Characterizing Duration and Frequency of Flood Events Across Geomorphic Settings

K. S. Lawson, Graduate Research Assistant, University of Vermont Department of Civil and Environmental Engineering, Burlington, VT, scott.lawson@uvm.edu
Kristen L. Underwood, Research Assistant Professor, University of Vermont Department of Civil and Environmental Engineering, Burlington, VT, Kristen.Underwood@uvm.edu
Rebecca M. Diehl, Research Assistant Professor, University of Vermont Department of Geography and Geosciences, Burlington, VT, Rebecca.Diehl@uvm.edu
Donna M. Rizzo¸ Professor, University of Vermont Department of Civil and Environmental Engineering, Burlington, VT, drizzo@uvm.edu

Introduction

Flood Characteristics Beyond Peak Discharge

Flood events drive numerous river processes, and while there are many ways to define and characterize floods, event duration is an important characteristic across several domains. In geomorphology, duration of high-energy flowrates can control the relative strength of sedimentological versus erosional adjustment (Lekach & Enzel, 2021; Magilligan et al., 2015; Wolman & Miller, 1960). For the built environment, post-flood inspections have found inundation duration to be a significant determinant in structure damages, and flood duration impacts emergency planning and response (FEMA, 2006; Pfurtscheller & Schwarze, 2008; Soetanto & Proverbs, 2004). Event duration is strongly correlated with event volume, which is important for designing storage systems and hydraulic modeling of lakes and river reaches with large in-channel storage or floodplain access. In ecology, the percent of time a parcel is inundated per year has been correlated with habitat cover, species richness, species diversity, and plant distribution patterns (Acosta & Perry, 2001; Arias et al., 2012; Ferreira & Stohlgren, 1999; Junk et al., 1989). For water quality, floodwater hydraulic residence time impacts nutrient retention and dissolved oxygen concentrations in floodplains (Baustian et al., 2019; Newcomer Johnson et al., 2016).

Despite the importance of flood duration, the bulk of flood frequency analyses (FFA) focus on one flood characteristic: frequency of flowrate exceedance (FEMA, 2019; Kidson & Richards, 2005; Olson, 2014). Advances in FFA over the past few decades have focused methods of fitting statistical distributions to the bulk of observed peak flow data and extrapolate flood quantiles in ungauged basins and into the future (Kidson & Richards, 2005; Stedinger Jery & Griffis Veronica, 2008). The result of these efforts has not been a better characterization of extreme events, but rather a suite of highly calibrated algorithms and tools. McDonnell et al. (2007) point out that advances in hydrologic science in the past 50 years have come not from parameterizing basin heterogeneity within a single model framework, but rather from exploring the functional traits of watersheds, which may underlie that heterogeneity. Characterizing flood events beyond their peak flowrate (e.g., inclusion of flood duration) may elucidate watershed functions that have been overlooked in our traditional approach to flood frequency.

Current Methods to Examine Flood Duration Dynamics

Perhaps the most common conceptualization of flood duration is the flow-duration curve, which defines the average percent of time within a year that river flowrate exceeds a threshold (Olson, 2002; USACE, 2022; Ward & Moran, 2016). This curve may be used directly to estimate sediment yields, model channel-forming processes, or assess components of ecosystem health (Diehl et al., 2020; Ward & Moran, 2016; Wolman & Miller, 1960). The power of flow-duration curves, however, is limited by their focus on annual duration instead of event-specific duration. An occurrence of 24 days of continuous inundation, for example, is markedly different than 24 hours of inundation every other week, in terms of potential impacts to built infrastructure, water quality, or habitat, to name a few.

For the design and modeling of storage-based systems – such as reservoirs, lakes, groundwater, and rivers with significant in-channel storage or floodplain access – event duration is important for its impacts on event volume. For these efforts, a useful conceptualization of flood duration is a moving window used to resample the flowrate timeseries. Various parameters may be tracked in the resampling process and summarized similarly to intensity-duration-frequency (IDF) curves used in rainfall prediction. Investigations in this vein are commonplace across the scientific literature under various names: flow-duration-frequency, volume-duration-frequency, n-day flood (Cunderlik & Ouarda, 2006; Devulapalli, 1995; Javelle et al., 2003; Kennedy et al., 2015; Lamontagne et al., 2012; Sherwood, 1994). While this approach to FFA is competent in predicting peak volumes, it lacks detailed flowrate/energy information, which is essential for many geomorphic, water quality, and ecosystem applications.

Copula methods have also been used to model the frequency of flood duration, and their popularity has risen sharply in the last 20 years. Copula methods involve fitting marginal distributions to a set of variables of interest and modeling their dependance structure using one or more copula functions (Genest & Favre, 2007). These models are similar to multivariate distribution models, such as those used by Yue et al. (2001), in that they are joint distributions of any two random variables; however, they allow the hydrologic modeler freedom in selecting both marginal distribution form and dependance structure of the random variables.

Copulas were first applied in the hydrologic sciences in the mid-2000's by Favre et al. (2004), and the flexible model has been applied in a variety of hydrologic systems since. Bivariate copulas have been used to model pairwise combinations of peak discharge, duration, volume, and time to peak (Bačová Mitková & Halmová, 2014; Razmkhah et al., 2022; Sraj et al., 2015). Vine copulas have allowed for the modeling of more than two random variables (Amini et al., 2022; Ganguli & Reddy, 2013; Tosunoglu et al., 2020). Copulas have even been used to derive design flood hydrographs (DFH) (Drobot et al., 2021; Goswami, 2022). When copulas are used to model both discharge and duration, discharge reflects the peak discharge of a flood event and duration reflects the time between rising and falling limbs of the hydrograph. While this event-focused analysis provides some idea of hydrograph shape by estimating duration above baseflow, it does not capture and discretize the expected amount of time spent above specific flowrate thresholds between baseflow and peak.

Another conceptualization of flood duration treats event duration as a conditional probability on event magnitude (Feng et al., 2017; USEPA, 2008). Feng et al. developed a simple threshold approach to extract events from stage timeseries, and applied this algorithm at two riverine gages, one estuarian gage, and one tidal gage within the mid-Atlantic region of the US. By generating populations of events corresponding to different stage-thresholds, Feng et al. validated their hypothesized relationship between stage-threshold and event duration. They then performed a standard FFA using the annual-maxima approach to define the marginal frequency of flowrate exceedance. This marginal distribution was combined with the conditional event-duration relationship to define a joint probability model for frequency of flowrate and duration. The method of Feng et al. overcomes many of the shortfalls of the previous two methods. By discretizing both threshold and duration by event, this model is applicable for a variety of river process applications (Feng et al. 2017).

Despite its many strengths, the method of Feng et al. could be enhanced to address some shortcomings. The annual-maxima approach is biased low for frequent events, the events we know drive the bulk of in-channel geomorphic and ecological processes (Karim et al., 2017; Pan et al., 2022). Feng et al. also used a stage timeseries instead of a flowrate timeseries. River stage is strongly influenced by local hydraulic configuration, whereas river flowrate is a product of the basin contributing to a point. While a stage-duration joint distribution will give the best representation of that information for a given gage, discharge is more easily regionalized and predicted given remotely-sensed basin characteristics. Lastly, because Feng et al. only analyzed two riverine sites, it was unclear whether the joint distribution shape they used adequately defines the flowrate-duration-frequency relationship at riverine sites across broader regions. For all these reasons, a new joint probability method warrants investigation.

This study presents a model for the frequency and duration of river flooding and fits the model at stream gages within the US state of Vermont. Specifically, our objectives are to: (1) Tailor the hierarchical model of Feng et al. to frequent events (average recurrence less than 10 years) that we know drive the bulk of geomorphological and ecohydrological processes; (2) Refine and validate the modeling assumptions that this hierarchical model is built upon by fitting it to 30 stream gages across the US state of Vermont; and (3) Relate the model parameters to basin characteristics, so that a regional model may be developed for predictions in ungauged locations.

Methods

This study uses the mountainous US state of Vermont (VT) as a case study for duration dynamics across heterogeneous basins. The 7,100 miles of perennial streams within VT range in form from mountain gorges to boggy wetlands and traverse the most remote areas of the state to the most populous urban centers (VTDEC, 2018). Morphologic diversity within a relatively homogeneous climatic region allows for the extraction of scaling relationships across landforms without strong interference from climate signals. For Vermont rivers, streamflow data were obtained from United States Geological Survey (USGS) gaging station Instantaneous Value Service. Of the 71 USGS stream gages currently operating within the state, a subset of 33 stations was selected based on their having more than 30 years of 15-minute instantaneous flowrate record. Analyzed basins are shown in Figure 1 and their characteristics are summarized in Table 1.

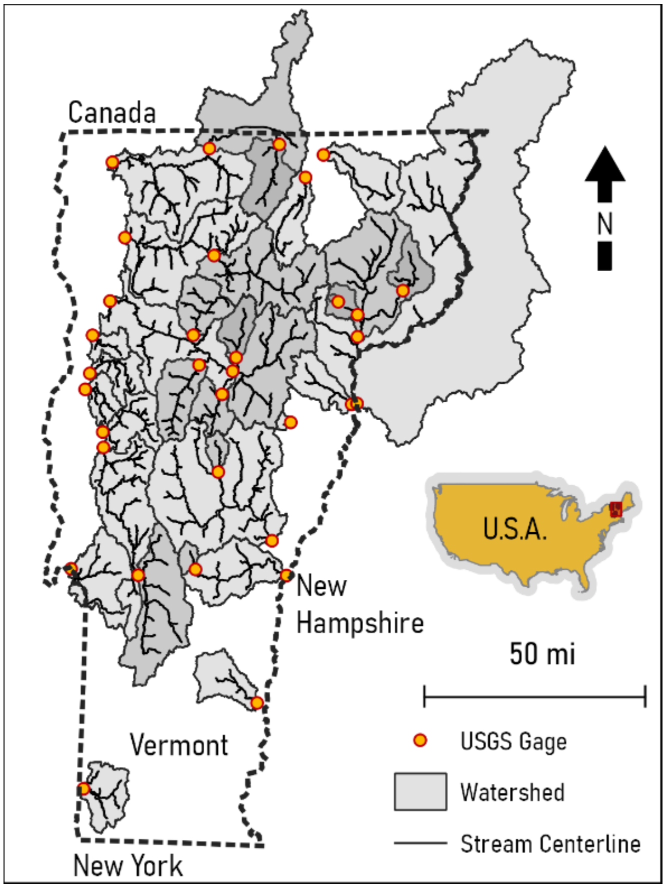


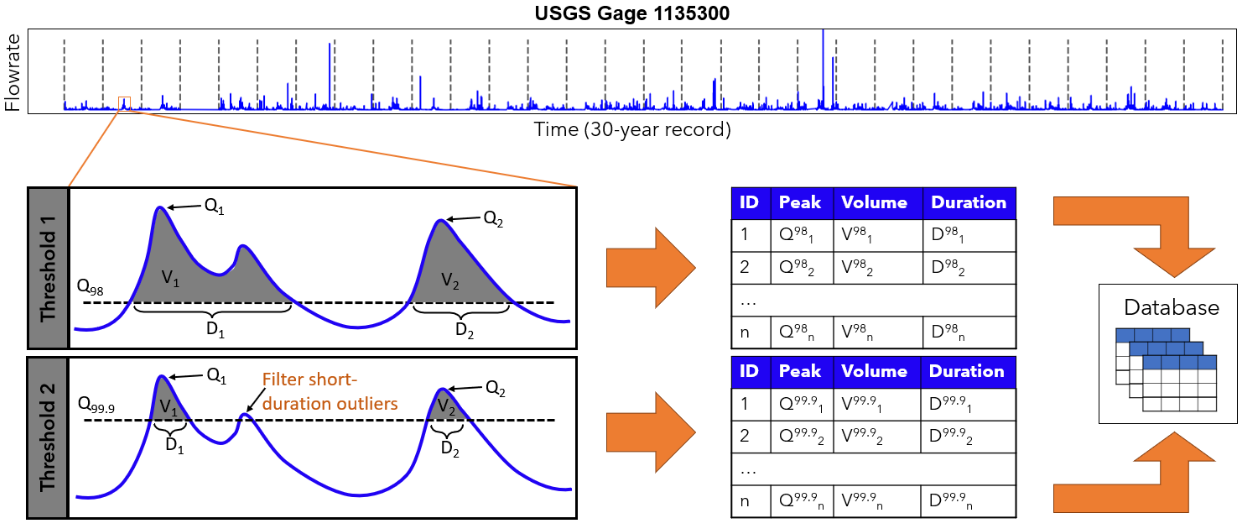
Figure 1. USGS gages in VT with more than 30 years of instantaneous record

Table 1. Summary of Basin Characteristics

	Drainage Area (Sq.Mi.)	Gage Elevation (ft NAVD)	Basin Storage (%)	Average Yearly Precipitation (in)	Analyzed Record Length (years)
Minimum	3	107	0	38	31
Maximum	2,643	1,180	11	56	34
Average	318	499	3	47	32 (rounded)

Our model defines a flood event as the hydrograph between up-crossing and down-crossing limbs of a flowrate threshold (Figure 2). A database of flood events was compiled for each gage by examining 30 flowrate thresholds and generating populations of flood events for each threshold. To generate event populations, we wrote a Python algorithm that takes a flowrate timeseries and a user-defined threshold, extracts all flood events above that threshold, merges select events to ensure independence, and then attributes each event with several hydrologic characteristics. Although an uncountable number of hydrologic characteristics could be recorded; for this analysis, we chose to attribute each event with 3 characteristics: 1) Duration, defined as the time between up-crossing and down-crossing hydrograph limbs; 2) Peak flowrate, defined as the maximum flowrate within the event; and 3) Base Threshold, defined as the threshold that generated the event.

We extracted events for each of 30 thresholds per gage. Selection of 30 thresholds was a balance between accuracy in duration-dynamic characterization and computational/data storage burden. The minimum threshold was set at the threshold that yielded the maximum number of cleaned events (see transition from zone two to zone three in figure 2 of Lang et al. (1999)). The maximum threshold was set as the highest threshold to generate three independent flood events. The remaining 28 thresholds were evenly spaced between the maximum and minimum.



ID	Peak	Volume	Duration
1	Q^{98}_1	V^{98}_1	D^{98}_1
2	Q^{98}_2	V^{98}_2	D^{98}_2
…			
n	Q^{98}_n	V^{98}_n	D^{98}_n

ID	Peak	Volume	Duration
1	$Q^{99.9}_1$	$V^{99.9}_1$	$D^{99.9}_1$
2	$Q^{99.9}_2$	$V^{99.9}_2$	$D^{99.9}_2$
…			
n	$Q^{99.9}_n$	$V^{99.9}_n$	$D^{99.9}_n$

Figure 2. Graphical summary of event extraction and attribution algorithm

Frequency of threshold exceedance was modeled using the Poisson-Pareto partial-duration series (PDS) approach. A truncation threshold for the PDS was selected for each gage to yield roughly four events per year. Event arrival was modeled using a Poisson distribution with a rate parameter equal to the number of peaks divided by the record length. We used the method of L-moments to fit a Generalized Pareto distribution (GPD) to the PDS (Stedinger & Foufoula-Georgiou, 1993). These two distributions were then merged into an equivalent generalized extreme value (GEV) distribution using the method of Coles (2001).

To model the conditional probability of event duration on threshold exceedance, we parameterized an exponential distribution. Quantile-quantile (QQ) plots of event duration were generated between the empirical distribution and a directly-fitted exponential distribution at each flowrate threshold for each gage. These plots were used to assess the assumption of an exponential distribution for event duration. A plot of mean event duration versus threshold was developed for each gage, and the logarithmic least squares method was fit to both a power law and an exponential decay relationship. The root mean square of log errors (RMSLE) was recorded for both relationship types and compared to determine the better-fitting form.

Results & Conclusion

Goodness-of-fit (GOF) for each of our frequency distributions was assessed graphically. An example of the graphical GOF check is shown in Figure 3. We found that the fitted GEV distributions matched the empirical plotting positions of PDS data well at all gages, implying a successful implementation of the L-moments approach. To compare our frequency estimates to a standard annual-maximum series (AMS) Bulletin 17B analysis, we plotted estimates of design events from USGS SIR 2014-5078 alongside our data (Olson, 2014). We found that our GEV flowrate estimates generally converged with USGS estimates for rare events (events with recurrence interval greater than 10 years) at two-thirds of our gages. While the PDS approach is often cited for its better representation of frequent event magnitude than an AMS analysis, we found that our distributions were very similar to USGS estimates for events with recurrence interval less than 10 years. Although our PDS approach yielded similar magnitude estimates for frequent events and did not converge perfectly to the AMS approach, we believe that our distributions still provide very good representations of the frequency of flood events.

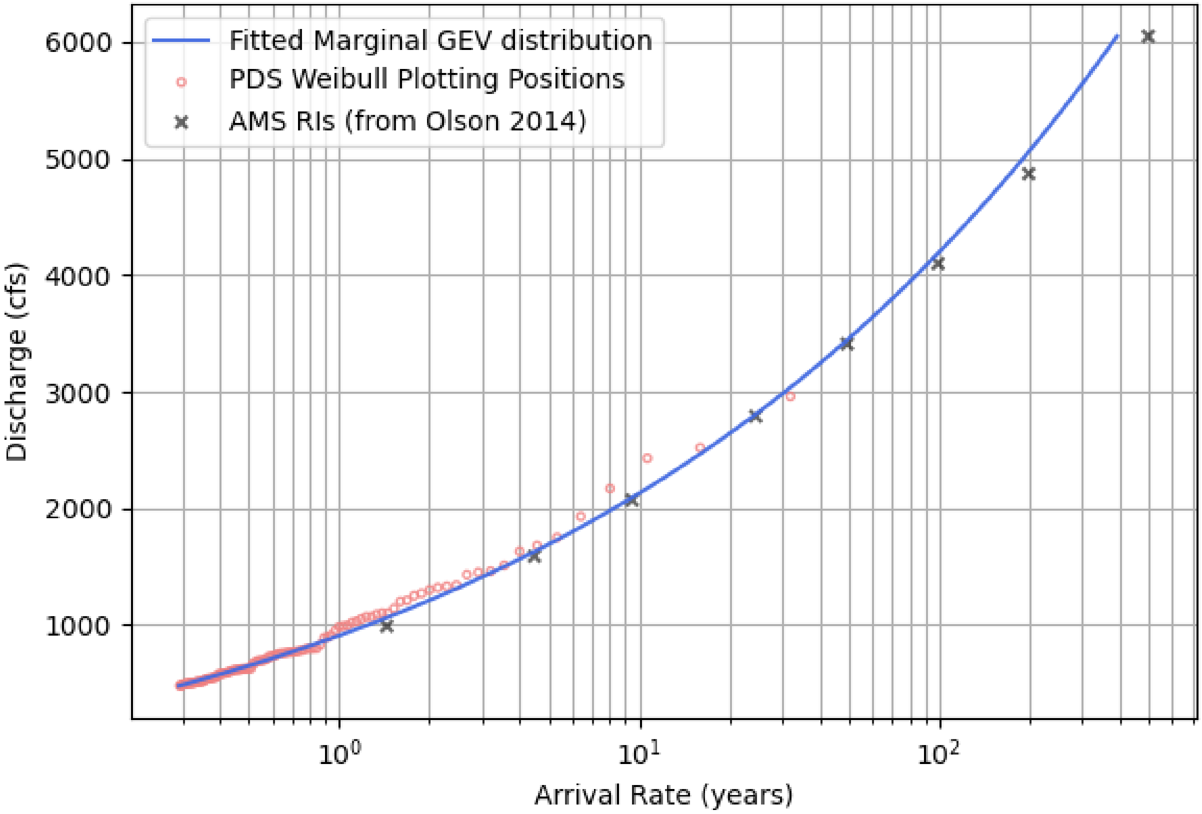


Figure 3. Graphical assessment of frequency distribution fit for gage 04282795. AMS data comes from Olson (2014) and were converted from annual-exceedance probability to arrival rate by assuming a Poisson arrival process.

The exponential distribution appears to be sufficient for modeling the conditional distribution of event duration. In Figure 4, the QQ plots for event duration at gage 04282795 are shown. Measured distributions of event durations tended to better match an exponential distribution as threshold flowrate increased. The ratio of the sample mean to sample variance, which should be one for the exponential distribution, generally fell around one for all gages and thresholds analyzed. The Anderson-darling test statistics proved to be less useful in determining distribution fit, and was more influenced by sample size than GOF.

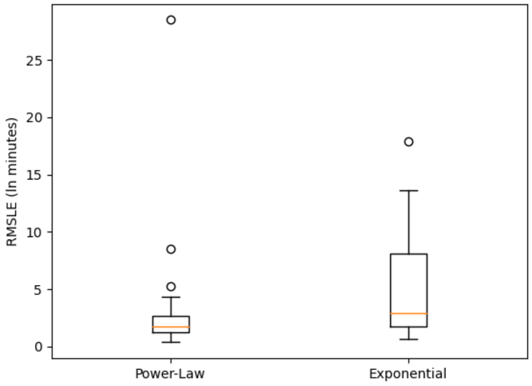


Figure 4. Comparison of RMSLE values for each gage's regression on threshold and mean duration.

We found that a power law better fits the relationship between event threshold and mean event duration than an exponential decay function. The power law regression had a lower RMSLE than the exponential decay regression at 21 of 33 gages; see the boxplot of the RMSLEs in Figure 4. Figure 5 shows an example of power law fit for gage 04282795.

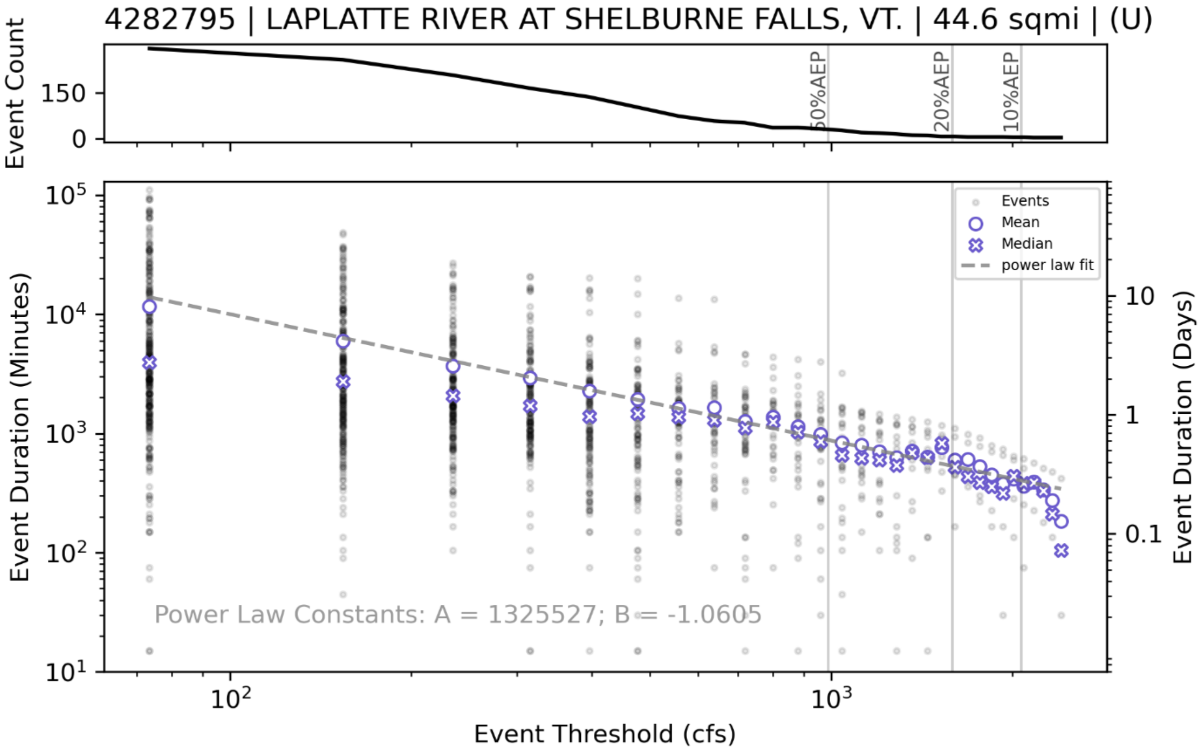


Figure 5. Example of power law regression fit at gage 0428795.

By combining the marginal distribution of threshold exceedance frequency with the conditional distribution of event duration, recurrence intervals of various events may be predicted. A 3D representation of the hierarchical model for station 0428795 is shown in Figure 6 alongside the same plot in 2D. The 2D representation of the model shows that a design event in this model can either be a short-duration exceedance of a higher threshold or a long-duration exceedance of a lower threshold. When duration goes to 15 minutes, the recurrence interval represents the peak flowrate frequency obtained from the PDS model.

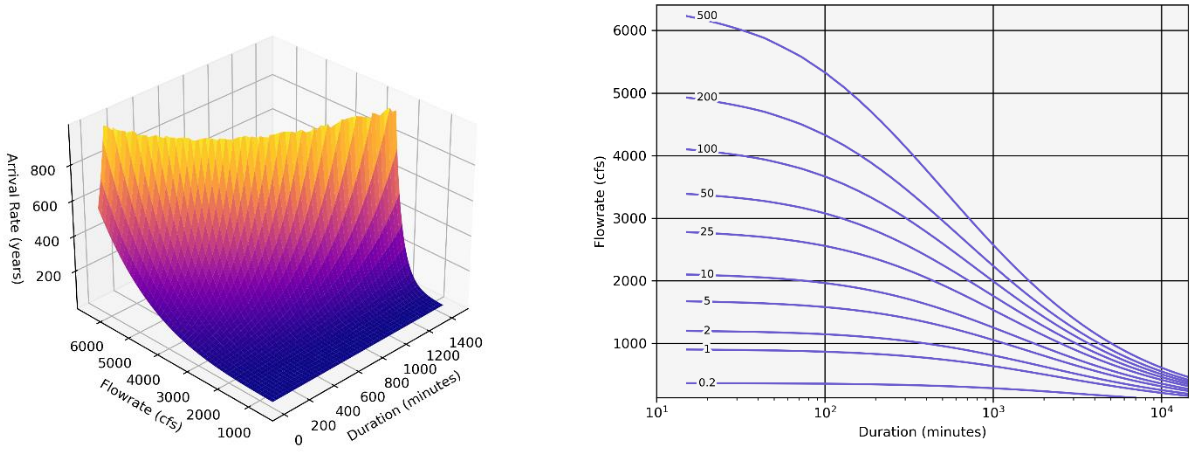


Figure 6. Example of model fit at gage 0428795. The left panel shows the event arrival rate surface in three dimensions. The right panel shows the same data in two dimensions, where the blue lines are labeled with their arrival rate in years.

This analysis builds upon the hierarchical model of Feng et al. (2017) with a more robust event extraction algorithm, frequency estimates tailored to frequent events that drive geomorphic and ecohydrologic processes, a better representation of mean duration for riverine settings, and a confirmation of the exponential distribution as adequate for representing event duration in our study area. The next steps on this project will involve relating fitted model parameters to basin characteristics, so that the model may be predicted in ungauged basins. Future research should involve the application of this model to engineering and river research projects. This model may be used within a 1D hydraulic model to map how long different areas of a river corridor would be inundated during an event with given recurrence interval. Given that erosion has been linked to event duration in many geomorphic effectiveness studies, this model could find applications in new sediment transport models. Overbank flow pulses have been noted as important for many species in river corridors, and this model may represent a useful tool for ecologists. Lastly, when combined with average time-to-peak information, the shapes of the curves in Figure 6 may be used to generate a synthetic flood hydrograph for an event with given recurrence interval.

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