Flood Variability in the Western United States: Overview and Examples

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Abstract

Greater understanding of riverine flood hazards, and how they vary in space and time, is needed to protect lives, property, and infrastructure. To this end, the variability of floods within the wide-ranging climatological conditions of the contiguous United States west of the Mississippi River were assessed using the flood potential method. This procedure fosters the comparison, visualization, and communication of flood hazards, for highlighting the status of flooding given observational data from the nation's streamgaging network, and how floods are changing due to such non-stationarity mechanisms as climate change. Within the study area, 117 zones of similar flood response were delineated using 4621 streamgaged watersheds with areas <3860 mi². Explained variances of the regressions were high, with an average $R^2 = 0.91$. The central tendency and variability of flood magnitudes experienced within each zone is an intrinsic characteristic, with exceedingly large floods systematically defined and ranked as extreme. The highest flood potential occurs in the southern Midwest and Texas, and along the West Coast, with the lowest flood potential in the Great Basin, Rocky Mountains, and northern Midwest. Extreme floods are not becoming larger or more frequent. However, some zonal areas (29%) are currently experiencing increasing trends in the magnitude or frequency of large floods, though magnitudes vary considerably more in space than in time. Results are presented through the Flood Potential Portal, a decision support system to explore flood variability at a full range of scales and predict flood discharge magnitudes using multiple methodologies. Examples are provided, including for the Yellowstone region floods of 2022 and Oroville Dam flood of 2017, to provide applications that use the methodology for enhancing knowledge of flood hazards.

Introduction

Floods are a leading environmental threat to life, infrastructure, and property (Figure 1); climate change may be increasing such threats in some areas. Common practice does not encourage systematic approaches for visualizing and communicating the spatial variability of large riverine floods, consequently not encouraging enhanced understanding of the physical mechanisms that produce such variability. Adequate knowledge of this status of flood events is needed for the consistent monitoring of flood trends, to assess stationarity, and for enhanced understanding of dominant mechanisms inducing spatial and temporal variability. Such knowledge, with language and tools for communication, are essential for informing the work of practitioners to maximize resilience within limitations imposed by available funding. The flood potential method (Yochum et al., 2019), and the associated Flood Potential Portal (Yochum et al., 2023), were developed to help provide such enhanced understanding.

The flood potential method was utilized for quantifying flood variability and predicting flood discharges, and for consistently assessing streamgage data for trends in flood magnitudes, frequencies, and flashiness (to monitor for climate change impacts). For an extent that consists of the western 2/3's of the contiguous United States, from the Pacific Ocean to the Mississippi River, this article's goals are to examine the status of large floods and how they vary, quantify and rank extreme floods, present trends in the magnitude and frequency of large and extreme floods, and provide examples on how these tools can be utilized for enhanced understanding of hazards. A summary of these results, as well as the products of traditional flood frequency analyses, are presented within this article as well as within the Flood Potential Portal; readers are encouraged to use the Portal to explore flood variability in their region of interest, to enhance understanding and societal resilience to these hazards.

Figure 1: US-34 over the Big Thompson River, CO, just after a 100-year (and expected flood potential) discharge event peaked in an area with increasing trends in both the magnitude and frequency of large floods (9/13/2013).

Overview of Flood Variability

The flood potential method (Yochum et al., 2019) quantifies the central tendency of large flood magnitudes across zones of similar flood response, for watersheds < 3860 mi^2 (10,000 km^2). This central tendency is the expected flood potential, a regression of the maximum recorded (record) discharges for streamgages within each zone. Floods of this size can reasonably be expected to occur at a stream valley point of interest, which (in concert with flood-frequency methods) makes these estimates valuable for floodplain management and infrastructure design. The method includes streamgage data collected in both regulated and unregulated watersheds, and is limited to < 10,000 km^2 watersheds due to shifting flood response characteristics within larger watersheds. The expected flood potential discharge (Q_{efp}), the central tendency in record peak discharges, has been found to not be statistically different from the flood-frequency derived 100-year (1% chance of occurrence) discharge (Q_{100}; Yochum et al., 2019). The flood potential method has an advantage over flood-frequency methods for addressing bimodal (or multimodal) peak flow magnitudes due to mixed populations, an acknowledged issue (England et al., 2018), as well as sidestepping issues stemming from varied streamgage lengths and periods of record; this is important for the determination of most appropriate design flood discharges. The 90% prediction limit of the regressions is the maximum likely flood potential. Floods with discharges (Q) greater than the maximum likely flood potential discharge (Q_{mlf}) are quantitatively defined as extreme, with the departure above this limit indicating the degree of extremity. Hence, this method provides a systematic approach for identifying and ranking extreme floods. Zones have flood potential plots that vary in scale (variability of the central tendency of large flood magnitudes) and slope (variability of how watersheds of different sizes experience floods). Such characteristics are quantified and compared between zones through the use of indices. Finally, the flood potential method enhances the assessment of trends in flood magnitudes, flood frequencies, and flashiness. Where trends in flood magnitudes have been detected, correction factors can be applied to adjust for such changes.

Methodologies utilized in these interpretations have been previously published in several reports, specifically Yochum et al. (2019) and Yochum (2019), as well as the Flood Potential Portal User Manual (Yochum et al., 2023). The reader is referred to these reports for details.

Flood Potential Portal

To maximize resilience, it is essential that enhanced interpretations of riverine flood hazards be developed and made readily available to hydrologic professionals, for floodplain management and infrastructure design. Additionally, within the context of climate change, the stationarity assumption needs to be tested through time series trend detection of the magnitude, frequency, and flashiness of flooding, and addressed accordingly. The Flood Potential Portal (Portal) was developed to assist practitioners with developing enhanced understanding of flood hazards, using both traditional and new techniques that leverage the power of more than a century of streamgaging efforts in the United States. Readers are encouraged to use this tool to explore large flood characteristics in their region of interest.

The Flood Potential Portal (https://floodpotential.erams.com) provides mapping and regional-scale cross section tools for comparing and communicating how flood magnitudes vary over space and time, as quantified using the flood potential method. Users can explore flooding variability from continental and regional levels to the catchment level. The Portal also provides tools for the prediction of flood discharge magnitudes for infrastructure design and floodplain management at user-selected points, including flood potential, index flood frequency, and USGS regional regression (StreamStats) flood frequency results through a “one-stop shop” approach to the software design (Figure 2). Where trends in flood magnitudes have been quantified as being significant (p-value ≤ 0.05) or possible ($0.05 < p$-value ≤ 0.15), flood potential results are adjusted by the observed percent change to account for these trends. Providing predictions from three methods allows for flagging of results that may be misrepresenting the actual flood hazards. Generally, predictions can be made for watersheds ranging from < 1 mi^2 to 3860 mi^2.

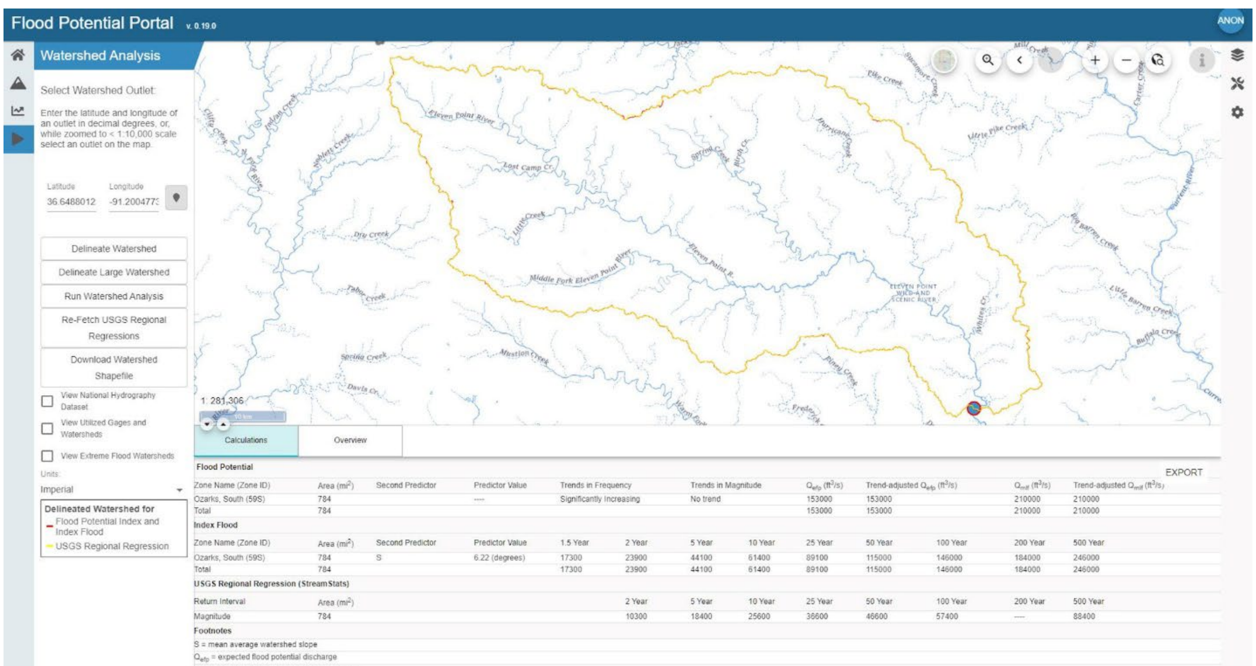


Figure 2: Watershed analysis in the Flood Potential Portal (https://floodpotential.erams.com).

Thoughtful consideration of results is required for the selection of most appropriate design flood discharge estimates – a well-educated and experienced hydrologist, floodplain manager, or civil engineer is needed for this interpretation. The Flood Potential Portal was developed to help with this decision making, but does not replace this expertise. Extensive information on the capabilities and use of the Portal is available in the User Manual (Yochum et al., 2023).

Spatial Variability of Large Floods

The Western United States has 117 zones of similar flood response delineated across almost 2 million square miles. These zones were developed using 4621 streamgaged watersheds, including watersheds that originate in Canada and Mexico. Explained variance (R^2) of the flood potential regressions ranged from 99% to 69%, with an average (adjusted) R^2 of 0.91 and 72% of the zones having $R^2 \geq 0.90$.

To rank the magnitudes of experienced and expected floods, and compare how floods vary between any two zones, flood potential index (P_f) values are utilized (Figure 3). Variation in the sizes of floods extend across two orders of magnitude, with high flood potential in the central and southern Midwest, Texas, and West Coast, moderate flood potential in the Southwest and along the Rocky Mountains Front and High Plains, and generally low flood potential in the Rocky Mountains, Great Basin, and the northern Midwest.

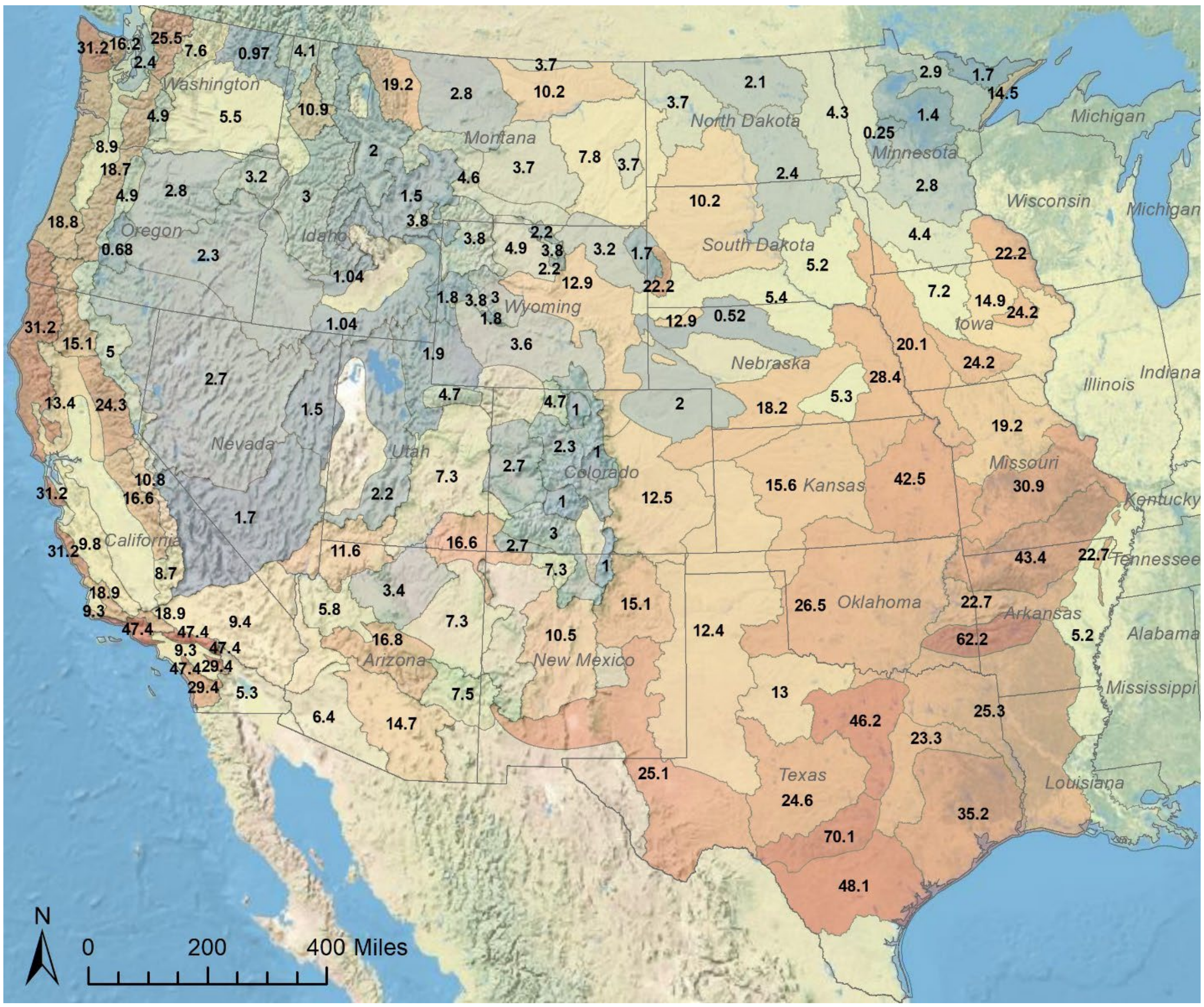


Figure 3: Flood potential index (P_f) variation across the Western United States. Higher P_f values (and warmer colors) indicate higher flood magnitudes (higher flood potential), while lower P_f values indicate lower flood potential.

The two zones with the highest identified flood potential (in the West) are in the relative vicinity of the Gulf of Mexico (Figure 3), specifically the southeast Edwards Plateau of Texas (zone 51; P_f = 70.1; Balcones Escarpment and neighboring areas of the plateau) and the Ouachita Mountains (zone 57; P_f = 62.2) of eastern Oklahoma and Arkansas. Floods in zone 51 (Figure 5) are 280 times larger, on average, than floods in the lowest flood potential zone (zone 67W; $P_f = 0.25$) in the headwaters of the Mississippi River and the Red River of the North [($P_f = 70.1$)/($P_f = 0.25$) = 280]. Flood magnitudes of up to 616,000 cfs have been recorded in zone 51 while the largest flood in zone 67W was only 2380 cfs (for similar-sized watersheds).

In an additional example, consider (again) the Ouachita Mountains, the Oregon and Washington Coast Ranges (zone 27; $P_f = 18.8$; moderate flood potential), and the Mississippi River Headwaters, South (zone 67S; $P_f = 2.8$; low flood potential). Comparative flood potential plots for these three zones are presented in Figure 4. Compared with the Oregon and Washington Coast Ranges and the Mississippi River Headwaters, South, floods in the Ouachitas are, on average, 62.2/18.8 = 3.3 times larger than in the Oregon and Washington coast ranges, and 62.2/2.8 = 22.2 times larger than in the southern headwaters of the Mississippi River. Note not only the difference in scale between floods within these three zones, but also the differences in slopes. The watershed scale ratio (R_f) quantifies the relative magnitude of floods across a range in watershed sizes. Lesser R_f values indicate that smaller watersheds experience relatively large flood magnitudes, with greater values indicating that larger watersheds experience relatively large flood magnitudes. The steeper sloped zone 27 flood potential plot has $R_f = 2.40$, while the milder sloped zone 67S has $R_f = 0.66$.

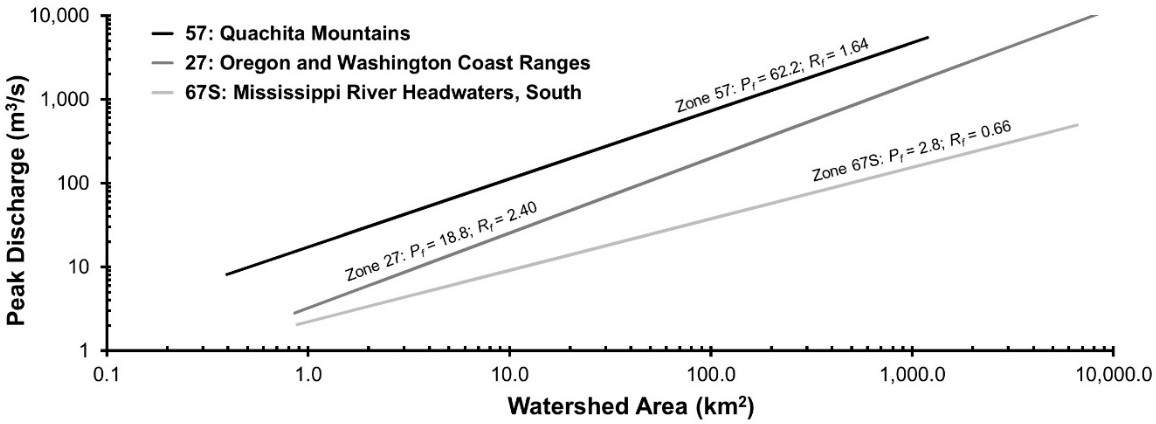


Figure 4: Flood potential plots for zones 27, 57, and 67S, with labeled flood potential index (P_f) and watershed scale ratio (R_f) values.

Flood potential decreases from south to north across the Central Highlands and Midwest (Figure 3), declining with more distance from the moisture source of the Gulf of Mexico. The Rocky Mountain Front, and the neighboring plains to the east, are areas with moderate flood potential that also generally decreases from south to north. These moderate zones typically extend westward to the first major ridge of the Rockies. Between the Rocky Mountain Front and the Sierra-Nevada and Cascade mountains, and north of the Southwest region, flood potential is generally low, with P_f typically ranging from 1 to 4. The flood potential of the American Southwest is elevated compared to the Great Basin and Southern Rockies, in a triangular-shaped region that extends from the Mojave and Sonoran Deserts through the Colorado Plateau to the Uinta Mountains, and southeast to the Rio Grande Valley of central New Mexico. The rain shadow from the Sierra-Nevada Mountains marks the northern limit of this elevated flood potential, which extends as a curved line from Tehachapi, California to Vernal, Utah. With an average $P_f = 18$, the flood potential along the West Coast is generally smaller than in the southern Midwest and Texas, though higher than most areas along and near the Rocky Mountain Front. The Los Angeles Ranges (zone 20; $P_f = 47.4$) experience the highest flood potential on the West Coast and the highest flood potential west of Texas.

Extreme Floods

Extreme floods within 502 streamgaged watersheds (with ≥10 years of record) were identified and ranked (Figure 5). These extreme events experienced discharges greater than the upper 90% prediction limits of the expected flood potential regressions ($Q > Q_{mlf}$), and are quantified using the flood extreme index (E_f). Zonal watersheds experience floods that appear to be constrained by an upper bound in flood magnitudes (Enzel et al., 1993; Yochum et al., 2019), with extreme events defining the upper limit of experienced floods (the envelope curve) – not only is the central tendency of large flood magnitudes (the expected flood potential) an inherent characteristic of a zone, but the upper bound in flood magnitudes may also be an inherent characteristic determined by limits in the supply of precipitation and watershed response. This contrasts with a flood-frequency perspective, which essentially assumes an unbounded distribution with a non-zero probability of an ever larger flood occurring (Enzel et al., 1993).

It is reasonable to use extreme floods to identify envelope curve boundaries, for such purposes as checking if streamgage data support the results of probable maximum flood studies (Spirit Lake example). The threshold for extreme floods (Q_{mlf}) can also be used to check freeboard discharges; it is typically unreasonable to design infrastructure to pass extreme flood discharges.

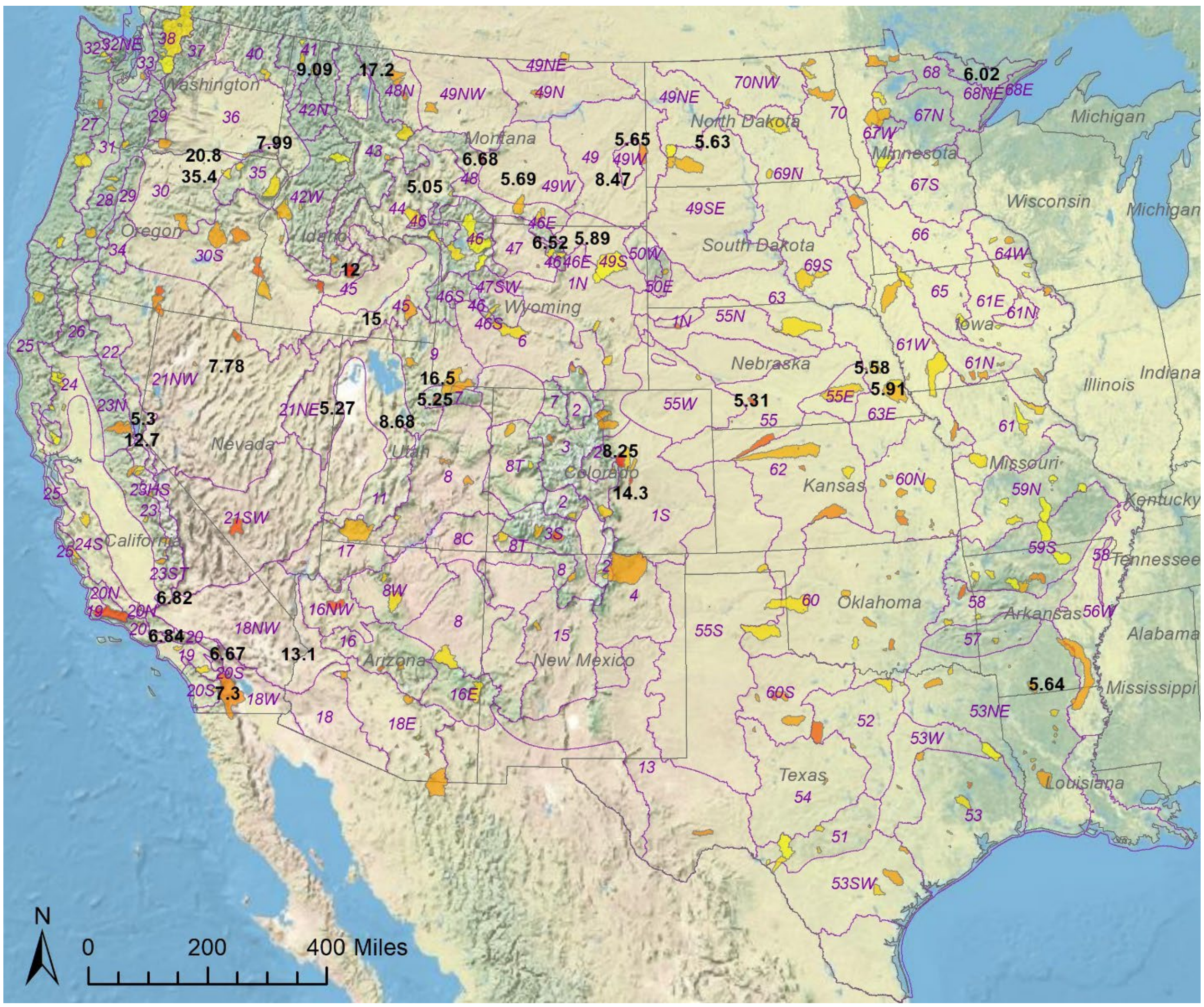


Figure 5: Watersheds that have experienced extreme floods, with warmer colors (and higher flood extreme index values, E_f) indicating events with greater extremity. E_f values are labeled where greater than 5.0. Zone boundaries, with ID's, are also provided for reference.

Trends in Large Floods

The flood potential method provides a framework for monitoring where there are changes in flooding over time. This approach accounts for flood variability by zone while identifying observational trends due to climate change and other non-stationarity mechanisms (Milly et al., 2008; Lins and Cohn, 2011; Galloway, 2011). Trends in magnitude or frequency are considered significant if p-value ≤ 0.05, or possible if 0.05 < p-value ≤ 0.15.

As an initial step in monitoring for trends, extreme floods were tested. Mann-Kendall tests for trends in extreme flood magnitudes for a period of 1921 to 2020 were not significant, with the frequency of extreme events significantly decreasing (p-value = 0.012) for a period of 1945 to 2020. The decreasing trend has likely been influenced by variable record lengths, periods, and decreased streamgaging (Yochum et al., 2019), which complicates interpretations of the result. In any case, extreme floods are not occurring more frequently or more severely. Instead, the magnitude of large floods are mostly within the expected range of variability within each flood potential zone, with trends in magnitude or frequency of floods detected in 29% of the extent.

The largest 5% of annual peak discharges are increasing in magnitude in some zones, and decreasing in other zones (Figure 6). Specifically, 14 of the 117 zones (16% of the area extent) are experiencing significant or possible increasing large flood magnitudes while 15 zones (13%) are

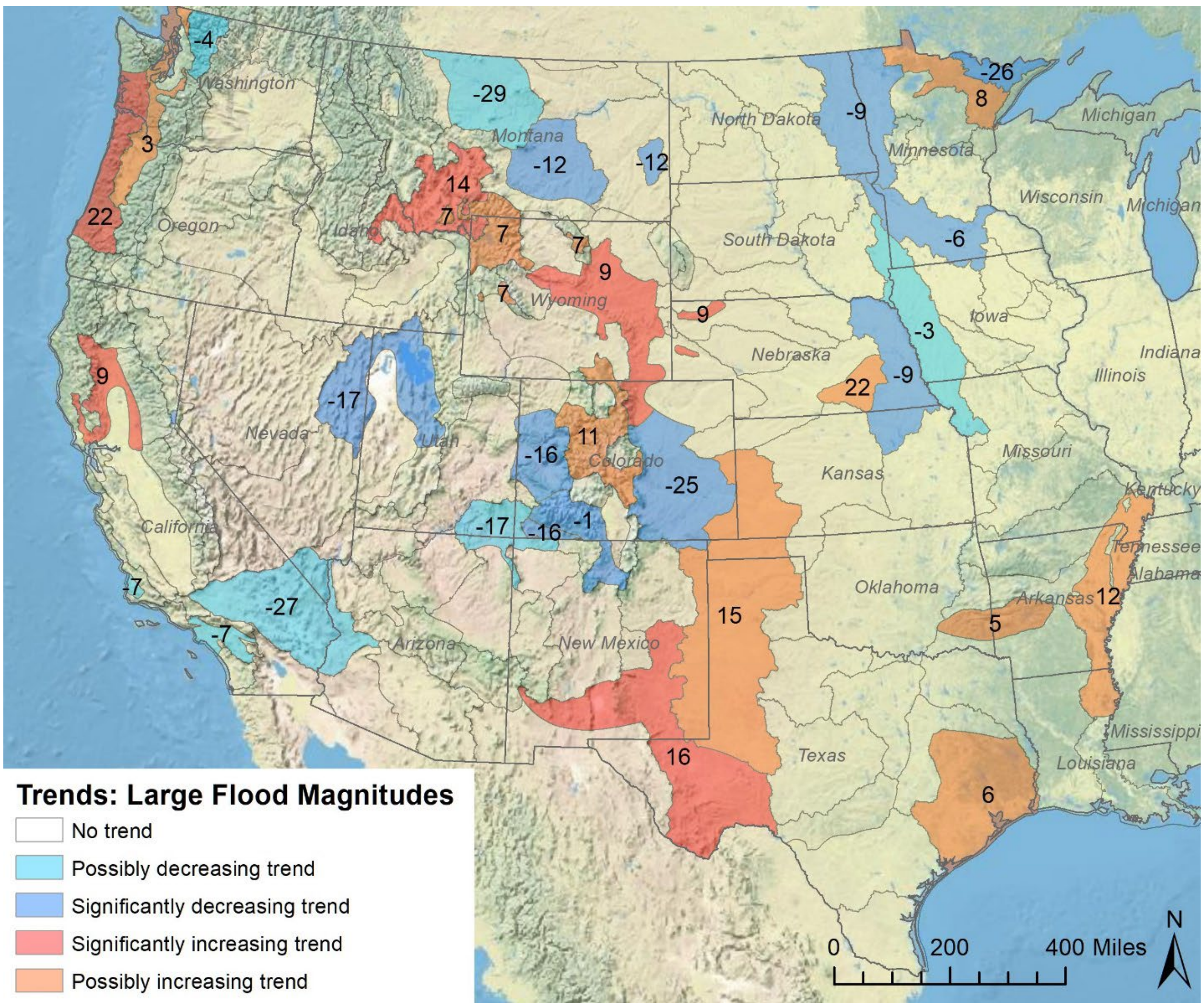


Figure 6: Trends in flood magnitudes (largest 5% of annual peak Q), with % change (start of zone record to ~2020).

experiencing decreasing magnitudes. Generally, floods are increasing or not changing in a band from the Oregon Coast through the Central Rocky Mountains and arcing southeast to the Gulf Coast. Northeast and southwest of this band, floods are generally decreasing or not changing. Decreasing flood magnitudes in the southwest are likely associated with the ongoing megadrought (Williams et al., 2022). Additionally, the preponderance of no trends and decreasing trends in large flood magnitudes (84% of the extent) is likely attributed (in part) to reductions in soil moisture with a warming climate (Liu et al., 2022). This appears to be counteracting the mechanism of increasing water-holding capacity of airmasses as temperatures rise in the lower atmosphere resulting in increasing observed rainfall depths and heavy rainfall events (Peterson et al. 2013). Comparison of the observed percentage change indicates that flood magnitudes vary much more between the 117 zones than over time within each zone – floods vary in magnitude considerably more in space than in time.

Frequency trends were evaluated using both annual peak discharges as well as average daily discharge values, to identify individual flood events. Large flood frequency is increasing in 18 zones (16% of the area extent), while decreasing in 17 zones (13%), for both annual and event analyses (Figure 7). Generally, large floods are becoming more frequent (or are not changing) within and east of the Rocky Mountain Front, and are becoming less frequent (or are not changing) within the Rocky Mountains, Southwest, Great Basin, and West Coast regions.

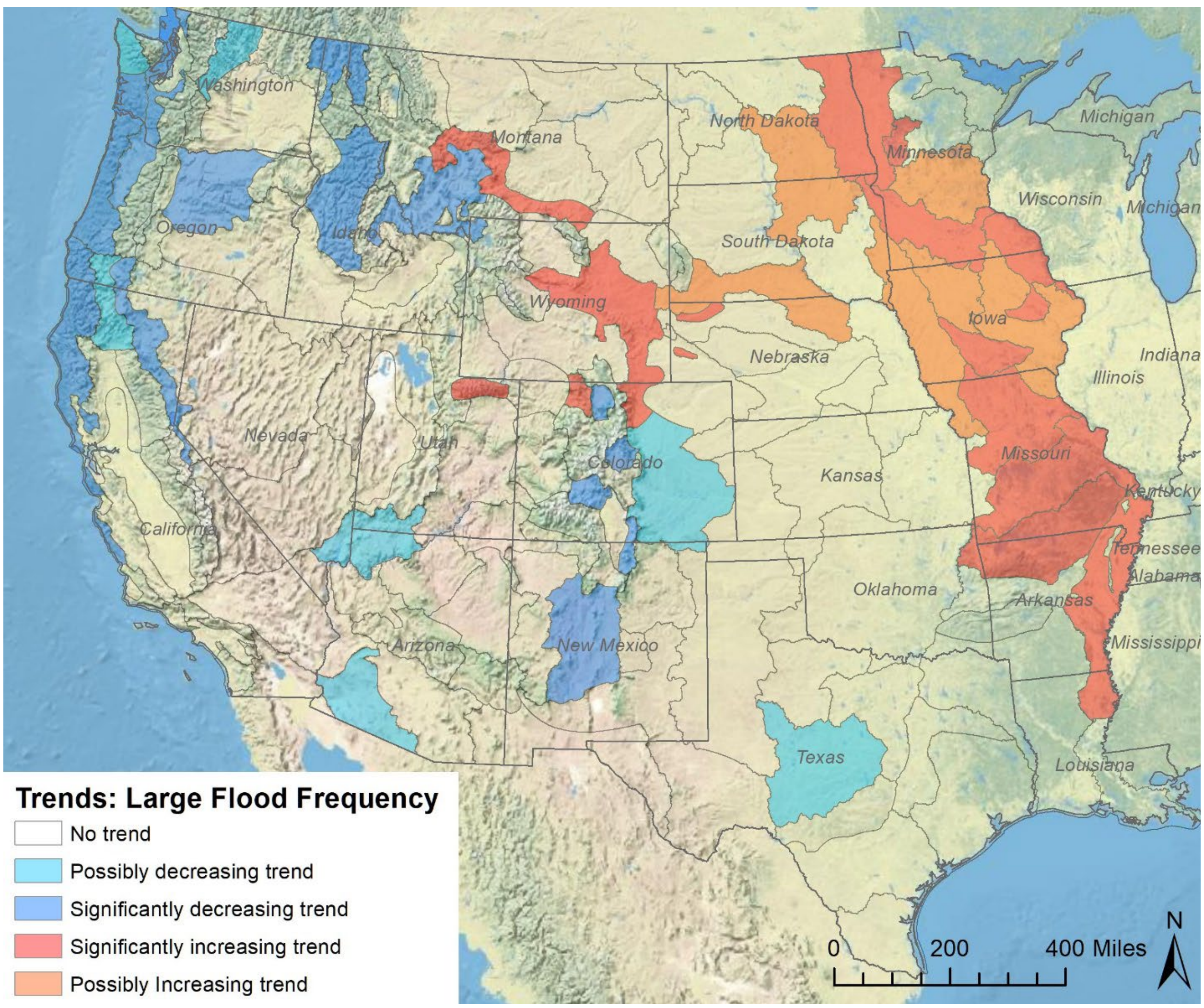


Figure 7: Trends in large flood frequency, including results from annual and event analyses (1945 to ~2020).

Example Applications

The flood potential method provides opportunities to place magnitudes of flooding within the context of what has previously occurred in an area, as measured by the streamgaging network. The ability to systematically assess floods can strategically assist in the development of flood hydrology science by helping to understand if floods are: (1) of a magnitude within the normal variability within an area; (2) if they are extreme and beyond this variability; or (3) if they are unprecedented given the prior streamgaging records. Trend testing and understanding of the hydrology of the area can also provide perspectives on if such floods are an indicator of climate change impacts. Additionally, floods that are prognosticated to possibly occur (as the case with probable maximum flood studies) can be verified for reasonableness. Such assessments can help make infrastructure and floodplain management more resilient, by educating professionals and the public on how an experienced flood compares to what has previously occurred in an area, and informing the prediction of future floods while accounting for observed trends in flooding (non stationarity) and climate change.

Checking Probable Maximum Flood: Spirit Lake at Mount St. Helens

It is standard practice to utilize probable maximum precipitation estimates and rainfall-runoff modeling to estimate probable maximum flood (PMF) magnitudes for the most hazardous structures, such as high hazard dams and nuclear power plants. The occurrence of extreme events (and the highest E_f values) that have been experienced within a flood potential zone can be valuable for checking these PMF estimates for reasonableness.

Consider Spirit Lake at Mount St. Helens, Washington, which was dammed during the 1980 eruption by a landslide blockage across the headwaters of the North Fork Toutle River (Figure 8). The lake level is currently maintained by a tunnel, to prevent a catastrophic failure of this natural dam and a resulting lahar (volcanic mudflow) that would threaten thousands of lives. Seven extreme floods have occurred in this zone 28 (P_f = 18.7), with E_f ranging from 1.65 to 3.19. There are no trends in the observed magnitude or frequency of large floods within the zone, as assessed using the flood potential method. The most extreme flood (E_f = 3.19) occurred on January 20, 1972 for a 8.1 mi^2 watershed (ID 14138900). With an assumption that this event is on the envelope curve, and considering that Q_{efp} = 5800 cfs for the 18.6 mi^2 Spirit Lake watershed, the maximum flood size that the streamgage record indicates as being possible for Spirit Lake is 5800*3.19 = 18,500 cfs. This value is very similar with the computed probable maximum flood size (Q = 20,100 cfs; USACE, 2017) – streamgaging data indicate that the probable maximum flood estimate for Spirit Lake is reasonable.

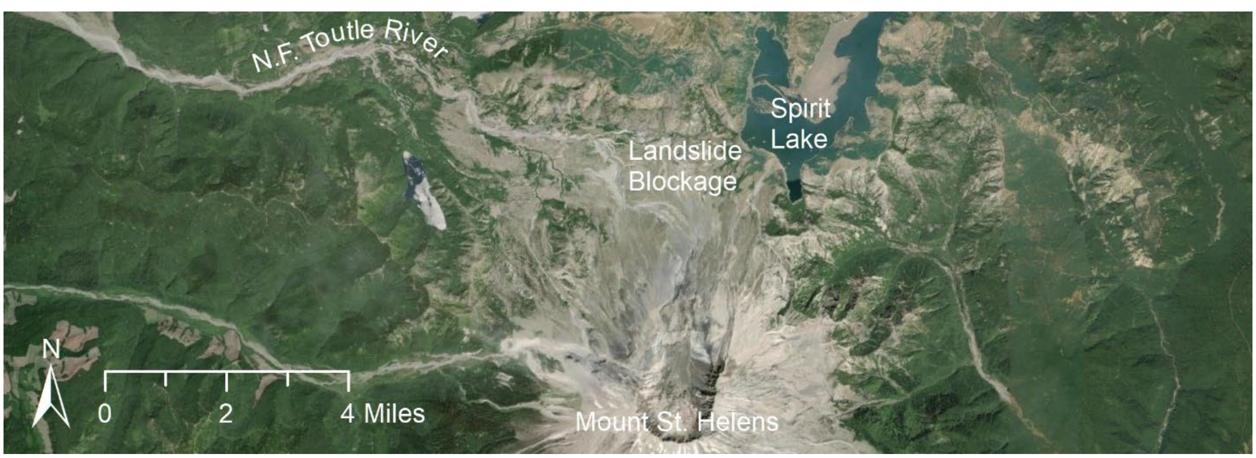
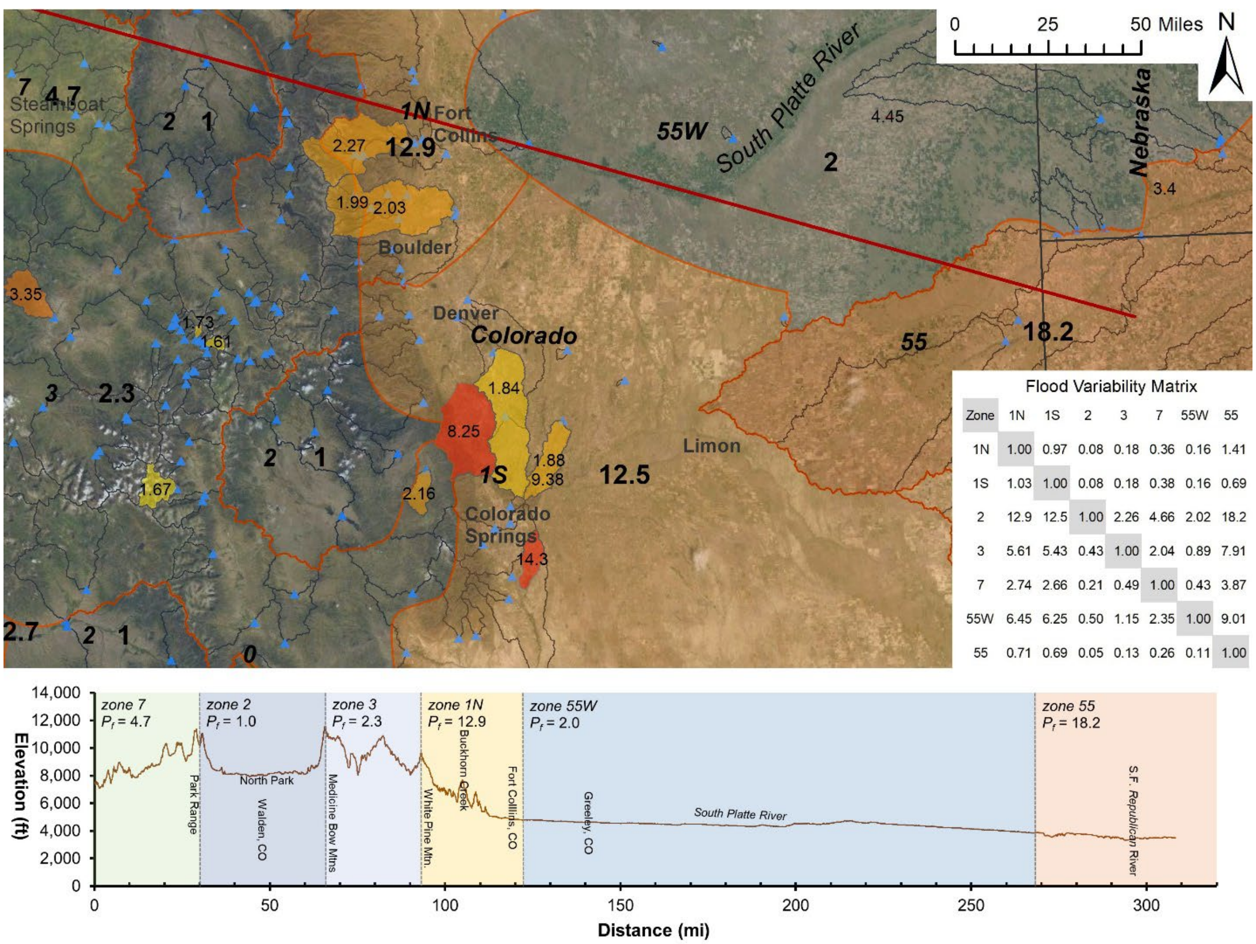


Figure 8: Spirit Lake at Mount St. Helens, Washington, USA.

Assessment: Colorado Front Range and Vicinity

The Colorado Front Range, and adjacent areas of the Southern Rocky Mountains and High Plains, experience flood magnitudes that vary more than an order of magnitude (Figure 9), as quantified by flood potential index values (P_f). The initial slopes of the Rocky Mountains, the Rocky Mountain Front (zone 1N in the cross section), experience larger flood magnitudes, as do the High Plains in Southeast Colorado (zone 1S: P_f = 12.5) and adjacent zones to the east (e.g. zone 55: P_f = 18.2). This area is the western limit of higher flood potential that extends from the Mississippi River across the southern Midwest (Figure 3), that are the result of the advection of Gulf of Mexico moisture northward by synoptic-scale storms and during mesoscale convective rain events. In contrast, the high country of Colorado (zone 3: P_f = 2.3; zone 1N: P_f = 1.0) experiences much lower flood potential, from snowmelt floods. Floods experienced in zone 1N are 12.9 times larger than floods in zone 2 (see matrix). Portions of this area are experiencing trends in large flood magnitudes (Figure 6) and frequency (Figure 7).

Several large flood events have been recorded by the streamgage record, with extreme floods experienced at some locations. These extreme events are ranked using the flood extreme index (E_f, Figure 9). Along the northern portion of the Colorado Front Range (zone 1N), flooding has been catastrophic but less extreme (1976 Big Thompson Flood: E_f = 2.27; 2013: E_f = 2.03). In contrast, the southern portion of the Colorado Front Range (zone 1S) has experienced some of the most extreme floods in the contiguous United States (1935: E_f = 9.38; 1965: E_f = 14.3).



Zone	1N	1S	2	3	7	55W	55
1N	1.00	0.97	0.08	0.18	0.36	0.16	1.41
1S	1.03	1.00	0.08	0.18	0.38	0.16	0.69
2	12.9	12.5	1.00	2.26	4.66	2.02	18.2
3	5.61	5.43	0.43	1.00	2.04	0.89	7.91
7	2.74	2.66	0.21	0.49	1.00	0.43	3.87
55W	6.45	6.25	0.50	1.15	2.35	1.00	9.01
55	0.71	0.69	0.05	0.13	0.26	0.11	1.00

Figure 9: Colorado Front Range and vicinity, illustrating flood potential zones with the utilized streamgages and watersheds. Zone IDs are in italics and flood potential index (P_f) values are in bold. A cross section is provided (red line). Watersheds that have experienced extreme floods are also illustrated, with flood extreme index (E_f) values.

Assessment: Ozarks and the Central Highlands

The Central Highlands of Missouri, Arkansas, and Oklahoma is a region that experiences elevated flood potential (Figure 3). The southern portion of the Central Highlands consist of the Ouachita Mountains (Ouachitas) of Arkansas and Oklahoma, which experiences some of the highest flood potential within the contiguous United States (zone 57: P_f = 62.2). The Ozark Plateaus (Ozarks) consists of two flood potential zones (Figure 10), with the southern Ozarks (zone 59S: P_f = 43.4) experiencing floods, on average, 40% larger than floods in the north (zone 59N: P_f = 30.9). The Central Highlands are experiencing increasing flood severity, with possibly increasing trends in magnitudes in the Ouachitas (Figure 6; 5%) and significantly increasing trends in frequency in the Ozarks (Figure 7).

A large flood event was experienced across the Ozarks in late April of 2017, with extreme flooding having occurred in the North Fork and Big Piney Rivers (E_f = 1.54, 1.51; Figure 10). Other extreme floods have occurred in 1909, 1914, 1945, 1960, 1982, 1993, 2004, and 2011. The most extreme floods have been experienced in the Southern Ozarks along the transition from the Arkansas Valley to the Ozark Plateaus (E_f = 1.88, 3.00).

Descriptions of this 2017 event include phrasing such as "incredible rainfall" and "historic flooding" (NWS, 2017). While this flooding was large-scale, and in some locations catastrophic to stream valley communities, generally it was not unprecedented with similar events experienced in 1915, 1960, 1982, 1985, 1993, 2008, and 2015; the use of sensationalistic language to describe such floods is counterproductive, since it can frame an event inappropriately and lead the public to believe that this magnitude of flooding is unprecedented. In actuality floods of this scale represent a high-mode (in a bimodal population of annual peak discharges) that has repeatedly occurred in the past and should be expected in the future, with increasing frequency that may be the result of climate change.

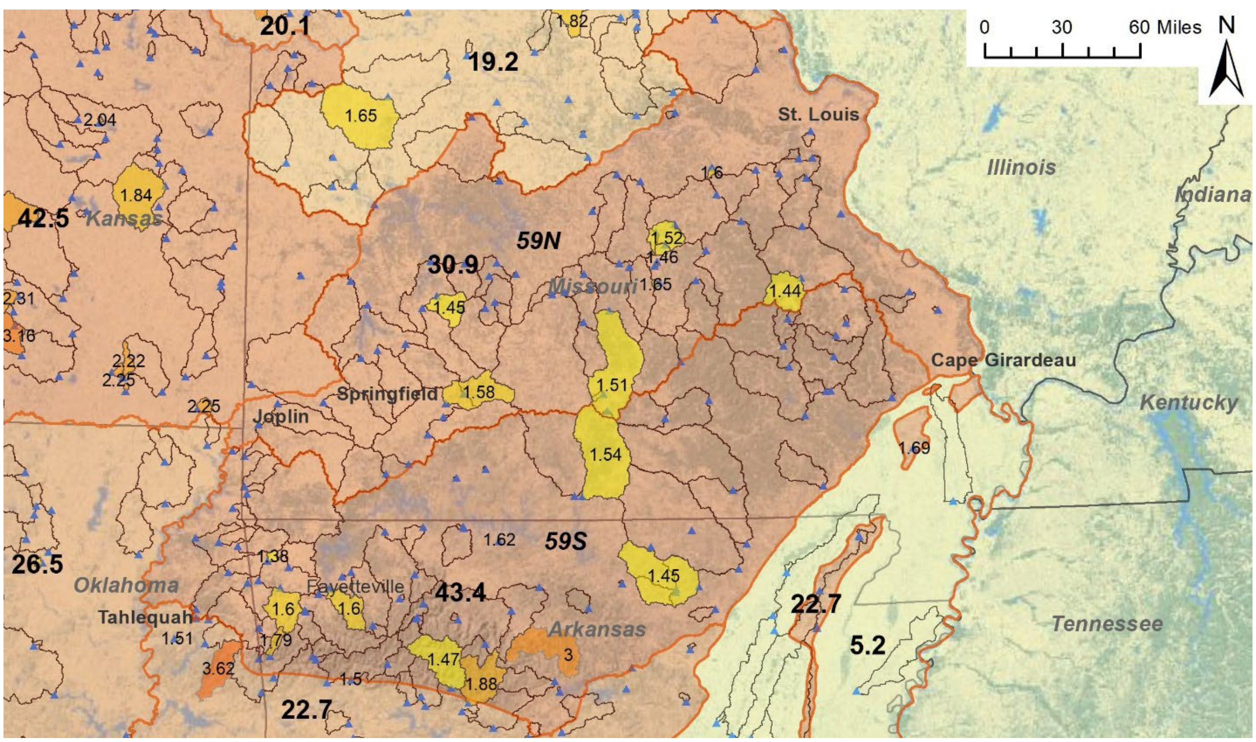


Figure 10: Ozark Plateaus (Ozarks) and vicinity, illustrating flood potential zones with the utilized streamgages and watersheds. Zone IDs are in italics and flood potential index (P_f) values are in bold. Watersheds that have experienced extreme floods are also illustrated, with flood extreme index (E_f) values.

Properly accounting for the high flood potential in the Ozarks can be problematic for streamgages that have not yet experienced a high-mode flood that neighboring watersheds indicate as being expected. Consider the Eleven Point River, Missouri, with two analyses performed: (1) using data up to 2016; and (2), using these data as well as the 2017 event.

The Eleven Point River streamgage (ID: 07071500), in zone 59S, had 96 years of data through 2016 with a maximum recorded discharge of 49,800 cfs (12/30/1982). Using standard procedures (IACWD, 1982; England et al., 2018), a logPearson frequency analysis in analysis (1) yields Q_{100} = 66,000 cfs; with 96 years of record and the tradition in flood hydrology to assume that streamgage data at a site with a long record is most valuable for selecting design flood discharges near a streamgage, infrastructure designs would have likely utilized this as a design flood discharge. However, the flood potential method using data from this same period provides a different perspective – with Q_{efp} = 142,000 cfs for this site (more than twice the Q_{100}), it is clear that this watershed had experienced substantially lesser magnitude floods than neighboring watersheds (in zone 59S). Either this watershed was unique when compared to its neighbors, or a much larger flood could have been expected.

When a large storm system impacted the Ozarks in March 2017, this streamgage experienced a flood of 122,000 cfs, a value similar to the expected flood potential discharge. Inclusion of the high 2017 value within the second logPearson analysis increases the Q_{100} (76,800 cfs), but still underestimates flood risk due to the Pearson distribution apparently not accounting for bimodal flood regimes with a long period dataset (100 years). The flood potential method is valuable for informing the selection of the most appropriate design flood discharges for such circumstances.

Assessment: Oroville Dam Flood of 2017

Trends in large flood magnitudes and frequency are typically not increasing in California, as computed from data collected prior to 2022 (Figure 6; Figure 7). The finding that floods are generally not changing or are becoming less severe in California can conflict with societal perspectives. For example, in February of 2017 the Oroville flood threatened the tallest dam within the United States, with coverage in the news media suggesting that this event was the result of climate change. Discharge at the streamgage downstream of the dam (ID: 11407000) peaked at 112,000 cfs on February 13. While substantial, this flood magnitude was only the 16^{th} largest in 116 years of record. This site, with its 3600 mi^2 drainage area, has a Q_{efp} = 249,000 cfs. This is the peak discharge expected at this location given the long record of previous floods, regardless of climate change. Oroville Dam can be expected to experience very large magnitude floods, with 46 percent of its area in a zone with a high flood potential index (zone 23N; P_f = 24.3) and a high watershed scale ratio (R_f = 1.57).

Storage by Lake Oroville reduces flood peaks substantially, complicating the analysis; to better understand the relative magnitude of the 2017 flood, analyses at streamgages upstream of the reservoir are helpful. Specifically, two mainstem streamgages (ID: 11404500, 11396200) within the reservoir's watershed experienced floods with E_f = 0.60 and 0.65 (60% and 65% of the Q_{efp}), respectively. Considering this, the 2017 event at Oroville was not unexpected in flood magnitude (since $Q < Q_{efp}$) – this event was not an indicator of increasing large flood peak discharges. Since this averted catastrophe was not caused by extreme or even expected flood peak magnitudes, but rather a discharge less than expected given the history of flooding in this portion of the Sierra Nevada Mountains, the flood potential analyses suggests that the Oroville Dam situation did not arise from an unexpected act of nature.

Assessment: Yellowstone Region Floods of 2022

The region in the vicinity of Yellowstone National Park experienced a large flood event in June of 2022, with catastrophic impacts on infrastructure and communities (Figure 11), primarily in the northern portion of the Park and in adjacent areas of Montana. This flooding was in response to an atmospheric river event that produced up to 5 inches of rain and nearly 5 inches of snow melt equivalent, or at least 4 to 9 inches overall, as a rain-on-snow event (NWS, 2022). This flooding was reported in the media as “unprecedented” and “caused by climate change.” Given analyses performed using the flood potential method, are such assertions accurate?

Figure 11: Impacts of June 2022 flooding on East Rosebud Creek on the Custer National Forest.

The areas most impacted by this event include portions of zone 46 (Figure 5; Central Rocky Mountains) and downstream in adjacent zone 48 (Great Plains Transition). Zone 44 (Orographic Sheltered, Northern Rockies) may have also been impacted by this flooding. Generally, these zones have lower flood potential than most of the western United States, though zone 46 does experience somewhat higher flood potential than much of the Rocky Mountains. Zone 46 experiences floods with P_f = 3.8 (33rd percentile) and R_f = 1.01 (65th percentile); 2/3’s of the zones in the West experience larger flood magnitudes, through larger watersheds in zone 46 tend to experience relatively larger floods.

Much of the Yellowstone Region is experiencing more severe large floods; flood potential analyses (performed prior to this event) indicate that large floods are possibly increasing in magnitude in zone 46 (+7% increase; Figure 6), with zone 44 experiencing a significantly increasing trend in flood magnitudes (+14% increase). Transition zone 48 is experiencing a significantly increasing trends in (annual) flood frequency (Figure 7). These trends appear to be part of a larger pattern of large floods increasing in severity (or not changing) along and to the east of the Rocky Mountain Front.

Peak flow values from the June 2022 event can be placed within historical context using the flood potential method. As of November 2022, the U.S. Geological Survey had not yet provided peak flow values for the event; preliminary values were compared to the existing flood potential analysis (using data through 2018). These 2022 flood magnitudes were unprecedented (record values) at several streamgages, however flood magnitudes were generally within the variability in floods recorded from 1906 to present (Figure 12). From a zone perspective, this event produced flood magnitudes that were large but within the previously-determined variability identified for this area. At least three watersheds experienced peak flood magnitudes that were extreme (Figure 13), with these floods on the upper end of the range of variability and of a similar scale to extreme flooding that occurred in 1955, 1963, and 1996, and less extreme than a flood that occurred in 1945. From this perspective, the 2022 event impacted an unusually large aerial extent, and was extreme in places, but was not unprecedented.

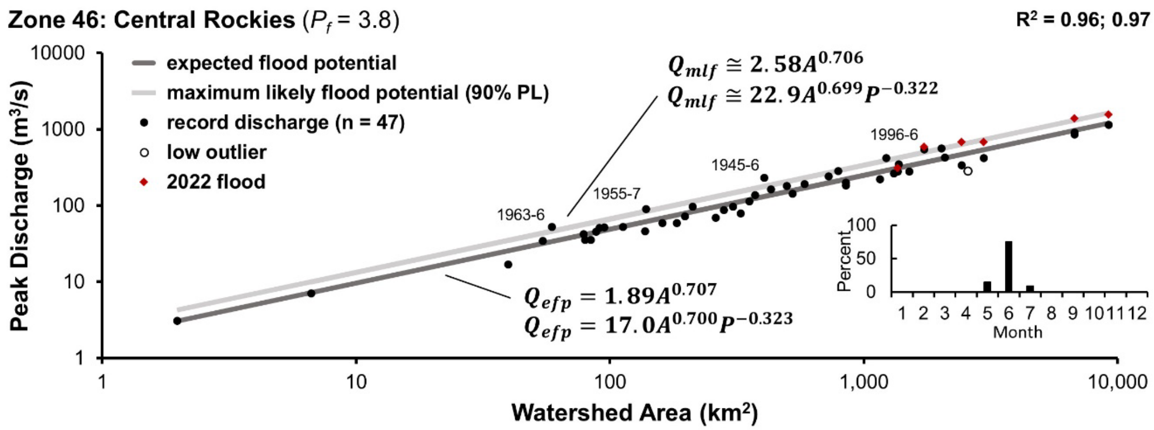


Figure 12: Flood potential and seasonality plots for zone 46, including preliminary 2022 flood peaks (red triangles).

The impacts of the Yellowstone Region Floods of 2022 were clearly catastrophic to the communities and infrastructure in the path of the floodwaters, with the flood potential analysis indicating some extreme flooding. However, these flood magnitudes were not unprecedented considering the historical record of flooding as measured by the streamgaging network. Instead, this event was at the upper end of the range of variability of large floods, at a larger spatial scale than what has previously been measured, and in a zone that had already been experiencing increasing flood magnitudes. Due to the increasing trends and the large spatial scale (and a lack of alternative hydrologic mechanisms), this event may likely be a consequence of increasing flood severity from climate change.

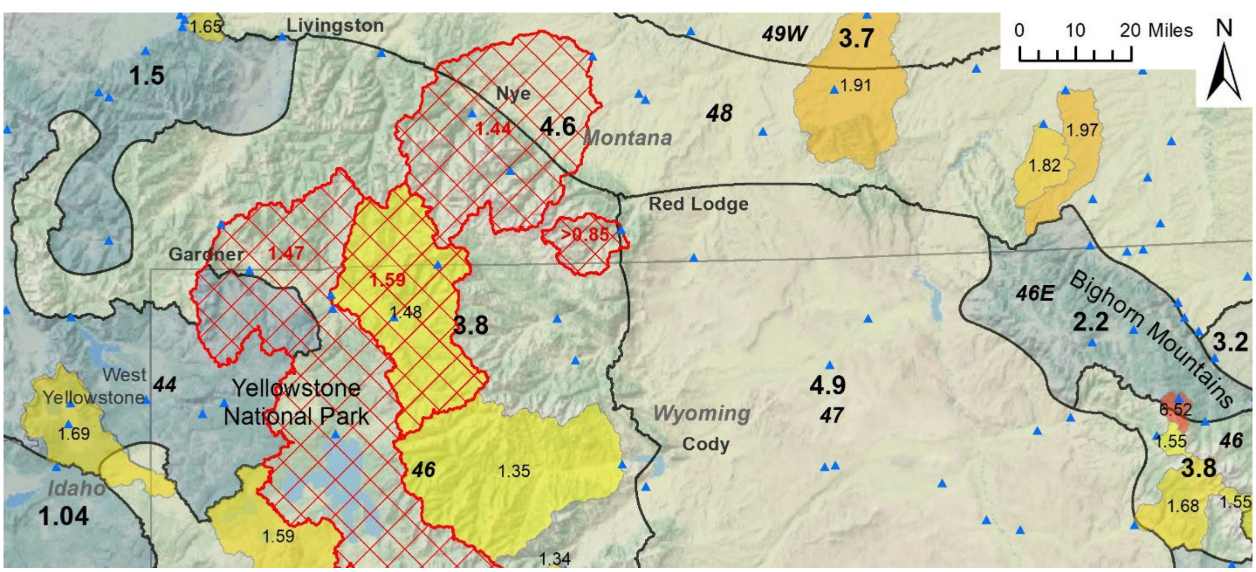


Figure 13: Yellowstone region floods, with watersheds that experienced extreme magnitudes (red cross hatched). Zone boundaries are provide (in black), with IDs in italics and flood potential index (P_f) values in bold, and utilized streamgages marked as blue triangles. Extreme watersheds are shown with extreme index (E_f) values.

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