biomass peaked with residence times of 2 to 3 weeks. Of the established flood types, intra-annually frequent *Small and Late*, *Long and Late*, and *Late Peak* flood types offer the shorter reconnection events that support these floodplain functions. The *Small and Late* and *Long and Late* types as well as later season *Late Peak* events occur during the time of the year when juvenile fish, such as Chinook salmon or California native and obligate floodplain spawning Sacramento splittail, use floodplain habitats, including those along the Cosumnes River, for rearing (Jeffres et al., 2008; Sommer, Baxter, & Herbold, 1997). Research has shown that native fish populations on the Cosumnes River are supported over alien fishes by early spring flooding, followed by disconnection (Crain, Whitener, & Moyle, 2004). Also, the temporal and spatial complexity of habitat produced by variable flooding conditions allows fish to locate optimal habitat conditions (Jeffres et al., 2008). Although the *Very Large* and *Large and Long* events may also serve such functions if they continue into the spring months, their low frequency and long periods of connection suggest that these events alone would be inadequate to sustain viable fish populations.

4.4 | Management implications

The flood typology presented here offers characterization both within and across years of a variety of flood conditions within floodplains that could be used to achieve greater variability reflective of more natural conditions in managed riverine systems. As such, this flood typology can provide an important basis for hydrodynamic modeling, flood type forecasting, and ecological studies linking flood types to specific functions to inform management decisions. Overall, this approach supports efforts to maintain natural variability, a core principle in river restoration (Naiman et al., 2002; Petts, 2009; Poff et al., 1997; Ward, Tockner, Uehlinger, & Malard, 2001). Managing toward a more natural flood regime, with the flood typing methods presented here helping define spatial and temporal variability of flood characteristics driving floodplain habitat diversity, is expected to promote ecosystem diversity and productivity (Ward, Tockner, & Schiemer, 1999).

For the largely unregulated Cosumnes River, the primary management variables are landscape modifications, which could be made to best take advantage of the identified flood types for supporting a suite of ecological functions and processes within the floodplain. At the Cosumnes River floodplain restoration site of focus here, managers can use these flood types in a variety of applications to refine expectations for the type and extent of physical habitat provided within and across years. Previous research on the Cosumnes River has influenced the development of setback levees in other river systems of California's Central Valley (Andrews, 1999; Stofleth, Collison, Bowles, & Andrews, 2007), and the established flood types could be used to evaluate how these restoration projects have changed floodplain inundation patterns. Additionally, future projects can use these flood types to evaluate the potential effectiveness of different restoration scenarios through characterizing the varying response to different flood types. For example, hydrodynamic modeling of these flood types could improve understanding of floodplain inundation spatiotemporal variability, and specific flood types could be targeted through floodplain restoration for the physical habitat they would be expected to provide.

By characterizing variable conditions, a flood regime typology of unimpaired hydrology also offers detailed information that can be applied, for example, to environmental flow targets of regulated rivers to better prioritize the range of conditions to which species are adapted (Nislow, Magilligan, Fassnacht, Bechtel, & Ruesink, 2002). Specifically, it can provide a simplified set of flood types with associated characteristics and frequencies to target in given years. Further, a flood typology for a regulated system can be used to compare to unimpaired conditions and more explicitly characterize regulation impacts and potential ecological consequences. Having multiple metrics and flood types also allows for finer resolution of particular aspects of change. For example, land-use change may affect the rising rate of spring floods or cause new summer floods (Sparks et al., 1998), flow regulation may increase the frequency of floods during particular seasons (Robertson, Bacon, & Heagney, 2001), dams may only affect high-magnitude flows, or climate change may increase the frequency of high-magnitude winter floods while changing the timing or existence of floods related to snowmelt (Safeeq et al., 2015; Stewart et al., 2004).

Tools to not only identify, quantify, and classify such dynamics, but to also manage for that variability are essential to better manage highly modified rivers for ecological functions. The flood types identified here capture the predominant flood characteristics from a complex flood record while offering greater detail that can be used to link floods to their ecological implications than a typical flood frequency analysis. In practice, ecosystem management goals can be more clearly articulated with flood type inter- and intra-annual frequency, and with association to water year type and other climatic and watershed conditions. More refined flood flow targets, in terms of annual variability, timing within a season, and magnitude and duration, may be possible knowing that only some years or certain flood types provide particular habitat conditions. For example, a better understanding of flood types and their variability could refine general conservation objectives concerning floodplain activation flows and connectivity to floodplain habitat in current Central Valley flood management plans (DWR, 2015). The clustering methods presented here identify flood types of a flood regime, drawing attention to this critical component of flow regimes. Analysis of flood type inter- and intra-annual variability offers greater opportunity to examine as well as manage for variability of a range of flood characteristics.

Furthermore, focusing on the flood regime and its inherent variability, as opposed to satisfying particular species requirements, can encourage process-based management approaches that support overall ecological integrity and resilience (Beechie et al., 2010; Tockner et al., 2003; Wohl et al., 2005). Application of this research can also inform the functional flows approach proposed by Yarnell et al. (2015), where established flood types could be included as targeted components of the hydrograph for their relationship to geomorphic and ecological functions. Overall, the flood regime typology established here provides a useful tool for understanding the lateral dimension of the natural flow regime and managing riverine and floodplain environments.

5 | CONCLUSIONS

Sustaining freshwater ecosystem functions and improving resilience to future anthropogenic change require not only a better understanding of floodplain inundation patterns but also readily applicable techniques to classify and quantify such patterns and their inherent variability. This study presents a flood typology to inform characterization of a river's flood regime, applied to a lowland floodplain site on the unregulated Cosumnes River of California, United States. Traditional hydrologic classification techniques are utilized, including k-means cluster analysis, to establish a systematic description of a river's flood regime relevant to floodplain ecosystems.

We show that flood event characterization, using ecologically meaningful metrics such as magnitude, timing, duration, rate of change, and hydrograph shape, is useful for classifying the highly inter- and intra-annually variable Cosumnes River flood regime. A total of six flood types were distinguished: (a) very high-peak magnitude floods, (b) high-peak and long-duration floods, (c) later season and longer duration floods, (d) low-magnitude and late-season floods, (e) low-magnitude and early season floods, (f) and floods where peak flows occurred later in the hydrograph. Assessing inter- and intra-annual frequencies of the flood types revealed a much higher resolution of flood variability than available with typical flood frequency analysis. High-magnitude and long-duration flood types were predominantly associated with wet years and the similarly timed small event type was associated with dry years; we also found that the small and early type was less associated with the type of year and instead typically marked the first floods of the season. Trend analysis showed that very large floods have significantly increased while the flood type with the second highest magnitude has decreased over the period of record.

While different typologies and associations to specific ecological functions are expected in other systems, the broadly applicable approach presented here is shown to systematically identify flood types and quantify them as a means to describe a river's flood regime. Application of these methods provides a refined understanding of floodplain hydrological conditions. Characterizing flood types using variables universally understood for their ecological significance, such as magnitude, timing, and duration, facilitates the ecological interpretation component of this approach. To the extent that ecological information is available, flood type interpretation can link types to the functions served (or identify types with little ecological relevance) and quantify characteristics and variability related to ecosystem functions. The identified flood types can also be used to improve understanding of climatic and watershed processes driving flood variability. We propose that this approach can be used to improve environmental flow targets for floodplain systems, by managing toward more natural flood regimes characterized by aspects, such as magnitude, timing, and duration, universally well-established as ecologically important. And, where possible, this approach can leverage existing information to better understand the ecological implications of flood types. In sum, this research offers new ways to establish needed information to support more functional floodplain inundation regimes within our current and future riverine landscapes.

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