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Flood Potential Assessment: Mark Twain National Forest and the Ozarks and Ouachitas

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SUMMARY

Flood risk was assessed for the U.S. Interior Highlands of the Ozarks and the Ouachitas, on the Mark Twain, Ozark & St. Francis, and Ouachita National Forests. Due to higher watershed elevations and gradients, and relatively close proximity to the Gulf of Mexico, this region experiences flooding with unique characteristics compared to other areas of the Midwest. The flood potential method was used in the assessment. This approach identifies the central tendency of large flood magnitudes, the maximum flood sizes that can reasonably be expected, and extreme events. The assessment area is composed of four flood potential zones that are defined through regressions with high explained variances.

Floods magnitudes generally increase from north to south in the assessment area, with floods in the southern Ozarks on the southern Mark Twain and the Ozark & St. Francis National Forests being 40% larger than floods on most of the northern Mark Twain. Flood magnitude decreases in the Arkansas Valley, to about half the size of floods in the southern Ozarks. The Ouachitas experience some of the largest floods in the United States west of the Mississippi River (44% larger than the southern Ozarks), with only the southeast Edwards Plateau of Texas experiencing larger floods – the Ouachita National Forest may have the highest flood potential of all the National Forests in the continental United States. Floods occur in almost every month of the year, though have dominant seasons (8 to 21 times more frequent than months with less common floods) during three seasons in the north (spring, late summer, and early winter), two seasons in the central portion of the analysis extent (spring and early winter), and primarily during two months in the south (May and December). Across the Mark Twain National Forest, and the Ozark & St. Francis National Forests, floods are not increasing in magnitude but are (or are likely) increasing in frequency. **For effective management of these National Forest System lands, management strategies that account for an increased frequency in the occurrence of large floods are warranted.** On the Ouachita National Forest, floods may be increasing in magnitude but are not increasing in occurrence frequency. Major flooding events are summarized in this assessment, including the 2017 flood in the northern and central Ozarks, as well as numerous other events of similar or larger magnitudes.

A detailed example is provided for the Mark Twain National Forest, to provide a logical process for quantifying flood design magnitudes for two hypothetical stream valley infrastructure projects. The high flood potential in this area and increasing frequency of large flood events is taxing stream valley infrastructure and dated hydraulic structures; this example illustrates best methods for sizing replacements.

The Flood Potential Portal is being developed to serve the results of the flood potential method alongside the results of traditional flood-frequency methods, to provide a “one-stop shop” for understanding and communicating about flood variability and trends across the United States, and to provide flood magnitude predictions at points of interest for infrastructure design.

INTRODUCTION

Flood risk is detailed for the U.S. Interior Highlands of the Ozarks and the Ouachitas of Southern Missouri, Northwest Arkansas, and Eastern Oklahoma. Due to its relatively higher watershed elevations and gradients, this area experiences unique flooding characteristics compared to bordering areas of the Midwest. This flood risk assessment focuses on the Mark Twain National Forest for use in the Mark Twain Recreation Vulnerability Assessment, but also includes information on adjacent areas, for use by other National Forests (Ozark & St. Francis, and Ouachita), and to place within regional context flooding experienced on the Mark Twain.

The flood potential method (Yochum et al., 2019; Yochum, 2019) was utilized as a framework for understanding flood risk. This method provides the status of large floods, with variability in large flood magnitudes, flashiness, and seasonality, systematically identifies extreme floods, and identifies trends in the magnitude and frequency of experienced floods due to such non-stationary mechanisms as climate change.

This assessment presents the results of the flood potential analyses and provides interpretations for the National Forests. The body of the report is composed of presentations of the flood potential zones, seasonality, major flood events, trends in flooding, flood magnitude prediction, an example application for two rivers on the Mark Twain National Forest, and an introduction to the Flood Potential Portal. Fundamental results and interpretations are provided in the body of the report, while additional details and supporting documentation on the methods are presented in Appendix A. A glossary of terms is provided in Appendix B.

FLOOD POTENIAL ZONES

The flood potential method quantifies the central tendency of large flood magnitudes across zones of similar flood response. This is the *expected flood potential*. Through comparison with streamgaged watersheds across the zone, floods of this size can be expected to occur at a stream valley point of interest, which makes this estimate valuable for floodplain management and infrastructure design.

The Ozarks region is composed of four flood potential zones, with an adjacent 5th zone provided for comparison purposes (Figure 1). The magnitude, seasonality, and trends of experienced (and expected) floods vary between each zone. The flood potential plots for these zones are provided as Figures A-1 through A-5, with a comparison of the expected flood potential regressions illustrated in Figure 2. In these figures, the regression line is the *expected flood potential*, and the 90% prediction limit is the *maximum likely flood potential*. Floods greater than the maximum likely flood potential are quantitatively defined as extreme, with the departure above this limit indicating the degree of extremity.

Each zone has flood potential plots that vary in magnitudes and slopes (larger watersheds having relatively larger or smaller flood response during a large flood event), with these characteristics quantified by indices. The flood potential models have high explained variances, with R^2 ranging from 0.94 to 0.97 (Table 1). Indices comparing flooding characteristics between the zones are provided in Table A-1. The most important is the *flood potential index* (P_f), a summary index that compares flood magnitudes to a low flood potential reference zone (2), and facilitates comparisons between any zones.

Table 1: Flood potential model summary for the Ozarks region. R^2 = explained variance; n = number of streamgages included model.

Zone	Second Predictor	R^2	*n*
59N	ave. annual precipitation	0.97	62
59S	none	0.97	85
58	none	0.97	41
57	none	0.97	30
56W	dominant aspect	0.94	32

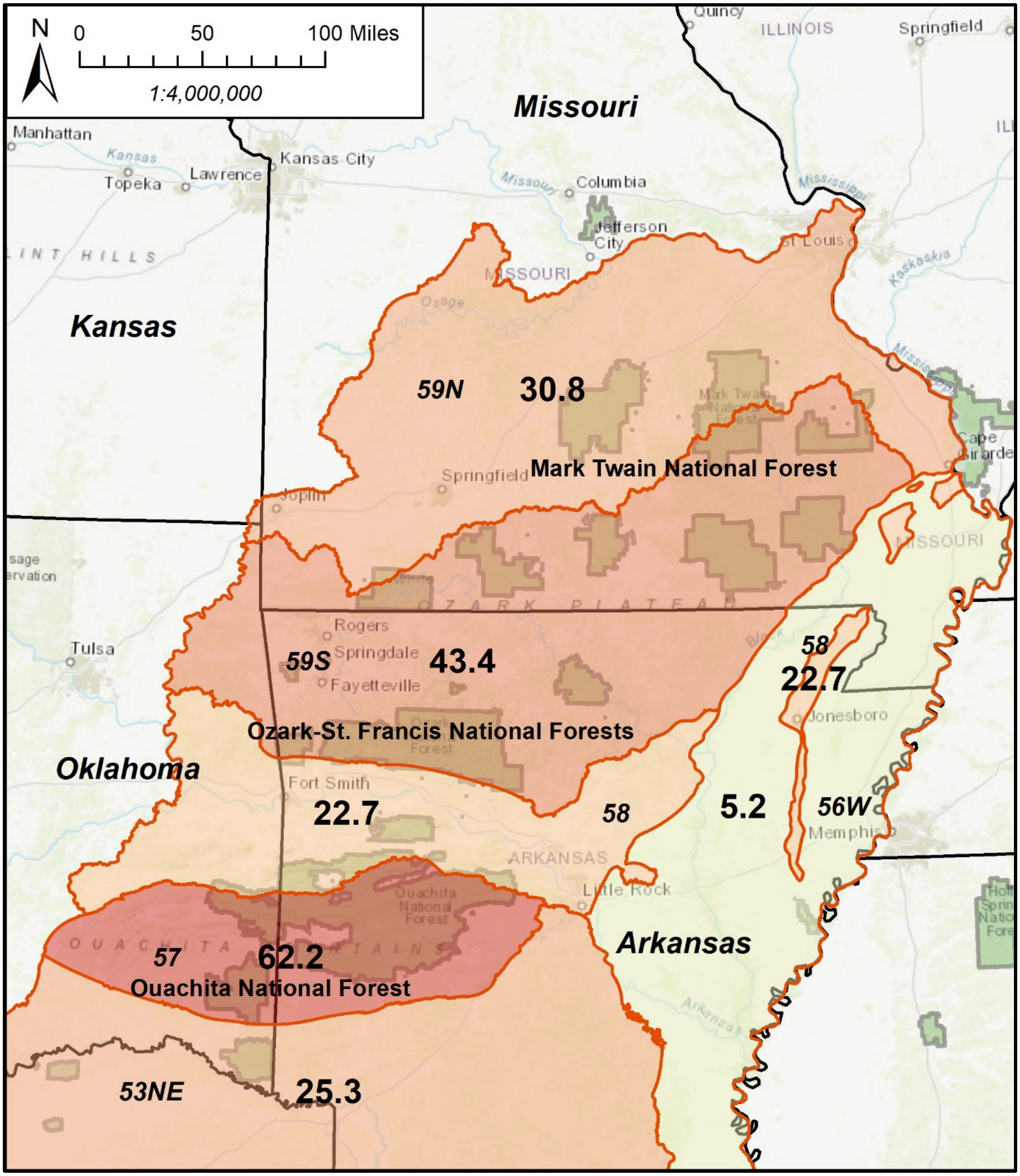

Figure 1: Flood potential zones for the Ozarks, Ouachitas, and adjacent areas, on the Mark Twain, Ozark-St. Francis, and Ouachita National Forests. The zone labels include the zone IDs (smaller, italics) and the flood potential index values (larger). Zone 57 (Ouachitas) has one of the highest flood potentials (flood magnitudes) in the continental United States, with the Southern Ozarks (zone 59S) experiencing floods on average 30% smaller, and the Northern Ozarks (zone 59N) experiencing floods on average 50% smaller. The Lower Mississippi Alluvial Plain (zone 56W) experiences floods with magnitudes, on average, of only 12% the magnitude of the Southern Ozarks and 8% of the Ouachitas.

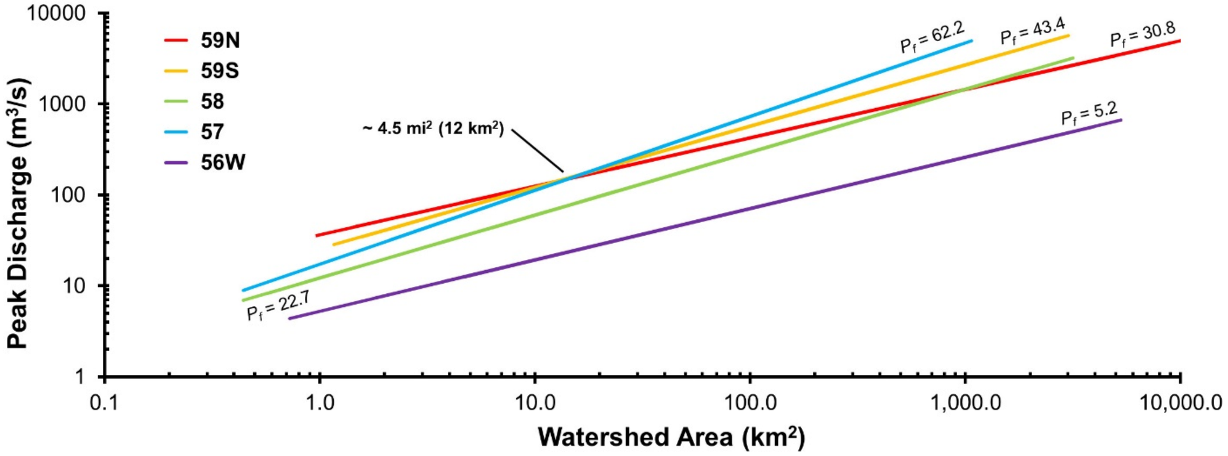

Figure 2: Comparative flood potential plots for zones 59N (Ozarks, North), 59S (Ozarks, South), 58 (Ozarks Transition), 57 (Ouachita Mountains), and 56W (Lower Mississippi Alluvial Plains, West).

Northern Areas

Most of the northern portion of the Mark Twain National Forest is in zone 59N (Ozarks, North; Figure 1), a flood potential zone that stretches from the far northeastern corner of Oklahoma to St. Louis, Missouri. Higher flood potential index (P_f) values indicate greater experienced flood magnitudes across the zone. With $P_f = 30.8$, this zone has lower flood potential than areas to the south, but still has higher flood potential than most zones west of the Mississippi River. And for watersheds <4.5 mi^2, zone 59N experiences the largest flood magnitudes (Figure 2). Zone 59N experiences moderate to low flashiness ($F = 0.78$), with low variability (in space and time) in large flood magnitudes ($V_f = 1.41$).

The southern portion of the Mark Twain National Forest and most of the Ozark-St. Francis National Forests experience the same flood potential, in zone 59S (Ozarks, South). This zone, which stretches from Tahlequah, Oklahoma to Farmington, Missouri, has a $P_f = 43.4$; floods in this zone are substantially larger, on average than in the north. Specifically, large floods in zone 59S are 43.4/30.8 = 1.4 times larger than floods in zone 59N (Table 2). Interestingly, in smaller watersheds (<4.5 mi^2), floods in 59S are smaller than in 59N, but in larger watersheds (>4.5 mi2) floods tend to be substantially larger in zone 59S than 59N, as indicated by the different slopes of the flood potential plots in Figure 2. Zone 59S experiences moderate flashiness ($F = 0.85$), with low variability in large flood magnitudes ($V_f = 1.38$).

Table 2: Matrix comparing the variability of flood magnitudes across the region of interest, through utilization of the flood potential index (P_f). Zone boundaries are shown in Figure 1. Example: $P_{f,57}/P_{f,59N} = 62.6/30.8 = 2.03$: large floods are, on average, a bit more than twice the magnitude in the Ouachitas than in the northern Ozarks.

Zone	**59N**	**59S**	**58**	**57**	**56W**
59N	1.00	1.41	0.74	2.03	0.17
59S	0.71	1.00	0.52	1.44	0.12
58	1.35	1.91	1.00	2.76	0.23
57	0.49	0.69	0.36	1.00	0.08
56W	5.92	8.35	4.37	12.0	1.00

The boundary between zones 59N and 59S is primarily composed of watershed boundaries between river basins, with rivers in 59N (Meramec, Gasconade, and Osage) flowing predominantly to the northeast and rivers in 59S (St. Francis, Black, Current, Eleven Point, Strawberry, and White) predominantly flowing to the southeast. However, the Current River is special in that its headwaters (upstream of Jacks Fork) are in zone 59N and experience 29% smaller flood magnitudes than the remainder of the basin. The James River, a tributary to the White, also crosses over the zone boundary.

The small unit of the Mark Twain National Forest between Columbia and Jefferson City is in zone 61 (Disected Till Plains), with the analysis of this zone not yet complete. With a preliminary P_f = 18.9; this zone experiences flood magnitudes that are, on average, 61% of the flood magnitudes in zone 59N and 44% of the flood magnitudes in zone 59S, on the southern portion of the Forest. Flood magnitudes, hence, vary substantially across three flood potential zones on the Mark Twain National Forest, with floods in the south being 2.3 times larger than in the north.

Southern Areas

The southern-most unit of the Ozark-St. Francis National Forests, southeast of Paris, Arkansas, as well as the northern edge of the Ouachita National Forest in the vicinity of Waldron, Arkansas, is in zone 58 (Ozarks Transition; Figure 1). This lower flood potential zone (P_f = 22.7) is primarily composed of the Arkansas River Valley between the Ozarks and the Ouachitas, but also includes a few isolated higher relief landforms in the Mississippi Alluvial Plain (zone 56W), such as Crowley's Ridge. This zone primarily extends from Muskogee, Oklahoma to Little Rock, Arkansas. Zone 58 experiences moderate to low flashiness (F = 0.76), with low variability in large flood magnitudes (V_f = 1.48).

Most of the Ouachita National Forest is in zone 57 (Ouachita Mountains). This zone (P_f = 62.2) has one of the highest flood potentials west of the Mississippi River, with only the Southeast Edwards Plateau of Texas having a higher flood potential (P_f = 70.1). West of Texas and the Southwest Transition zone (13), the highest flood potentials are in the Los Angeles Ranges (P_f = 47.4), the California Coast Ranges and western Klamath of Oregon (P_f = 31.2), the western Olympics (P_f = 31.2) and the Northwest Cascades (P_f = 25.5) of Washington, the northern Sierra Nevada of California (P_f = 24.3) and the southeast Black Hills of South Dakota (P_f = 22.2). In comparison, the Ouachitas experience floods between 1.3 and 2.8 times larger than these high flood potential zones to the west. Zone 57 experiences moderate to low flashiness (F = 0.76), with moderate variability in large flood magnitudes (V_f = 1.51).

Adjacent zone 56W (Lower Mississippi Alluvial Plain, West; Figure 2) is also provided in this assessment, for comparison. This zone experiences low flood potential (P_f = 5.2), with floods in the Ouachitas being, on average, 12 times larger (Table 2). Zone 56W experiences very low flashiness (F = 0.46), with moderate variability in large flood magnitudes (V_f = 1.75).

FLOOD SEASONALITY

The seasonality of large floods was quantified using the largest 5% floods in the streamgage record. These results are provided in plots imbedded in Figures A-1 through A-5, as well as in Figure 3 through Figure 6.

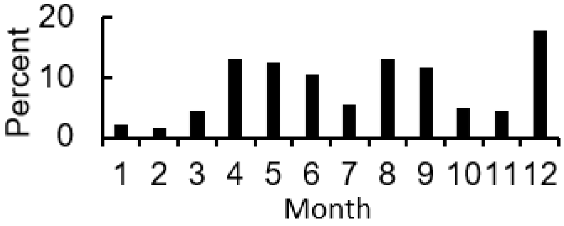

Figure 3: Large flood seasonality for zone 59N.

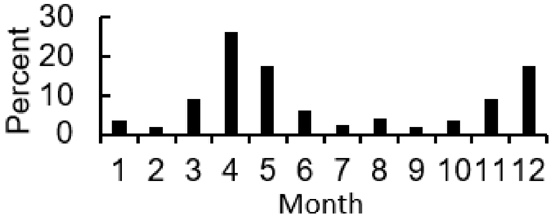

Figure 4: Large flood seasonality for zone 59S.

Northern Areas

In both zones 59N (Ozarks, North) and 59S (Ozarks, South) large floods occur any month of the year. However, there are seasons when large floods are much more frequent. In zone 59N (Figure 3), floods occur preferentially during three seasons, during the early winter (December), Spring (April, May, June) and late Summer (August and September), with floods in these months occurring 8 to 13 times more frequently than in February, the month with the least frequency. In zone 59S, however, floods primarily occur during two seasons (Figure 4), during spring (April and May) and early winter (December) without a prevalent summer season. Floods during the peak months in 59S occur 11 to 16 times more frequently than in February.

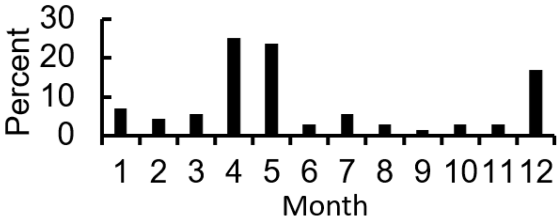

Figure 5: Large flood seasonality for zone 58.

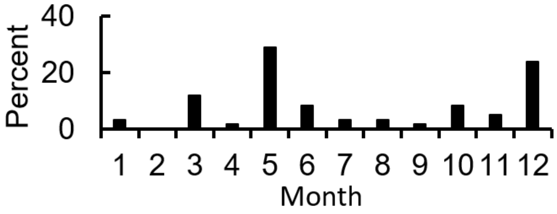

Figure 6: Large flood seasonality for zone 57.

Southern Areas

Floods in zone 58 (Ozarks Transition; Figure 5) occur every month of the year with a similar seasonality as zone 59S, though with an even lesser prevalence of large floods during the late summer. Floods in the spring (April and May) and early winter (December) occur 12 to 18 times more frequently than in September, the month with the least frequency. In zone 57 (Ouachita Mountains; Figure 6), large floods occur in all months except February, with April floods being much less common than those in the Ozarks to the north. Floods primarily occur in spring (May) and early winter (December), and occur 14 to 21 times more frequently than in September.

Floods in zone 56W (Lower Mississippi River Alluvial Plain, West; Figure A-5) occur most frequently during the winter and spring, with 78 percent of the events occurring from January through May.

MAJOR FLOOD EVENTS

Major floods are large, but are frequently not extreme as quantified by the flood potential method. This practice contrasts with the common, less systematic use of the word “extreme” to essentially describe all large floods. It is important to make a distinction; large floods are most frequently of a scale that streamgage records indicate as being of an expected magnitude, with less than 10% being sufficiently large to be considered extreme and unlikely.

The flood potential method provides a systematic approach for identifying and ranking extreme floods within each zone (see Appendix A). This approach is used throughout this section, to present flood risk in a consistent zone-relative manner. Systematic and historic streamgage data were used in this analysis. Paleofloods have not been included to extend the periods of record, though previous work has utilized such data in flood potential analyses (Yochum et al., 2019). Major floods refers to extensive events that induced a top 5% discharge for a number of streamgages (with the record peak discharges represented in the flood potential plots in Figures A-1 through A-5), and may or may not have watersheds that experienced extreme flooding.

The flood extreme index (E_f) is used throughout this section (and the TRENDS in FLOODING section), to quantify relative flood magnitudes. See Appendix A for details on this index. This section is technical and detailed; such a level of detail is needed to systematically describe the major floods that have been experienced across this region.

Flood of up to 244,000 cfs have been recorded within this area of interest. This specific flood discharge was recorded on the Spring River at Imboden, Arkansas (USGS ID: 07069500) on 12/3/1982, in zone 59S. This flood is not extreme (E_f = 1.22: 22% larger than the expected flood potential discharge), due to the relatively large watershed size (1160 mi^2) and the scale of typical large floods experienced across zone 59S (Figure 2; Figure A-2). However, an extreme flood did occur on the Middle Fork of the Little Red River at Shirley, Arkansas (USGS ID: 07075000) on this same date. This peak discharge was 241,000 cfs (E_f = 3.0), from a 301 mi^2 watershed. Both of these large floods occurred in the southeastern portion of zone 59S, on the southeastern edge of the Ozarks as this higher relief emerges from the adjacent Mississippi River alluvial plain and Arkansas River Valley areas.

The flood potential plots of Figures A-1 through A-5 show extreme events as points with labeled years and months. These plots allow readers to place within context the scale of each extreme flood to the expected flood potential and maximum likely flood potential predictions, to compare each event with the central tendency and 90% prediction limit of the record peak discharges.

Extreme floods are illustrated in Figure 7 for the area of interest. The labeled values and coloring indicate E_f values, with higher index values (and warmer colors) indicating that a flood is more extreme relative to its zone. These watershed polygons correspond to the labeled points provided in Figures A-1 through A-5.

With E_f typically less than 2, floods are generally less extreme in this region than many other areas in the United States. For example, in zone 53NE (West Gulf Coastal Plain, Northeast) the adjacent zone to the south of the Ouachitas, two floods have been experienced in small watersheds with E_f > 4 (4.46, 5.75); these floods were more than 4 times the expected flood potential discharge. Further afield, in zone 1S (Eastern Slopes and Great Plains, South) in the vicinity of Colorado Springs, Colorado, floods have been documented with E_f = 8.1 (Plum Creek, 154,000 cfs from a 303 mi^2 watershed in June 1965) and E_f = 15.2 (Jimmy Camp Creek, 124,000 cfs from a 65 mi^2 watershed in June 1965). The most extreme floods documented to have occurred West of the Mississippi River occurred on the Columbia Plateau (zone 30) of north-central Oregon, with experienced E_f = 34.7 (Balm Fork, 36,000 cfs from a 26 mi^2 watershed in June 1903) and E_f = 35.1 (5220 cfs from a 1.36 mi^2 watershed in June 1948); these streams experienced floods 35 times the expected flood potential discharge! All of these zones have less flood potential than the area of interest (P_f = 25.3 in zone 53NE; P_f = 12.6 in zone 1S; P_f = 2.8 in zone 30). Instead, floods are

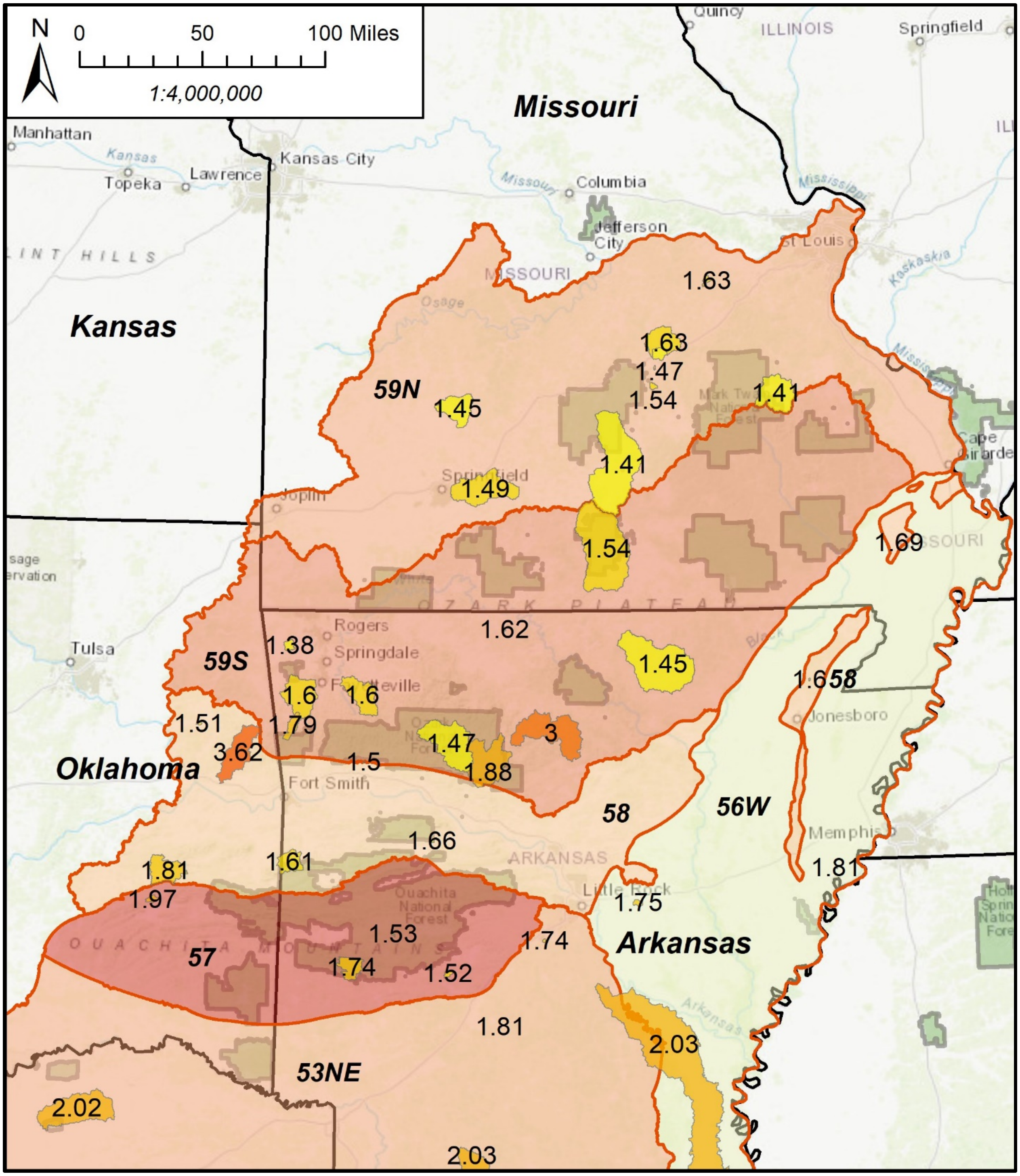

Figure 7: Extreme floods that have occurred in the Ozarks, Ouachitas, and adjacent areas, on and in the vicinity of the Mark Twain, Ozark-St. Francis, and Ouachita National Forests. The flood potential zones are labeled in italics. Flood extreme index values (E_f) for all the measured extreme floods are labeled. The two most extreme floods occurred along the southern edge of the Ozarks, on the southern half of zone 59S and the northern edge of zone 58. These floods occurred on the Middle Fork of the Little Red River, Arkansas, on 12/3/1962 (241,000 cfs = 6820 cms; E_f = 3.00), and on Sallisaw Creek, Oklahoma, on 4/15/1945 (110,000 cfs = 3120 cms; E_f = 3.62).

generally large in the Ozarks and Ouachitas, with low variability (Table A-1) and high flood potential, and regularly-experienced large flood magnitudes.

Northern Areas

Major floods that have occurred in zone 59N (Ozarks, North), on most of the northern portion of the Mark Twain National Forest, include events in 1897 (January), 1915 (August), 1945 (June), 1958 (July), 1982 (August), 1993 (September and November), 2008 (September), 2015 (December), and 2017 (late April & early May). The largest flood in this zone (Q = 197,000 cfs) occurred on the Gasconade River on 5/1/2017. This was not an extreme flood (E_f = 1.32), though it was 32% larger than the expected flood magnitude for this streamgage (USGS ID: 06933500) and close to the threshold for being extreme in this zone. Large flood events have occurred consistently throughout the streamgage record, from 1897 to present; these events were all incorporated into the flood potential plot of Figure A-1.

Extreme floods that have occurred in zone 59N are provided in Table 3 and Figure 7, with E_f ranging from 1.63 to 1.41; these floods were 41% to 63% larger than the expected flood potential discharge for each of these watersheds. The most extreme floods have occurred on Cedar Fork, a tributary to Boeuf Creek which flows directly into the Missouri River, and the headwaters of the Bourbeuse River.

Table 3: Extreme floods experienced in zone 59N, ranked from most to least extreme. E_f = flood extreme index, Q = peak discharge.

E_f	USGS ID	Peak Q (cfs)	Date
1.63	06935175	11,600	5/7/2000
1.63	07015720	49,300	12/3/1982
1.55	07012000	4,000	2/22/1979
1.54	07011300	10,000	7/17/1958
1.49	07050700	62,000	7/1909
1.47	07015000	18,600	6/8/1945
1.45	06921200	38,500	9/1914
1.41	06930000	90,200	4/30/2017
1.41	07017200	49,100	11/14/1993

Major floods that have occurred in zone 59S (Ozarks, South), on the southern portion of the Mark Twain National Forest and most of the Ozark & St. Francis National Forests, include events in 1904 (March), 1915 (August), 1949 (January), 1960 (May), 1961 (August), 1982 (December), 2008 (March and April), 2011 (April), 2017 (April). The largest flood in this zone (Q = 244,000 cfs) occurred on the Spring River on 12/3/1982. This was not an extreme flood (E_f = 1.22); it was 22% larger than the expected flood magnitude for this streamgage (ID: 07069500) and close to the threshold for being extreme in this zone. Large flood events have occurred consistently throughout the streamgage record in this zone, from 1904 to present; these events were all incorporated into the flood potential plot of Figure A-2.

Extreme floods in 59S (E_f ranging from 3.0 to 1.38; Table 4 and Figure 7) are more extreme than those experienced in 59N. This is on top of the situation that the expected flood potential in zone 59S is 41% larger than in zone 59N (Table 2). Extreme floods in zone 59S also appear to be clustered and more extreme on the southern part of this zone (Figure 7), on the Ozark & St. Francis National Forests. These floods have occurred on the southern slopes of the Ozarks, as this higher relief emerges from the Arkansas Valley and the Mississippi alluvial plain to the south and east and induces orographic-driven enhanced precipitation of moisture derived from the Gulf of Mexico.

Table 4: Extreme floods experienced in zone 59S, ranked from most to least extreme. E_f = flood extreme index, Q = peak discharge.

E_f	USGS ID	Peak Q (cfs)	Date
3.00	07075000	241,000	12/3/1982
1.88	07257500	130,000	12/3/1982
1.79	07249500	33,600	5/5/1960
1.62	07054450	2,480	10/13/1968
1.60	07048800	76,700	4/24/2004
1.60	07194800	86,900	4/25/2011
1.54	07057500	189,000	4/30/2017
1.47	07257000	111,000	12/3/1982
1.45	07074000	158,000	12/3/1982
1.38	07195800	14,600	6/8/1974

The most extreme floods that have occurred in zone 59S have been the 241,000 cfs peak flow (E_f = 3.00) experienced on the Middle Fork of the Little Red River, on 12/3/1982 from a 301 mi^2 watershed, and the 130,000 cfs flood (E_f = 1.88) that occurred on the same date on the Illinois Bayou, from a 241 mi^2 watershed. Also, the extreme flood that occurred on the North Fork River from a 561 mi^2 watershed, on 4/30/2017 (E_f

= 1.54), was experienced across an entire unit of the Mark Twain National Forest (Figure 17).

Please note in Table 3 and Table 4 that the extreme floods experienced in both zones 59N and 59S do not appear to have become more prevalent in more recent decades, but instead are distributed in time throughout the streamgage records.

Southern Areas

Major floods that have occurred in zone 58 (Ozarks Transition), on the southern-most unit of the Ozark & St. Francis National Forests and the northern edge of the Ouachita National Forest, include events in 1935 (June), 1939 (April), 1945 (end of March), 1960 (May), 1968 (May; the most substantial event), 1982 (December), and 2015 (May). Major floods have less frequently occurred in this zone in the last few decades than zones 59S and 59N, to the north. The largest flood in this zone (Q = 110,000 cfs) occurred on Sallisaw Creek in Oklahoma on 4/15/1945. This was an extreme flood ($E_f = 3.62$). Sallisaw Creek drains the lower southern flank of the Ozarks, in an area that generally receives smaller floods than the Ozarks – this flood is in the boundary area between zone 58 and 59S. With the exception of the Sallisaw Creek flood (which is a high outlier), these events were all incorporated into the expected flood potential predictions plotted in Figure A-3, with the Sallisaw flood marked as an outlier.

Extreme floods that have occurred in zone 58 are provided in Table 5 and Figure 7, with E_f ranging from 3.62 to 1.50. The Sallisaw Creek flood, at 3.6 times what is expected, is the most extreme flood experienced in the Ozarks and Ouachitas, with the remaining extreme floods being 50 to 81% larger than the expected flood potential discharge.

Major floods documented to have occurred in zone 57 (Ouachita Mountains), on the Ouachita National Forest, include events in 1945 (end of March), 1961 (May), 1968 (May), 1971 (December), 1982 (December, the most substantial event), 1990 (May), and 2015 (December). The largest flood in this zone (Q = 195,000 cfs) occurred on Fourche LaFave River on 5/31/2013. This flood was not extreme (E_f = 1.11).

Extreme floods that have occurred in zone 57 are provided in Table 6 and Figure 7, with E_f ranging from 1.97 to 1.52. The most extreme flood had a peak about twice the expected flood potential in this high flood potential zone.

Table 5: Extreme floods experienced in zone 58, ranked from most to least extreme. E_f = flood extreme index, Q = peak discharge.

E_f	USGS ID	Peak Q (cfs)	Date
3.62	07245500	110,000	4/15/1945
1.81	07247500	41,500	5/19/1960
1.69	07040040	710	7/1/1968
1.66	07260630	2,200	12/3/1982
1.61	07249300	25,400	5/14/1968
1.60	07077340	1,000	4/19/1973
1.51	07194515	1,860	4/19/1968
1.50	07252200	729	4/3/1964

Table 6: Extreme floods experienced in zone 57, ranked from most to least extreme. E_f = flood extreme index, Q = peak discharge.

E_f	USGS ID	Peak Q (cfs)	Date
1.97	07231950	18,000	3/27/1977
1.74	07360200	70,800	6/11/2010
1.53	07356700	3,070	12/3/1982
1.52	07359805	10,500	5/20/1990

TRENDS in FLOODING

The flood potential method provides a consistent framework for identifying trends in both the magnitude and frequency of floods, due to such non-stationary mechanisms as climate change due to global warming. This allows practitioners to understand if floods are becoming larger or more frequent, through a comprehensive evaluation of floods experienced across each zone. This approach is backward looking, and does not prognosticate future changes in flooding. However, it is a method for evaluating what we are currently experiencing in regard to flooding, and includes a method for adjusting flood magnitudes where there are significant trends in the size of floods within a zone. The flood extreme index (E_f) is utilized for this testing; see Appendix A for details on the methodology.

Northern Areas

The results of trend tests for the magnitude and frequency of large floods in zones 59N and 59S, on most of the Mark Twain National Forest, and the Ozark and St. Francis National Forests, are shown in Figure 8 through Figure 11. No trends are indicated for the magnitude in floods for the periods of streamgage records, from 1895 to 2020 for zone 59N and 1904 to 2020 for zone 59S. However, there are increasing trends in frequency of large floods for a period of 1945 to 2020. Specifically, zone 59N is experiencing significant increases in the frequency of large floods (Figure 9), while zone 59S appears to be experiencing an increasing trend in the frequency of large floods (Figure 11) but this trend is not (yet) significant (p-value = 0.09 > 0.05 = α.). Floods may likely be becoming more frequent in 59S, but the trend test is not definitive.

Hence, it can generally be stated that across the Mark Twain National Forest, and the Ozark and St. Francis National Forests, floods are not increasing in magnitude but are (or are likely) increasing in frequency. For effective management of these National Forest System Lands, management strategies that account for an increased frequency in the occurrence of large floods are warranted.

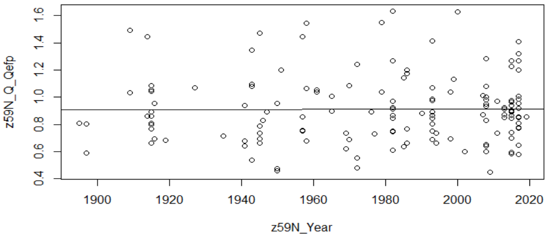

Figure 8: Trend test for the magnitude of large floods experienced in zone 59N (as quantified using E_f). p-value = 0.96 >> 0.05 = α.

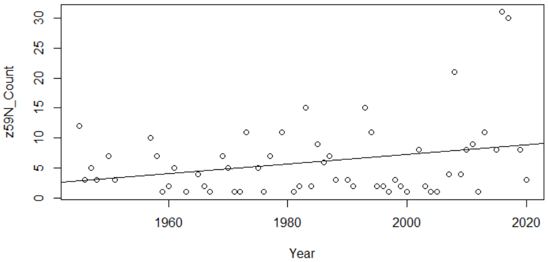

Figure 9: Significantly increasing trend in the frequency of large floods (where $E_f > 0.5$) experienced in zone 59N, from 1945 to 2020. p-value = 0.04 < 0.05 = α.

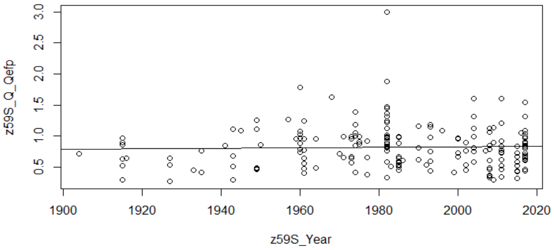

Figure 10: Trend test for the magnitude of large floods experienced in zone 59S (as quantified using E_f). p-value = 0.65 >> 0.05 = α.

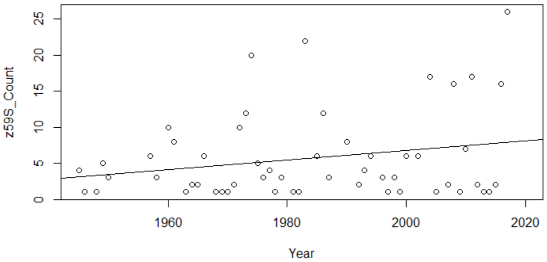

Figure 11: Trend test for the frequency of large floods (where $E_f > 0.5$) experienced in zone 59S, from 1945 to 2020. p-value = 0.09 > 0.05 = α.

Southern Areas

The results of trend tests for the magnitude and frequency of large floods in zones 58 and 57, on the southern-most unit of the Ozark and St. Francis National Forests, and the Ouachita National Forest, are shown in Figure 12 through Figure 15. No trends are indicated for the magnitude in floods from 1895 to 2020 for zone 58, however a non-significant increasing trend in flood magnitudes (p-value = 0.13 > 0.05 = α) is indicated for zone 57 (Figure 14) for 1904 to 2020. There may be slightly decreasing trends in frequency for zones 58 for a period of 1945 to 2020, but this possible trend is far from significant and should be regarded as nonexistent. There are not trends in flood frequency for zone 57.

Hence, it can generally be stated that across the Ouachita National Forest streamgage data indicate that floods may be increasing in magnitude, but are not increasing in occurrence frequency. Flood magnitudes have increased by a multiplier of 1.05 for 1990 through 2020, compared to the entire record. For the most effective management of the Ouachita National Forest, it can be argued that designing for floods being 5% larger (than the expected flood potential discharge) is warranted, but the lack of significant trends in the existing streamgage data indicate that such a precaution may not be necessary at this time. Further investigation through comparison of these results with projections of a suite of climate models is advisable.

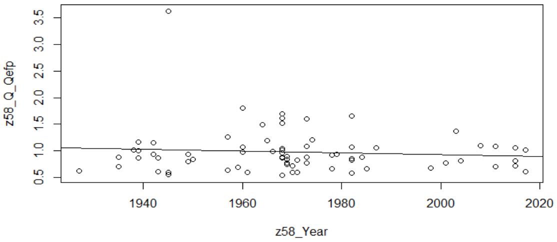

Figure 12: Trend test for the magnitude of large floods experienced in zone 58 (as quantified using E_f). p-value = 0.47 >> 0.05 = α.

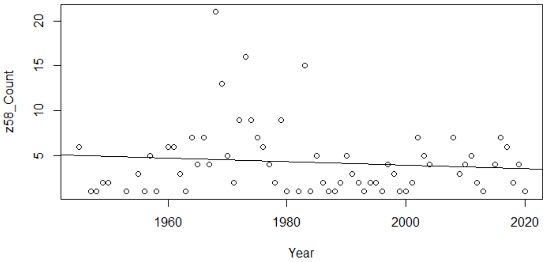

Figure 13: Trend test for the frequency of large floods (where $E_f > 0.5$) experienced in zone 58, from 1945 to 2020. p-value = 0.40 >> 0.05 = α.

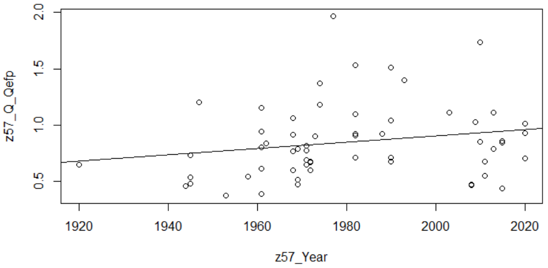

Figure 14: Trend test for the magnitude of large floods experienced in zone 57 (as quantified using E_f). p-value = 0.13 > 0.05 = α.

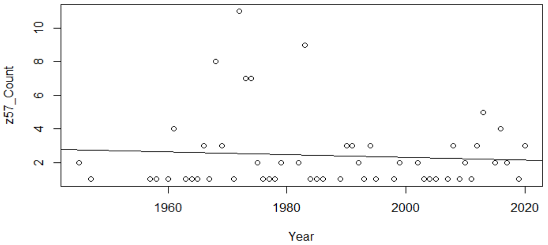

Figure 15: Trend test for the frequency of large floods (where $E_f > 0.5$) experienced in zone 57, from 1945 to 2020. p-value = 0.0 >> 0.05 = α.

EXAMPLE: ELEVEN POINT and NORTH FORK RIVERS

The Eleven Point and North Fork Rivers drain watersheds that are composed in part by units of the Mark Twain National Forest. These adjacent watersheds are in zone 59S. In 2017, both of these watersheds experienced large floods that heavily impacted the stream valleys managed by the Forest (Figure 16), with all three of the streamgages in these watersheds having their floods of record on 4/30/2017 (Table 7). These watersheds are illustrated in Figure 17. Considering the history of flooding within these and neighboring watersheds, what flood discharges should be used for designing stream infrastructure? How should climate change impacts be integrated into the selection of the most appropriate flood design discharges?

In general, there are several approaches for estimating flood discharges for design: (1) utilize streamgage data and appropriate analyses; (2) simulate flooding through rainfall-runoff modeling; and (3) utilize downscaled climate models to estimate future flood magnitudes, and how they may be expected to change. Each approach has advantages and disadvantages. In this example, the streamgage analyses are focused upon, with results of climate modeling also provided for comparison. The streamgage analyses involve several different methods, including traditional flood-frequency methods, as well as the flood potential method.

Figure 16: Geomorphic and riparian impacts from the April 2017 flood on the Eleven Point River, Missouri, on the Mark Twain National Forest (5/31/2017).

Table 7: Comparison of flood discharges experienced and predicted for streamgages on the Eleven Point and North Fork Rivers. Streamgages: 07071500 = Eleven Point River near Bardley, Missouri; 07072000 = Eleven Point River near Ravenden Springs, Arkansas; 07057500 = North Fork River near Tecumseh, Missouri. Q_{2017} = peak discharge experienced during the 2017 event; Q_{efp} = expected flood potential discharge.

			Flood Potential		**Flood Frequency**		
					Streamgage		**Regional**
USGS ID	**Watershed Area (mi^2)**	**Q_{2017} (cfs)**	**Q_{efp} Pre-2017 Data (cfs)**	**Q_{efp} All Data (cfs)**	**100-Year, Pre-2017 Data (cfs)**	**100-Year, All Data (cfs)**	**Regression 100-Year (cfs)**
07071500	784	122,000	142,000	153,000	66,000	77,000	85,000
07072000	1118	164,000	179,000	195,000	100,000	124,000	130,000
07057500	562	189,000	114,000	122,000	88,300	119,000	75,500

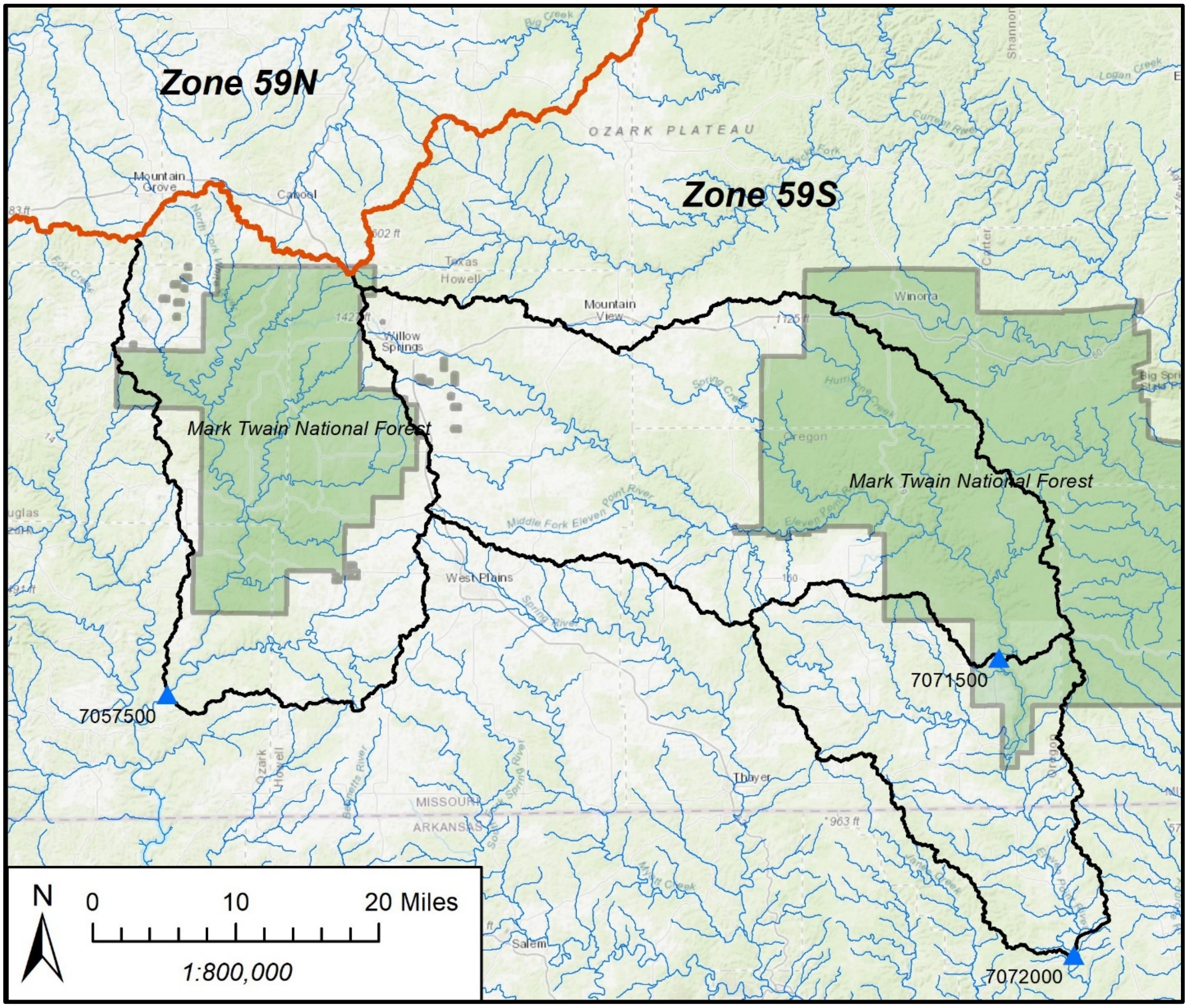

Figure 17: Eleven Point (east) and North Fork River (west) watershed delineations, along the boundary between Flood Potential zones 59N and 59S. Streams in zone 59N typically drain to the northeast, while streams in zone 59S drain to the southeast.

Utilizing streamgage data analysis approaches, three methods are presented for developing flood design discharges in this example: flood potential analyses, regional regression analyses as developed by the USGS, and flood-frequency analyses of streamgage data. All three are appropriate for streamgaged locations, with the first two relevant for ungaged locations. Table 7 presents the key results of these analyses, as well as the 2017 flood peak discharges.

Flood Prediction Scenario #1

Consider a situation where stream valley infrastructure is being designed for a site in close vicinity to streamgage 07071500, which is located at the US-160 crossing of the Eleven Point River. The design needs both bankfull discharge and flood discharge estimates. What design flood discharge magnitude should be used? To illustrate the complexity of the flood hydrology at this site, and to provide the perspective of a hydrologist working in the area, two analysis scenarios are presented: a March 2017 analysis, just before the April 2017 flood event, and an additional 2021 analysis that utilizes all the currently-available data.

March 2017 Analysis

Compared to floods experienced across the extent of zone 59S, the Eleven Point River at streamgage 07071500 has had relatively low magnitude flooding. Prior to April 2017, this 784 square mile watershed experienced a maximum discharge of 49,800 cfs (12/3/1982) over 96 years of record. A streamgage flood frequency analysis using the Bulletin 17B method (IACWD 1982) and the station skew indicate a Q_{100} = 66,000 cfs (Table 7). In March of 2017, it would have been tempting to utilize this discharge as a design discharge; after all, there are 96 years of record and in flood hydrology we have traditionally assumed that streamgage data at a specific site is most important for selecting flood design discharges near that streamgage.

However, further evaluation could have revealed possible issues with the selection of a 66,000 cfs flood design discharge. Specifically, it would have been good practice to perform additional streamgage analyses for other streamgages on the Eleven Point River, with streamgage 07072000 being a prime candidate. With a watershed area of 1118 mi^2 (43% larger), this gage had experienced much more severe flooding than the upstream gage, with a pre-2017 peak flow of 162,000 cfs on 12/3/1982. This results in Q_{100} estimate of 100,000 cfs (using 85 years of record). With a discharge 3.3 times larger than the flood experienced at the upstream gage and 2.5 times larger that the Q_{100} at the upstream gage, the presence of this flood could have been a flag indicating a possible problem with using the 66,000 cfs design flow near the upstream gage. Though such situations are not uncommonly disregarded by simply assuming that this 1982 flood was extreme and isolated to the lower portions of the 1118 mi^2 watershed; after all, streamgage flood frequency analyses are extreme value analyses that, by definition, indicate that the record peak discharges at a streamgage is frequently extreme. In defense of such an assumption, the 1982 flood at the lower streamgage for both streamgages does appear to be extreme compared to more common flood magnitudes at these sites. But what if neighboring watersheds had also had flood magnitudes of a similar scale?

Zooming out from focusing solely on the Eleven Point River can provide some additional understanding for what the magnitude potential is for large floods at this point of interest. Record peak discharges for neighboring streamgages are provided in Table 8. This comparison indicates that, prior to the 2017 flood, large floods have occurred throughout this area and the Eleven Point River at the upper streamgage appears to be an anomaly compared to its neighboring watersheds with similar or smaller watershed areas.

Table 8: Peak discharges for the Eleven Point (asterisks) and neighboring streamgages, for both the pre-2017 period (record peak) as well as for the 2017 flood. 07057500 = North Fork River; 07058000 = Bryant Creek; 07069500 = Spring River; 07074000 = Strawberry River; 07068500 = Little Black River; 07065200, 07066000 = Jacks Fork.

USGS ID	Watershed Area (mi2)	$Q_{pre\text{-}2017}$ (cfs)	Q_{2017} (cfs)
07071500*	784	49,800	122,000
07072000*	1118	162,000	164,000
07057500	562	73,100	189,000
07058000	568	71,100	111,000
07069500	1160	244,000	54,800
07074000	472	158,000	23,300
07068500	184	52,800	----
07065200	185	43,700	33,400
07066000	403	58,500	106,000

Should all the large floods shown in Table 8 be considered extreme, and consequently unexpected to occur in the future as the use of this term conveys in common vernacular? The flood potential method indicates that most of these floods should not be considered extreme, and only floods that truly are quantified as being unusually large across zones of similar flood response be considered extreme. Combined with the knowledge of the 162,000 cfs flood in 1982 at the lower Eleven Point River streamgage, it does appear that the Q_{100} = 66,000 cfs at the upper streamgage is low and may not be suitable for infrastructure design.

Had the flood potential method existed in March of 2017, and considering the large floods experienced in neighboring watersheds, it would have been reasonable (and conservative) to utilize the larger (expected flood potential) discharge of 142,000 cfs (Table 7) for the infrastructure being designed near streamgage 07071500, rather than the 100-year discharge of 66,000 cfs. The rationale for this decision to use the central tendency of record peak discharges would have been that the largest recorded floods at the upstream Eleven Point streamgage are low outliers compared to the remainder of the zone, and that either this watershed is unique compared to its surrounding neighbors (which is likely unknowable), or a large flood may be due and should be expected to occur during the design life of the planned infrastructure.

2021 Analysis

The wide-ranging 2017 flood event initiated in late April of 2017 (NWS, 2021), with high flows experienced in rivers and springs in zones 59N and 59S for many weeks. This flood overtopped bridges over the Eleven Point River and substantially impacted the geomorphic and riparian conditions (Figure 16), with these impacts observed by canoe for the accessible portions of the river in the Mark Twain National Forest one month after the flood. Recreation values and access on the National Forest were negatively impacted. The geomorphic adjustment was lesser (Class 2 or 3 disturbance, as defined by Yochum et al., 2017) compared to flood impacts that have occurred on other Forests (such as the Arapahoe-Roosevelt in 2013), with this likely due in large part to the thick and extensive riparian vegetation present on the floodplains in this humid area. However, much of this vegetation was pushed over, as if a monster had come along and pushed most of the trees partially or fully down onto the floodplain. That “monster” was a flood with 25 ft deep flows on the floodplains and 2.4 times larger than anything that had occurred over the last century on the Eleven Point River on the Mark Twain National Forest, inducing extensive damage to many sites.

At the upper Eleven Point Streamgage (07071500), a peak flow of 122,000 cfs was estimated by the U.S. Geological Survey from high water marks. When only considering this streamgage’s dataset, it appears that this flood is a high outlier and extreme The inclusion of the 2017 peak flow and performing a flood-frequency analysis using the entire 100 years of record provides a new Q_{100} = 76,800 cfs. This is a 16% increase from the March 2017 analysis. Is this new streamgage flood frequency analysis providing an appropriate flood design discharge? The downstream streamgage (07072000) provides insight into this question. This site has experienced two floods of similar magnitude, 164,000 cfs in 2017 and 162,000 cfs in 1982, with a resultant 100-year discharge estimate of 124,000 cfs using 89 years of record. Considering that two large floods have occurred of a surprising similar magnitude in this basin, using a Q_{100} = 76,800 cfs as the design flood at the upstream gage may be insufficient. Once again comparing this 100-year discharge with the record peak discharges for neighboring streamgages (Table 8) indicates that this upper watershed may be an anomaly compared to its neighboring watersheds with similar or smaller watershed areas, and in any case it is substantially less than the 122,000 cfs experienced in 2017.

As a side point, it is interesting and relevant to note that the lower Eleven Point streamgage (07072000) has a Q_{100} of 124,000 cfs estimated, despite two floods having discharges 40,000 cfs higher with 89 years of record. These floods have a 200-year return interval. However, if an additional year with another 160,000 cfs flood is hypothetically added, the 90 years of record now indicate Q_{100} = 151,000 cfs, with the experienced floods of 1982 and 2017 now being not much larger than the Q_{100}, and Q_{200} = 213,000 cfs. Flood frequency analyses for streamgages using a logPearson distribution are sensitive to multiple large flood events, increasing 100-year discharges as more are experienced. This can especially be a problem in areas where there are bimodal annual flood distributions, where several large floods are experienced, while more “every-year” floods are much smaller in magnitude (see Appendix A for another example of this situation, where the flood potential results indicate the 100-year flood is being overestimated instead of underestimated). The increased frequency in large floods in zone 59N, and likely increased frequency in zone 59S, indicate that such bimodal flood distributions may be becoming more prevalent in the streamgage records of this area, and should be accounted for.

Regional regression analyses have traditionally been utilized to address uncertainties regarding streamgage analysis, as well as (more commonly) for predicting flood frequency at ungaged locations. In such regional analyses log-Pearson frequency analyses are fit to each utilized streamgage analyses and regressions are developed for each return interval for application at ungaged locations. Flood frequency predictions in the USGS StreamStats tool utilizes the results of such analyses. However, each of these individual streamgage flood frequency analyses have the same issues described here, potentially inducing a systematic bias in the results. The 100-year discharge predicted using the regional regression model is 85,000 cfs, a 29% increase from the original Q_{100} = 66,000 cfs, and 11% larger than the gage analysis Q_{100} = 76,800 cfs.

Instead of utilizing the results of one of the flood-frequency analyses and assuming that we shouldn't expect such large flood magnitudes in the future as were experienced in 1982 and 2017, a simpler and more appropriate approach could be to use the central tendency of the record peak discharges experienced across flood potential zone 59S. This expected flood potential estimate is Q_{efp} = 153,000 cfs (an 8% increase compared to the pre-2017 analysis), with a maximum likely flood potential discharge of Q_{mlf} = 211,000 cfs. These results indicate that large floods in this portion of the Ozarks tend to be relatively massive, with the flood experienced in 2017 at this location of interest not being as large as what can be expected ($E_f = 0.80$), and only floods over 211,000 cfs should be considered extreme. Such a departure from the initial pre-2017 analysis of the streamgage data (Q_{100} = 66,000 cfs) can be surprising, though the analysis indicates that such flood flow magnitudes are underestimating the true expected flood response to large storm events in this watershed. These flood potential estimates are predicted with high explained variance ($R^2 = 0.97$) and very low variability ($V_f = 1.38$). Additionally, as presented in the previous section, the flood potential results indicates that floods are not becoming larger in magnitude (Figure 10), but large floods are likely occurring more frequently (Figure 11). Over time, flood records may become more bimodal, shifting 100-year flood magnitudes higher during the design life of stream valley infrastructure.

Climate modeling provides an opportunity to forecast future climate projections on flooding that may occur as a result of climate change. These estimates are quite approximate and should not solely be relied upon for design, but are important to add to backwards looking approaches like flood frequency and flood potential analyses to address the possibility of flooding at a point of interest being non stationary. The flood potential method tests for historical trends in floods, and adjusts flood magnitudes where appropriate, but it can't project other changes into the future. Forest Service specialists (Charlie Luce, Daniel Isaac, Nathan Walker, and others) are working towards a national tool for presenting climate modeling results to practitioners for land management decisions. For this site, preliminary projections using an ensemble of 5 climate models suggest that, in the 2080s, mean annual flow may decrease, but the maximum modeled flood may increase in magnitude and become more frequent by 10 to 25 percent. This modeling suggests greater variability, with less mean annual flow but larger and more frequent large-scale floods. This result supports utilizing the larger magnitude Q_{efp} in the design.

Hence, it is concluded that the use of **Q_{efp} = 153,000 cfs as the flood design discharge at our point of interest** is most appropriate, and that it's especially important to select such a large design flood considering the floods are likely becoming more frequent in this portion of the Ozarks.

Flood Prediction Scenario #2

Consider a second situation where additional stream valley infrastructure is being designed for a site in close vicinity to streamgage 07057500, on the North Fork River, about a mile upstream of County Road PP off of US-160. What design flood discharge magnitude should be used?

As of 2020, this streamgage has 76 years of annual peak flow data for its 562 mi^2 watershed area. The primary flooding characteristics are provided in Table 7. The largest peak discharge experienced at this site was 189,000 cfs on 4/30/2017, with a second largest discharge of 73,100 cfs on 11/19/1985. The 2017 flood is extreme, as determined using the flood potential method (E_f = 1.54). A comparison of this flood with the largest flood magnitudes is provided in Table 8; this streamgage has experienced the largest flood magnitude for watersheds that are of similar size or larger in the area.

A flood-frequency analysis of the streamgage record indicate a Q_{100} = 119,000 cfs. However, the regional regression analysis indicates a Q_{100} = 75,500 cfs, quite a bit smaller. Standard practice would lead a designer to utilize the 119,000 cfs value. Would this be correct, or would it be too high, leading to an oversized and overly expensive project?

The flood potential method indicates an expected flood potential discharge (Q_{efp}) of 122,000 cfs. The maximum likely flood potential discharge (Q_{mlf}) is 168,000 cfs, with floods larger than this being extreme (such as the 2017 flood).

Considering these results, **either the Q_{100} = 119,000 cfs from the streamgage analysis or the Q_{efp} = 122,000 cfs from the flood potential analysis would be appropriate for the design flood discharge at this site.** Floods as large as what was experienced in 2017 (or greater than 168,000 cfs) should not be expected again at this site, though the unexpected is still a possibility, just unlikely.

Summary

Using both flood frequency and flood potential methods, design flood flow discharges were developed for two sites on the Eleven Point and North Fork Rivers. A detailed description of the methods and considerations are presented for both examples, to help practitioners utilize such an approach on projects in the future. The flood potential method for flood magnitude estimation provides a valuable addition to the results of traditional flood-frequency methods to help practitioners select the most appropriate design discharges; this method can help resolve otherwise controversial or disputed estimates of the most appropriate flood discharge magnitudes for infrastructure design and floodplain management.

A substantial number of values have been provided as a part of this example, which can be confusing and involves performing a number of distinct analyses that may be beyond the experience of a practitioner that needs to select design discharges for a project. To assist with this issue, the Flood Potential Portal is being developed to perform these analyses automatically at user-selected points of interest. Once this tool is fully deployed in ~January 2022 for the United States west of the Mississippi River, it will be of great value to practitioners to make more informed decisions for specific projects.

FLOOD POTENTIAL PORTAL

This report provides an interpretation of flood risk across the analysis area using the flood potential method. To develop their own interpretations, practitioners need an automated tool to effectively utilize this method for infrastructure projects. Utilizing multiple methods, as was done within the example, is needed to exercise due diligence for establishing the most appropriate design flood discharges. The Flood Potential Portal is being developed to assist practitioners with these needs.

The Flood Potential Portal is being developed by One Water Solutions Institute at Colorado State University to serve the results of the flood potential method alongside the results of traditional flood frequency methods, to provide a one-stop shop for hydrologic analyses for infrastructure design. This tool will be valuable for helping to understand and communicate about flood variability and trends across the United States, as well as provide specific point values for flood magnitudes. The Flood Potential Portal is focusing initially on streamgage analyses, with plans to also include the results of climate modeling. It will be linked to from the National Stream and Aquatic Ecology Center Flood Potential project page. The Portal is currently in alpha testing, and is expected to be released in early 2022 for areas west of the Mississippi River, with the Southeast expected to be available in 2023 and the Northeast in 2024.

It is important to recognize that a well trained and experienced hydrologist or civil engineer will still be needed to interpret the results from the various analyses presented in the Flood Potential Portal, to select the most appropriate flood design discharges. The Portal was developed to help with this decision making, but does not replace this expertise.

CONCLUSIONS

River valley infrastructure design and floodplain management requires estimates of flood design discharges. A variety of approaches are available to practitioners for estimating these discharges, though traditional flood-frequency methods can provide inconclusive results. The addition of the flood potential method can help resolve these situations, as well as help us understand and communicate about how floods vary across regions, help us quantify what floods are extreme rather than of a magnitude that previous flooding in the area indicates is not unusual for a large flood, and provides methods for detecting trends in the magnitude and frequency of floods for monitoring the possible effects of climate change. An extensive example is provided, as a practical template for the use of the available methods for designs. The Flood Potential Portal will be valuable for practitioners to utilize to help make these design decisions.

The large flood events that occurred along the Colorado Front Range in 2013, West Virginia in 2016, and the Ozarks in 2017, on the Arapahoe-Roosevelt, Monongahela, and Mark Twain National Forests, prompted questions revolving around how unusual and extreme these floods were considering the streamgage records of these areas. These questions led to the development of the flood potential method. I have appreciated the opportunity to apply this approach to help understand flooding in one of the areas that inspired its development.

ACKNOWLEDGEMENTS

David Levinson and Robert Gubernick are appreciated for their helpful suggestions for increasing the clarity of the information shared within this report. Appreciation is also expressed to the great many hydrologists, hydraulic engineers, and technicians who have collected and analyzed peak stage, discharge, and other streamgage data, and the U.S. Geological Survey and partner agencies who have collected and served data, provided technical expertise, and funded flood science across the United States.

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APPENDIX A: TECHNICAL DETAILS

Greater insight into the expected magnitudes and spatial variability of riverine floods is needed to effectively manage our stream valley resources and build more sustainable communities. However, our understanding of floods is limited and hazards can be poorly communicated by technical specialists to decision makers and the public.

The flood potential method (Yochum et al., 2019; Yochum, 2019) was developed to help address these issues. This methodology uses a space-for-time substitution to predict expected large flood magnitudes given the streamgage record in similarly-responding nearby watersheds. Regressions of record peak discharges using drainage area and additional watershed characteristics are fit across areas with similar flood records, with these areas referred to as *zones*. Each of these regressions define the *expected flood potential* (Q_{efp}) for each zone, which quantifies expected flood magnitudes. The 90% prediction limit defines the *maximum likely flood potential* (Q_{mlf}), with discharges above this level being extreme and departure indicating the degree of extremity. A glossary of terms is provided in Appendix B, for simple reference.

This method was developed to help answer common questions for quantifying flood risk:

- *What large flood magnitudes can be expected at a given ungaged location, for designing infrastructure?* It is best to use multiple approaches for flood magnitude prediction, including flood potential and flood-frequency methods.
- *Is a flood frequency analysis at a specific streamgage providing reasonable results, or are results biased due to the presence or absence of larger floods?* This method helps identify bias in flood frequency analyses that are induced by the presence of floods that are atypically large compared to what neighboring watersheds have experienced, or the absence of large floods that neighboring watersheds indicate do occur.
- *How reasonable are the results of regional flood frequency regression equations?* The flood potential method provides independent verification of the reasonableness of the results of regional flood-frequency equations. This method utilizes zones that experience similar flood magnitudes, flashiness, and seasonality that are typically smaller in spatial extent than the regions used in regional studies.
- *What areas are inherently prone to larger or smaller floods?* Such understanding can help make more informed decisions regarding:
    - Erosion hazards of stream corridors
    - Higher costs for stream valley infrastructure maintenance or replacement
    - Inherent risks of stream restoration
    - Risks of wildfire-induced debris flooding on communities and infrastructure
- *Was a specific flood extreme, or instead a typical large flood?* Is it reasonable to assume that an experienced flood was extreme and unlikely to occur at such a magnitude at this location again, or is it the case that a particular event was large but not uncommon compared to the scale of floods that have occurred in nearby watersheds? Such understanding is essential for thoughtful land management and community planning.
- *Compared to other large floods in an area, how extreme was a flood?* The flood extreme index can be used to rank flood extremes throughout a region and across the United States.
- *Are floods increasing in magnitude or frequency over time?* Zonal-based trends in flood magnitude and frequency are assessed and, where magnitude trends are significant, a flood magnitude adjustment is computed for these non-stationary areas.

The flood potential method utilizes streamgages with watersheds less than 3860 mi^2 (10,000 km^2), though is typically smaller due to each zone's characteristics. Above a certain watershed size (that varies by zone), the watershed does not exist, or it experiences floods of a smaller magnitude than what the flood potential relationship indicates using zonal data from smaller watersheds. Hence, there is an upper limit for application of the flood potential method in each zone.

A problem with traditional flood-frequency methodologies is that logPearson distributions (IACWD, 1982; England, et al., 2018) may not fit annual peak flow data from some streamgages. Specifically, some areas experience bimodal flood distributions, where repeated large floods occur that are much larger than more common annual peak flood magnitudes. Additionally, in some areas large floods may be becoming more frequent, though are not increasing in magnitude. This situation can bias streamgage flood-frequency analyses.

For example, the streamgage on Buckhorn Creek (USGS ID: 06739500), west of Fort Collins, Colorado, has 32 years of annual peak flow record collected over a period from 1923 to 2013. The record indicates bimodal flood peaks, with 4 floods greater than 10,000 cfs (10,500 cfs in 1923; 10,200 cfs in 1938; 14,000 cfs in 1951, due to a dam failure; and 11,200 cfs in 2013) and the remaining annual peak floods having an average magnitude of 780 cfs. A logPearson analysis of the streamgage records (using Bulletin 17C procedures; England et al., 2018), excluding the 1951 peak, indicates a 100-year discharge estimate of 21,400 cfs. Using Bulletin 17B (IACWD, 1982) procedures, the difference is even more stark, with a 100-year discharge estimate of 38,000 cfs. In contrast, the expected flood potential discharge is computed to be 10,400 cfs (or 11,500 cfs using a 1.11 magnitude adjustment for a significant increasing trend in the magnitude of large floods), with a maximum likely flood potential of 17,600 cfs (19,500 cfs with adjustment) – the bimodal flood distribution is biasing the streamgage flood frequency analysis, resulting in what can be considered overestimated flood magnitudes. Instead, it would be reasonable to design stream valley infrastructure in this area to safely pass 11,500 cfs, since this is the central tendency of large floods in this zone while accounting for increased flood magnitudes across this zone due (likely) to climate change, while designing to the 100-year flood discharge would probably lead to oversized stream valley infrastructure, forcing unnecessary additional costs.

The flood potential method can provide flood design discharges that side step problems arising from using flood distributions in such situations. However, this method has the weakness of not providing return intervals of predicted flood magnitudes. Additionally, peak discharges are estimated with an assumption that hydrologic conditions of the watershed above the point of interest are unaltered by any large disturbances, such as recent wildfires.

Considering the advantages and disadvantages of the various flood risk analysis methods, it is best to use a combination of approaches. An expert can then select the most appropriate flood design discharge from a suite of estimates.

Flood Potential Plots

Flood potential plots for the area of interest in this study are provided as Figures A-1 through A-5. The plots provide the record peak discharges used in each of the analyses, with low and high outliers also presented where they exist. Regression lines are provided, as well as the upper 90% prediction limit (maximum likely flood potential). Explained variance is also noted in the upper right, and equations are provided to define the expected flood potential and maximum likely flood potential for the zone. Where additional tested watershed characteristics were significant and utilized, these equations are also provided. Floods that were extreme are labeled by a year and month. The flood potential index is also provided (P_f, defined below), as well as an embedded seasonality plot for the largest 5% floods. Additional flood potential plots are provided on the NSAEC project page, for other regions of the continental United States.

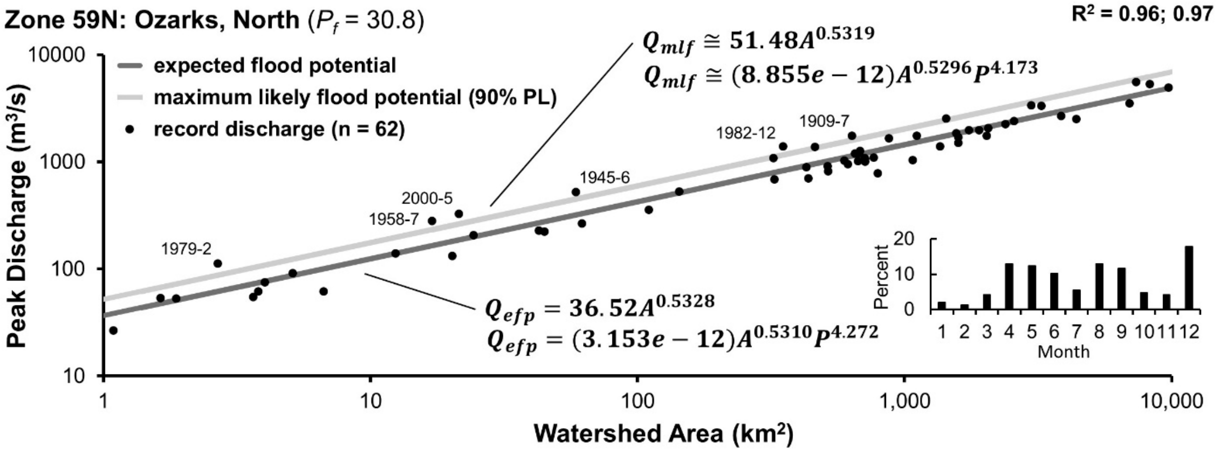

Figure A-1: Flood Potential plot with seasonality, Zone 59N (Ozarks, North).

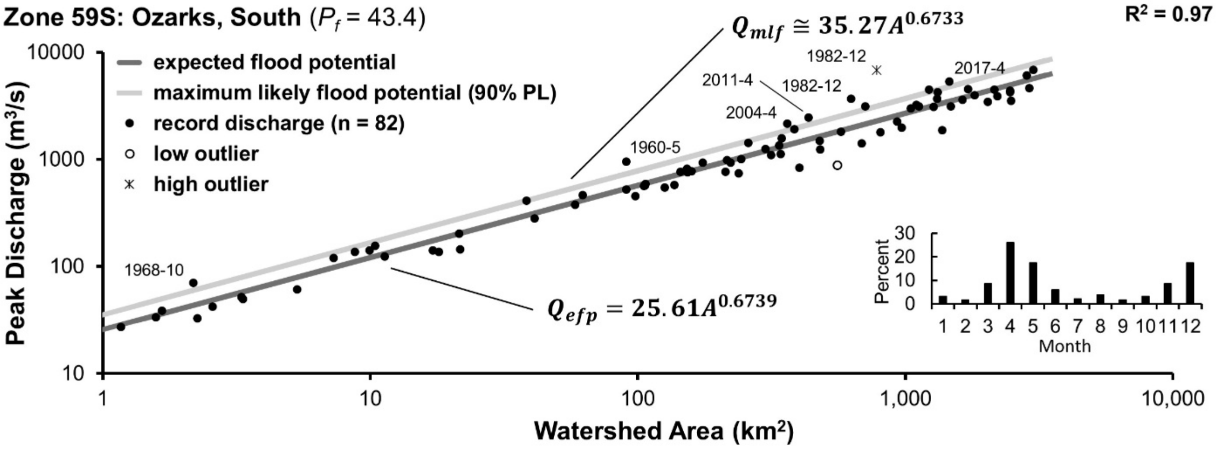

Figure A-2: Flood Potential plot with seasonality, Zone 59S (Ozarks, South).

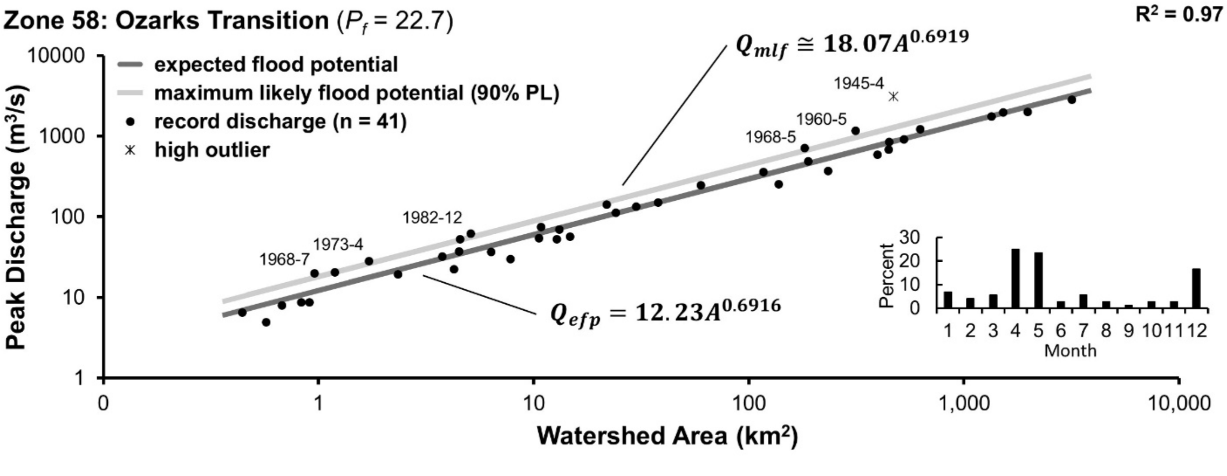

Figure A-3: Flood Potential plot with seasonality, Zone 58 (Ozarks Transition).

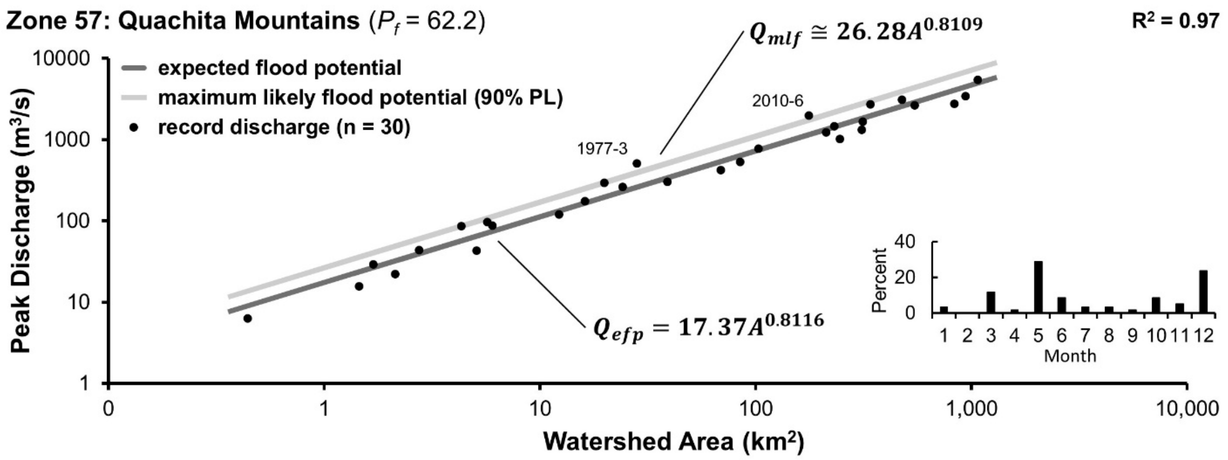

Figure A-4: Flood Potential plot with seasonality, Zone 57 (Ouachita Mountains).

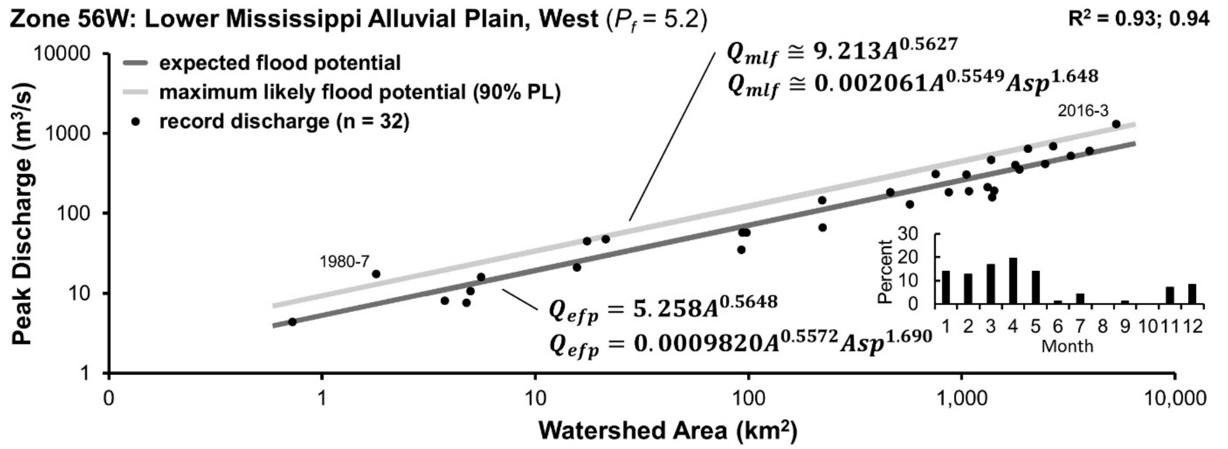

Figure A-5: Flood Potential plot with seasonality, Zone 56W (Lower Mississippi Alluvial Plain, West).

Zonal Indices

Index values defined from application of the flood potential method for the zones in the area of interest are provided in Table A-1. The *flood potential index* (P_f) is a summary index that compares flood magnitudes to a low flood potential reference zone (2), and facilitates comparisons between any zones; the *flood variability index* (V_f) describes within-zone flood magnitude variability, with higher values indicating greater variability in both space and time; the *Beard flash flood index* (F) quantifies flashiness, with higher values indicating greater difference between the magnitude of the largest and smallest annual peak flows with more typical annual floods; the *flood hazard index* (H_f) provides a summary of overall hazard, accounting for both flood magnitude and flashiness (product of P_f and F), with higher values indicate greater hazard; and P_{f2000} / P_{f20} , the ratio of flood potential index computation component for a 2000 km² watershed to a 20 km² watershed, with lower values indicating that smaller watersheds experience higher flood magnitudes on a relative basis to other zones, while higher values indicating that larger watersheds experience higher flood magnitudes on a relative basis to other zones.

Table A-1: Index values for the zones of the area of interest.

Zone	P_f	V_f	F	H_f	P_{f2000} / P_{f20}
59N	30.8	1.41	0.78	24.1	0.45
59S	43.4	1.38	0.85	37.1	0.87
58	22.7	1.48	0.76	17.3	0.94
57	62.6	1.51	0.76	47.0	1.64
56W	5.2	1.75	0.46	2.4	0.53

Flood Extreme Index

The flood extreme index ($E_f = Q/Q_{efp}$) is a frequently used unitless index for normalizing any flood magnitude (Q) using the expected flood potential discharge (Q_{efp}) for a point of interest. It is valuable for ranking experienced floods from any watershed by what is expected for the individual zone or multiple zones that compose its watershed. E_f values can then be compared globally, since they are normalized by what the zone typically experiences for large floods. Higher values indicate larger or more extreme events, with values less than 1 indicating a flood is less than the expected flood potential discharge. This index is used for ranking floods, and for testing for trends in both the magnitude and frequency of flooding.

Record peak discharges for each streamgage have been utilized to define each flood potential zone, but only 9% of these discharges are considered extreme (Yochum et al., 2019). This differs from an extreme value analysis of an individual streamgage record, with a core concept that: how can many or most record peak discharges be actually extreme when similar flood magnitudes (that have been normalized by contributing watershed areas) have also been experienced by neighboring watersheds? Instead, the central tendency is used to define the expected flood potential within each zone. Experienced floods can then be compared to the expected flood potential using E_f, with floods greater than a zone-dependent threshold defined by the upper 90% regression prediction limit considered extreme, and the departure above the prediction limit (and greater E_f) quantifying the degree of extremity. In this way, floods experienced at any location can be ranked. For example, within the continental United States west of the Mississippi River, the most extreme (measured) floods have occurred along the Colorado Front Range, in the Northern Rockies near Glacier National Park and in the Idaho Panhandle, along the northern edge of the Uinta Mountains, on the Snake River Plain, in the Basin and Range, and on the Columbia Plateau. Again, these are not the areas that receive the largest floods, but rather the places where the most extreme floods ($E_f > 7$) have occurred compared to typical flood sizes.

Flood Trends

Trends in both the magnitude and frequency of floods are evaluated using the flood extreme index.

To test for increasing trends in flood magnitudes, Q_{efp} is computed for every streamgage within a zone and E_f is computed for the largest 5% floods at these streamgages. A trend in E_f over the zonal period of record is then tested for. If a trend is significant, the period of record is split between the most recent 30 years and the entire record, and the results compared to quantify how Q_{efp} is changing over time.

To test for changes in large flood frequency, a threshold approach is used. Specifically, all of the annual peak discharges for all the zonal streamgages are tested to assess if $Q \geq 0.5*Qefp$, with those years that are greater summed for the entire zone. These sums are then tested for trends from 1945 to the end of record. The year 1945 is used since streamgaging efforts were more plentiful and consistent after the 2nd World War (though, streamgaging records have been decreasing since the late 1960's, with this reduction not accounted for in this test). Hence, in testing for changes in frequency, we are testing for if floods that are greater than 50% of Q_{efp} are significantly increasing or decreasing in their frequency of occurrence over time.

APPENDIX B: GLOSSARY of TERMS

100-year flood: The return interval for a flood that has a 1% chance of occurrence in any year.

Beard flash flood index (F): Quantifies flashiness, with higher values indicating greater differences between the magnitude of the largest and smallest annual peak flows with more typical annual floods. It is computed as the standard deviation of the natural logarithms of the annual peak flow data for each streamgage and is used as a surrogate for indices that quantify flashiness using rates of change in discharge (which can only be computed for more recent streamgage data, where 15-minute interval data are available).

expected flood potential (Q_{efp}): Discharge magnitude expected for a point of interest given the floods experienced (and recorded) across the flood potential zone.

extreme flood: A major flood that has been quantified as being extreme in magnitude by the flood potential method.

flood extreme index (E_f): A unitless index for normalizing any flood magnitude (Q) using the expected flood potential discharge (Q_{efp}), specifically $E_f = Q/Q_{efp}$. Higher values indicate larger or more extreme events, with values less than 1 indicating a flood is less than the expected flood potential discharge. This index is used for ranking floods, and for testing for trends in both the magnitude and frequency of flooding.

flood hazard index (H_f): A summary of overall hazard, accounting for both flood magnitude and flashiness (product of P_f and F), with higher values indicating greater hazard.

flood frequency method: The traditional approach for quantifying flood magnitudes that fits a statistical distribution to annual peak flow records at a streamgage and, from that distribution, estimates a variety of return interval floods (i.e. 100-year flood). In the United States, typically logPearson distributions are used and regional regressions are fit for each return interval using a variety of watershed characteristics as predictors for estimating flood magnitudes at ungaged locations.

flood potential: A general term for describing how flood magnitudes vary between areas of interest. For example, the Colorado Front Range experiences much higher flood potential than the large mountain valleys of the Southern Rocky Mountains (such as South Park).

flood potential index (P_f): A summary index that compares flood magnitudes to a low flood potential reference zone (2), and facilitates comparisons between any zones. This index is computed as:

$$P_f = \frac{\left(\frac{Q_a}{Q_{a,zone2}} + \frac{Q_b}{Q_{b,zone2}} + \frac{Q_c}{Q_{c,zone2}}\right)}{3}$$

where a = 20 km^2, b= 200 km^2, c = 2000 km^2 and $Q_{20,zone2}$ = 4.15 m^3/s, $Q_{200,zone2}$ = 21.0 m^3/s, and $Q_{2000,zone2}$ = 106 m^3/s. Using this index, flood magnitudes can be compared between any two zones: for example, floods in the Los Angeles Ranges (zone 20) have floods 47.4/8.5 = 5.6 times greater, on average, than floods in the Mojave Desert (zone 18NW) and 47.4/2.3 = 20.6 times greater than floods in the Southern Rocky Mountains (zone 3).

flood potential method: A method that sidesteps issues associated with flood-frequency analyses to predict expected and maximum likely flood magnitudes, identifies and ranks extreme floods, and provides indices for communicating about the variability of large floods across regions and continents.

flood potential plot: A zonal plot of the expected flood potential and maximum likely flood potential with the record peak discharges, outliers, regression equations, and other key information. Figures A-1 through A-5 are example flood potential plots.

Flood Potential Portal: A decision support system being developed by the One Water Solutions Institute at Colorado State University, for serving the results of the flood potential method as well as traditional flood-frequency and regional regression methods.

flood variability index (V_f): Describes within-zone flood magnitude variability, with higher values indicating greater variability in both space and time. It is computed as the ratio of the zonal regression intercepts of the expected flood potential and maximum likely flood potential equations. For zone 59N, $V_f = 51.48/36.52 = 1.41$.

major flood event: Large flood events, in regard to the spatial extent or magnitude of the experienced discharge. Major floods are large, but are not necessarily the flood of record and are typically not extreme as quantified by the flood potential method.

maximum likely flood potential: The maximum size flood that can be expected for a point of interest given the history of record peak discharges experienced across a flood potential zone. Flood greater than this are extreme. This value is computed as the upper 90% prediction limit of the expected flood potential regression.

P_{f2000} / P_{f20}: The ratio of flood potential index computation components for a 2000 km^2 watershed to a 20 km^2 watershed, with lower values indicating that smaller watersheds experience higher flood magnitudes on a relative basis to other zones, while higher values indicating that larger watersheds experience higher flood magnitudes on a relative basis to other zones.

zone (flood potential zone): The area over which a flood potential analysis was performed, with this area experiencing similar flood characteristics in regard to magnitudes, flashiness, and seasonality.