CLIMATE CHANGE INFLUENCE ON HISTORICAL FLOOD VARIABILITY IN OZARK HIGHLAND RIVERS

A Masters' Thesis
Presented to
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In Partial Fulfillment
Of the Requirements for the Degree
Master of Science, Geospatial Science with Physical Geography

By
Andrew Thomas Foreman
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CLIMATE CHANGE INFLUENCE ON HISTORICAL FLOOD VARIABILITY IN OZARK HIGHLAND RIVERS

Geography, Geology, and Planning

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ABSTRACT

Climate change influence on the hydrology and ecology of Midwestern Rivers is poorly understood. Flood frequency analysis is used to interpret the historical variability of, and recent trends in, flood magnitudes in Ozark Highland Rivers. Flood frequency distributions for the annual maximum series were calculated over 30 year periods at 5 year intervals from 1922 to 2012 to examine temporal trends of flood magnitudes ranging from the 1.5- to 100-year recurrence intervals. Discharges of the 2-year flood have increased by an average of 30% over the past 30 years, in eleven of the twelve studied rivers. Eight of the studied rivers have 25-year flood discharges that are currently greater than the long-term 50-year flood magnitude. Discharges of the 100-year flood have increased by an average of 39% for eleven of the studied rivers. Urban area % seems to play a role in the observed increases in high frequency floods, but has little to no effect on moderate/low frequency floods changes. A potential climate-related latitudinal control on high frequency flood discharges exists, though more study is needed. Recent increases in floods are more prominent in basins > 2,000 km^2. This finding provides a potential drainage area threshold under which floods have not increased significantly over recent time. USGS regression equations under predict 100-year flood discharges for ten of the twelve studied rivers. Recent increases in flood discharges in the Ozarks are likely linked to increased precipitation extremes observed across the Midwest as a result of anthropogenic climate change.

KEYWORDS: Ozarks, flood, climate, rivers, change, time

This abstract is approved as to form and content

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INTRODUCTION

River flooding is fundamentally linked to watershed characteristics (land use, geology, etc.) as well as the local climate (Lebel *et al*., 2011). For example, rivers with deforested watersheds often show an increase in flood frequency (Bradshaw *et al*., 2007). Also, periods of wetter climate in past records are often periods in which floods become larger and more frequent (Knox, 1993). The flooding regime of a river is fundamentally linked to the geomorphology of a river system (Gergel et al., 2002; Santos *et al.*, 2012). As such, changes in the magnitude and/or frequency of river flood events can have devastating consequences for channel form and biology (Jacobson and Galat, 2006; Mundahl and Hunt, 2011). Perhaps more importantly, there is greater concern with hazardous flooding as a risk to life and property.

From a human perspective, flooding is a natural hazard that damages property and quality of life (Kundzewicz, 2008). Cartwright (2005) showed that there has been a noticeable upward trend in flood damage costs since the start of the 20th century. The (30 year) average annual expenditure on flood damages is currently just over $12.5 billion in the US alone, with single events such as the 1993 Mississippi River basin floods costing upwards of $30 billion (NWS, 2013). During the 20th century, flooding was the number one disaster in the US in terms of not only damage, but also lives lost (Perry, 2000). The Red Cross estimated that during the 25-year period ending in 1995, flooding worldwide affected more than 1.5 billion people and killed more than 300,000 (Pielke and Downton, 2000). The rate at which homes and businesses are being built in flood prone areas, accompanied with the natural human tendency to settle close to a plentiful water source has caused an observable increase in hazardous flooding over the past 100 years (Pielke and Downton, 2000; Pinter *et al*., 2008).

The US Midwest has faced numerous problems with regards to flooding in recent years. For example, as recent as June, 2008 catastrophic flooding caused widespread damage across eleven Midwestern states. This was the second "500-year" flood event in the region in the span of just 15 years (Holmes, 2008), and there are worries that such events will become more common in a changing climate. Moreover, the most recent report from the Intergovernmental Panel on Climate Change warns of the "risk of severe harm for large urban populations due to inland flooding" on a global scale (IPCC, 2013). It seems that understanding the variability and changes in Midwest flood behavior is vital to our cognition of, and response to, the issue of flooding (Booth *et al*., 2006).

Most previous hydroclimatological research has focused mainly on the Upper Midwest (due to the agricultural importance of the region) (Sharp, 1984; Gergel *et al*., 2002; Hejazi and Markus, 2009) or the Midwest as a whole (Changnon and Kunkel, 1995; Angel and Huff, 1997; Dirmeyer and Kinter, 2009; Villarini et al., 2011). Few studies have attempted to understand flood regime variability in the Ozark Highlands ecoregion. Hydrology in the Ozark Highlands is unique from the Upper Midwest. Steeper slopes and minimal groundwater influence dominates due to igneous outcrops in the east of the Ozark Highlands, and in the west shallower slopes and deep aquifers offer different hydrological behavior (MDNR, 2003). For example, some cross-basin flow occurs in the karst areas of the Ozark Highlands, though the extent of this is poorly understood (Hu *et al.,* 2005). The Ozark Highlands are generally warmer and experience greater rainfall amounts than the northern portion of the state (Harrington, 2012). It is likely that patterns and trends in flood behavior between the Ozark Highlands and northern Missouri are different due to differing hydrology and climate.

Modeling has be used to evaluate the effects of climate and land use change on stream discharges in the Ozark Highlands. One of the main findings was that there is a synergistic effect of land cover and climate change on basin discharge variability (Hu *et al*., 2005). When land use change of forest to grassland was modeled in combination with a wetter climate, discharge increases were double what they were when there was no climate change (Hu *et al.*, 2005). The authors suggest that changes in discharge caused by climatic variability are almost constant regardless of land cover changes, meaning that climate change seems to be the dominant factor on changes in discharges in the eco-region. This is important as the Ozark Highland eco-region has a long history of land use alteration, specifically from forested to agricultural land, though recent changes in rural watersheds are limited. The study by Hu *et al.* (2005) offers useful insight into the hydrological behavior of Ozark Highland watersheds, thought there is still a gap in our knowledge of how flood discharges have changed across the eco-region due to climate change and land use may effects. Understanding flood behavior, and the influences on it, in the region will have implications for the rest of the Midwest, especially if a climatic factor is involved. This study presents an analysis of historical flood records from the Ozark Highland ecoregion in order to understand trends and shifts in flood behavior over time.

Purpose and objectives

The purpose of this study is to analyze the longest available records of peak discharge data from Ozark Highland stream gages to evaluate trends in flood discharges since the 1920s. The focus is on the Ozark Highlands ecoregion due to the apparent lack of research in the area and the availability of long gage records. Annual maximum peak-flow time-series spanning 90 years from twelve Ozark Highland gages are examined. Using watersheds within a single ecoregion aids continuity in the fundamental geologic factors (i.e. geology, relief, soils, etc.) that influence flood discharges. This study will be the first to analyze trends in peak flow as well as large flood sensitivity and behavior of flood discharges over time in the Ozark Highlands. Recent trends (over the past 30 years) in flood discharges are described. Factors that influence the observed changes are discussed. The objectives of this study are as follows:

1) Analyze annual maximum peak-flow record trends, sensitivity to largest flood events, and discharge-drainage area relationships over time to evaluate Ozark Highland flood records;
2) Examine the behavior and recent changes in flood discharges using flood frequency analysis of the longest available peak flow records in the Ozark Highlands;
3) Evaluate the watershed-level factors involved in changing flood discharges using correlation analysis
4) Discuss the influence of climate change on the observed flood behavior and the management implications related to the observed changes in flood discharges.

BACKGROUND

Controls on flooding

Flooding is a natural process whereby a floodplain becomes highly adapted to its parent river in terms of the magnitude and frequency of flood events. Therefore, flood behavior is both essential to, and dependent on, the fluvial system (Knighton, 1993; Charlton, 2008; Booth *et al.*, 2006). Understanding flood behavior is needed for establishing best management practices to avoid unnecessary damage and loss of life due to flood events (Booth *et al.*, 2006). A number of factors influence variations in flood magnitude and frequency. Flow conditions are primarily controlled by topography, geology, soil, and vegetation that vary region to region (Tomer and Schilling, 2009). Climatic variability and land use change are generally considered the two main factors that influence changes in flood magnitude and frequency. It is essential to note that the significance of all of these factors can vary drastically, both spatially and temporally. Therefore, the application of an ecoregional framework is a logical way to approach fluvial hydrologic research, as an ecoregion contains watersheds with similar characteristics in terms of hydrology, geology, and biology (Nigh and Schroeder, 2002).

Climate. The most fundamental control on flooding is climate. Though wet antecedent conditions can exacerbate flood discharges, flood events are generally caused by the occurrence of extreme precipitation events in the US Midwest (Frost, 2000; Changnon and Kunkel, 2006; Dirmeyer and Kinter, 2009). The inherent link between precipitation and the hydrological cycle is the basis of the theory that a warming climate will have a drastic effect on flood regimes (IPCC, 2013). It stands to reason that an increase in precipitation from a changing climate is likely to increase flooding magnitude and frequency. Knox (1993) suggests that even modest climatic changes can have a drastic effect on flood magnitude, as shown by an analysis of a 7000-year floodplain record of overbank floods in tributaries of the upper Mississippi River. He associated smaller magnitude floods with a slightly warmer and drier period prior to a subsequent cooler and wetter climate shift that led to larger floods. More recently, Karlson *et al.* (2013) looked at climate change influence on catchment hydrology using a 133 year dataset from the Skjern River in Denmark. The authors found that a 46% in increase in precipitation and a 1.3˚c increase in temperature lead to a simulated 103% increase in discharge. While this study isn't focused in North America, it highlights the fact that climatic change can have a large effect on flood discharges.

An overall increase in the amount of precipitation in itself can increase flood risk. However, it is not the only rainfall factor involved in flood occurrence. The temporal distribution of a given amount of precipitation can also effect flood discharges, such as rainfall seasonality, duration, and intensity (USDA, 1989). High intensity rainfall leads to increased runoff when the watershed cannot cope with the amount of rainfall falling in such a short time span and infiltration or surface storage capacity is exceeded (Hewlett, 1961). Additionally, if all of the annual rainfall were to fall within a few days, then the duration of the intense rainfall event would be extended, further hampering the watershed's ability to absorb moisture and decrease runoff. Once soil becomes saturated, it acts much like an impervious surface where any additional rainfall would simply become runoff (Hewlett, 1961). Therefore, rainfall intensity and storm duration are both key factors in producing large flood events. This is of major importance in terms of the growing concern surrounding global temperatures, as higher temperatures lead to more rainfall during extreme precipitation events (Karl and Trenberth, 2003; Trenberth, 2011).

Land use. Evidence suggests that flood event frequencies increase with increasing land cover changes in a watershed (Solin *et al*., 2008). The removal of natural vegetation and an increase in impervious area will increase runoff rates through a decrease in resistance to overland flow (Gentry and Lopez-Parodi, 1980). Konrad (2003) suggested that the effects of urbanization on flood discharges is generally greater for high-frequency floods (2.33- or 5-year floods) than for low frequency floods (25-, 50-, or 100- floods). During large rainfall events, the infiltration rate of soil is drastically reduced as the soil becomes saturated. When this happens, soils behave much like impervious surfaces in an urbanized landscape, in that they create enhanced runoff conditions that add to stream flow (Holmes, 2014). Also in urbanizing areas, the connection of a storm sewer system to a natural stream network will also increase stream flow by producing an urban hydrology effect where rainwater reaches the streams much faster than in un-urbanized catchment (Burton and Pitt, 2001).

Soil disturbance and vegetation removal can also lead to soil erosion and thinning, decreasing the capacity for water retention and increasing runoff rates (Jordan and Zavala, 2008). Furthermore, at the height of agricultural production in Wisconsin (1920s and 1930s), flood events were approximately three times larger than expected under pre-settlement conditions (Fitzpatrick *et al*., 1999). Future re-forestation in previously settled watersheds would be expected to reduce flood discharges, and responsible land use management will likely become a vital tool in the endeavor towards flood damage reduction.

Geology. Geology and other related watershed characteristics (i.e. slope and soil thickness) also have important effects on river systems and flood behavior (Hu *et al*., 2005; Onda *et al*., 2006). Flood behavior between two adjacent undisturbed watersheds can be very different if they are underlain by different rock types and relief, even when within the same climatic regime. For example, porous bedrock in karst regions is known to display some level of cross-basin flow through complex bedrock conduit systems which may reduce runoff due to water percolation (Hu *et al*., 2005). Conversely, a watershed with relatively impervious bedrock (e.g. granite) would generally be expected to display increased runoff rates as the water cannot penetrate past the soil mantle (Onda *et al*., 2006). Watersheds with steep slopes can also produce higher flows during rainfall events because of increased runoff rates due to gravity increasing the energy of flow through the soil (El-Hassanin *et al*., 1993). In addition, soil thickness can play a role in flood behavior as the thickness of a soil is directly related to the soil's capacity to hold moisture. Thinner soils can hold less water, therefore during a rainfall event, these soils are likely to produce higher runoff rates than thicker soils under the same rainfall and slope conditions (Jordan and Zavala, 2008).

There are other important factors that influence floods including river channel modification, construction of flood defenses, and large-scale atmospheric oscillations (Pielke and Downton, 2000; Graf, 2006; Zhang and Delworth, 2006; Higgins *et al*., 2007; Pinter *et al*., 2008; Heine and Pinter, 2012). For example, dam influence can have a drastic effect on flow regime, where the amount water that flows downstream of the dam is no longer controlled by the river itself (Perry, 1993; Graf, 2006). Nevertheless, climate, land use, and geology remain the most significant controls in fluvial systems (Mahmood et al., 2010). The effects of climate and land use changes on stream flow can be difficult to separate as they seem to have a synergistic effect (Tomer and Schilling, 2009; Hu *et al.*, 2005). One notable study in Northeastern Illinois discovered that urbanization has caused a 34% greater increase in peak flows than climate variability, when they attempted to evaluate the impacts of both land use change and climatic variability (Hejazi and Markus, 2009). They key to discerning climatic change from land use alteration is the study of watersheds that have experienced low amounts of land use change over the study period. Logically, if significant patterns in flood behavior can be determined across these watersheds, it is likely that the changes occurred due to climate factors at a greater scale than the individual watershed level.

Midwest flood trends

There is a general consensus within the literature that rainfall amounts across the US Midwest have increased in recent years (Groisman and Easterling, 1994., Changnon, 1998., Kunkel *et al*., 1999., Olsen *et al.*, 1999., Easterling *et al*., 2000., and Goisman *et al*., 2001). Karl and Knight (1998) summarized that, across the US as a whole, there has been a 10% increase in precipitation since 1910. Furthermore, the increase seems to be due to a combination of increases in both the number of days with precipitation and the intensity in heavy rainfall events. Angel and Huff (1997) examined the patterns of heavy rainfall events, specifically those more associated with significant flooding, in the US Midwest. The authors found that precipitation gages were much more likely to experience their heaviest one-day rainfall events between the years 1948 to 1994 than during the 47 years prior. Similarly, Changnon and Kunkel (1995) found an increase in flood-related precipitation events in the northern Midwest between 1921 and 1985. These findings are further supported by flood evidence from the stratigraphic record of Mississippi River floodplains, which show that a shift to more frequent large flood events has occurred since 1950 (Knox, 2006).

A more recent study by Qiao *et al*. (2014) focused on the Lower Missouri River basin where stream flow was modeled with climate projections. The main result was a prediction of an even wetter environment in the future with the possibility of more flooding. Moreover, the authors also found that the largest modeled increases in stream flow were during the winter months (November to February), indicating a potential seasonal shift in large flood events given more rainfall falling on leaf-off watersheds. There are more studies that have linked precipitation increases to increases in flood severity in the Midwest (e.g. Changnon and Kunkel, 2006; Pinter *et al*., 2008; Villarini *et al*., 2011). All of these studies support the idea that precipitation amounts and intensity have increased in the Midwest since the middle of the 20th century. Increase in rainfall are expected to result in an increase in the frequency and magnitude of river flood events in the Midwest.

With regards to land use changes, the Midwest has undergone fairly drastic changes since early settlement. In general, this has occurred in the form of the deforestation for agriculture followed by a shift towards urbanization of agricultural and forested areas (Foley *et al*., 2005). Mishra *et al*. (2010) modeled the effects of land use and climate changes in the Upper Midwest based on historical land use data. One of the main findings was that with continuing trends of deforestation, surface runoff is likely to increase, while evapotranspiration would decrease. Decreased evapotranspiration and increased surface runoff means an overall increase of water in the rivers and streams and an increased risk of flooding. Markus and McConkey (2009) also suggest that ongoing urbanization in Illinois will increase flood discharges to a greater extent than what can currently be seen in the record. It is important to recall that land use and climatic change work in tandem to alter the flood regime of a river (Hu *et al.*, 2005).

Flood frequency analysis

The flood regime of a river can be studied and evaluated by understanding magnitude and frequency relationships of flood events through the analysis of recurrence interval discharge values. The primary approach for studying flood regime begins with flood frequency analysis (FFA) (Stedinger and Griffis, 2008). FFA outputs a series of maximum flood discharge values for a range of recurrence intervals (RIs) based on probability analysis of past annual flood peaks derived from stream gage records (USGS, 1982). A RI can be defined as the time period over which it is likely that a particular magnitude flood will occur (USGS, 1982). Therefore, the 100-year flood is expected to occur on average once every 100 years. Of course, floods do not usually occur in a cyclic pattern over time. In fact, the 100-year flood has a 1% chance of occurring in any given year, but there are numerous examples of more than one in any one year. For example, two 100-year floods could potentially occur in consecutive years as the 100 year return period is simply a probability and not the actual amount of time between 100-year flood events. In fact, the US Midwest floods of 1993 and 2008 were two 500-year flood events that occurred in the space of just 15 years, even though it was statistically unlikely (Holmes, 2008). In comparison, a 25-year flood occurs on average once every 25 years, and therefore has a four times greater chance of occurring than the 100-year flood in any given year (Dinicola, 1996; Knox, 1998; USGS, 1982).

FFA has been used to study and model flood discharges throughout the USA where the information has been applied in levee design, flood insurance programs, and urban stream restoration projects (Bailey *et al*., 1989; Alexander and Wilson, 1995; FEMA, 2012). USGS Bulletin 17B contains procedures for calculating discharges and frequency calculations from an annual maximum peak flow time series, thus flood regime can be evaluated for locations where USGS stream gaging records are long enough (e.g. >20 years) (USGS, 1982). While the geographic variability of flood regimes is routinely assessed (Stedinger and Griffis, 2008), trends and variability of FFA outputs over different periods are less studied. There is a gap in our understanding of historical changes in flood behavior, especially at timescales that have relevance to management and restoration practices. If flood frequency changes significantly over human time scales of around 30 years, then understanding historical flood regime behavior can inform policy makers and flood management authorities to improve and implement flood mitigation policies, evacuation plans, and flood defense engineering projects.

STUDY AREA

This study evaluates the flood record for relatively large watersheds (1,000-10,000 km2) in the Ozark Highlands (Ozarks) ecoregion which covers approximately 108,332 km^2 of southern Missouri, northern Arkansas, south-eastern Kansas, and north-eastern Oklahoma, and includes approximately 45% of Missouri’s land area south of the Missouri River (Karstensen, 2010) (Figure 1). The studied watersheds were selected based on specific criteria (see Methods) and are displayed in Table 1, along with basic watershed morphology information. The Ozark Uplift occurred during the Pennsylvanian period (approximately 300-320 Ma) due to the Ouachita orogeny and the collision of the North and South American landmasses (Kisvarsanyi, 1981). The Ozarks can be split into three main sections based on physiography and geology: the St. Francois Mountains, the Salem Plateau, and the Springfield Plateau.

Geology and soils

The St. Francois Mountains, located in the western portion of the Ozarks, are the structural apex of the Ozark uplift (Anderson, 1970). The mountains are the remnant peaks of a Precambrian basement that have been partly uncovered from sedimentary deposits in the range of 0-6000 feet thick (Stout and Hoffman, 1973; Imes and Emmet, 1994). The sub-region is composed primarily of the Precambrian, igneous (granite and rhyolite) outcrops with small amounts of dolomite and limestone (Table 2). The

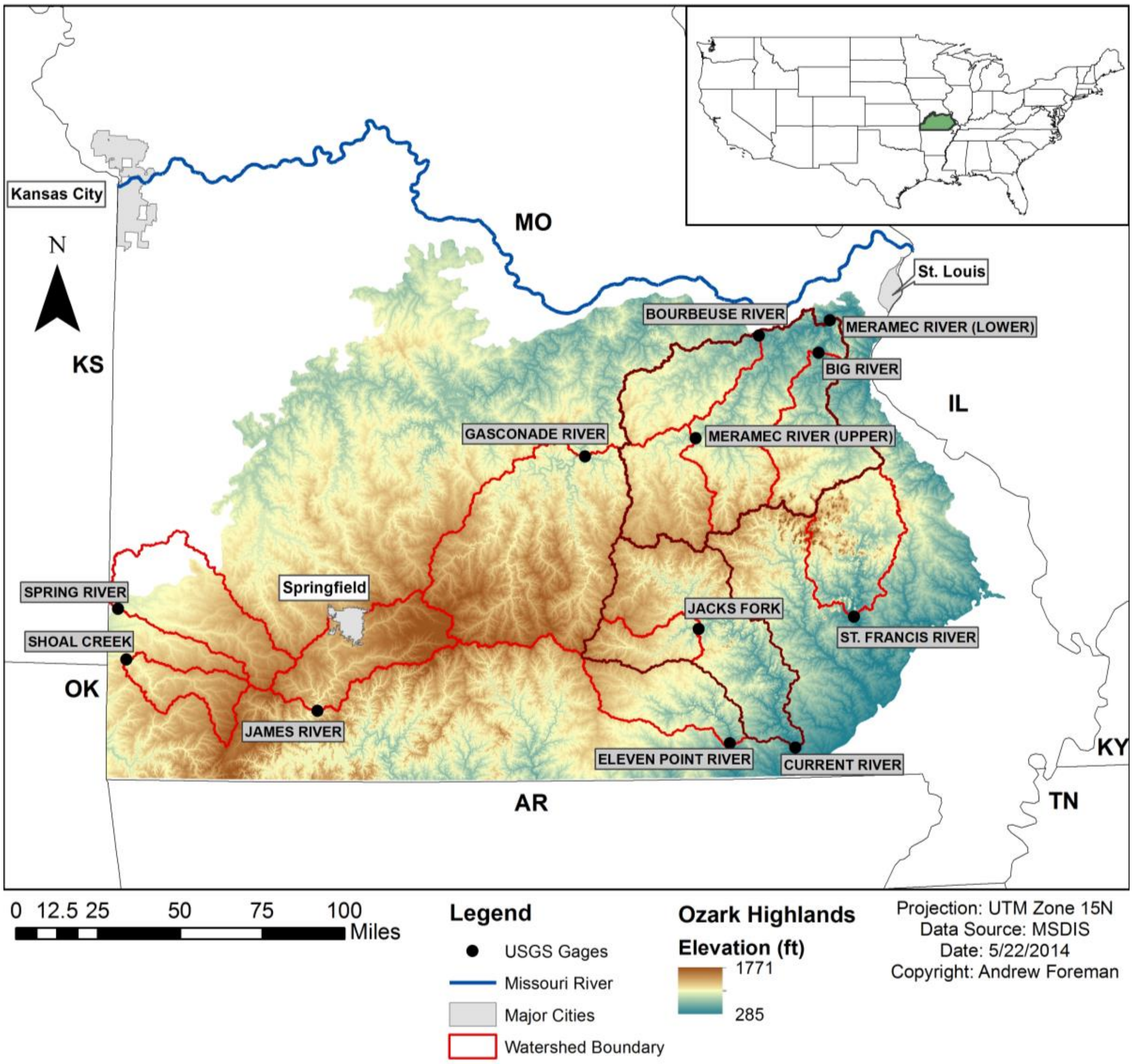


Figure 1. Elevation of the Ozark Highlands ecoregion in Missouri with major cities, studied watershed boundaries, and gage locations.

Table 1. Basin morphology of studied watersheds (ordered west to east based on the geometric watershed center)

Gage Number	Gage	Sub-Region[1]	Longitude	Latitude	Drainage area (km2)	Gage elevation (ft asl)	Maximum elevation (ft)	Basin relief (ft)	Channel slope (%)
07187000	Shoal Creek above Joplin	SGF	94.17	36.89	1106	884	1573	689	4.1
07186000	Spring River near Waco	SGF-OP	94.15	37.26	3015	834	1555	721	2.1
07052500	James River at Galena	SGF	93.21	37.07	2556	922	1738	816	6.1
06933500	Gasconade River at Jerome	SAL	92.26	37.51	7615	658	1741	1083	7.9
07066000	Jacks Fork at Eminence	SAL	91.66	37.09	1031	616	1608	992	10.3
07071500	Eleven Point River near Bardley	SAL	91.54	36.85	2054	793	1542	749	7.9
07013000	Meramec River near Steelville	SAL	91.53	37.76	2023	682	1463	781	7
07016500	Bourbeuse River at Union	SAL	91.42	38.23	2093	489	1215	726	5.9
07068000	Current River at Doniphan	SAL	91.39	37.15	5278	321	1608	1287	11.6
07019000	Meramec River near Eureka	SAL	91.13	38.02	9811	404	1730	1326	8.1
07018500	Big River at Byrnesville	SAL-STFM	90.7	37.97	2375	434	1730	1296	8.1
07037500	St Francis River near Patterson	STFM	90.49	37.53	2476	371	1771	1400	9.6

[1] SGF = Springfield Plateau, SAL = Salem Plateau, STFM = St. Francois Mountains, OP = Osage Plains.

Table 2. Bedrock geology of studied watersheds as per cent of drainage area, and per cent of drainage area within the main geologic sub-regions

Gage	Dolomite	Limestone	Sandstone	Igneous	Shale	Springfield Plateau	Salem Plateau	St. Francois Mountains	Central Plains
Shoal Creek	0	99	1	0	0	100	0	0	0
Spring River	0	99	1	0	0	70	0	0	30
James River	10	89	1	0	0	91	9	0	0
Gasconade River	64	1	35	0	1	0	100	0	0
Jacks Fork	52	0	48	0	0	0	100	0	0
Eleven Point River	50	0	50	0	0	0	100	0	0
Meramec River (Upper)	55	0	44	0	0	0	100	0	0
Bourbeuse River	36	0	64	0	0	0	100	0	0
Current River	56	0	44	1	0	0	100	0	0
Meramec River (Lower)	66	1	32	1	1	0	92	8	0
Big River	59	0	7	3	31	0	66	34	0
St Francis River	14	0	11	31	45	0	5	95	0

SGF = Springfield Plateau, SAL = Salem Plateau, STFM = St. Francois Mountains, CP = Central Plains.

mountains are rugged due to the igneous outcrops, and slope and relief are generally steep. Excessively drained, shallow ultisols and areas of rock outcrop can be found on steep slopes in the St Francois Mountain region, (Hemmerly, 2002). Basins with steep slopes and shallow soils tend to generate larger run-off rates during rainfall events due to better hydrologic conveyance, and generally create larger peak flows than basins with shallower slopes and thicker soils (Thomas and Leopold, 1978).

To the west of the mountains, the Salem Plateau sits at approximately 1,250 ft and is underlain by a mixture of dolomite, sandstone, and limestone (Table 2). The Springfield Plateau is further west still and is primarily underlain by limestone (Table 2). A number of large, first magnitude (>100 ft^3/s) springs can be found in the region including Blue Spring (Current River), Big Spring (Current River), Alley Spring (Jacks Fork), Greer Spring (Eleven Point River), and Meramec Spring (Meramec River). Cross-basin flow in porous bedrock areas of the Ozarks has the ability of altering stream discharges, though the extent of this affect is poorly understood (Hu et al., 2005).

Fertile alfisols are common across the Salem and Springfield Plateaus These soils are fairly fertile and can support good vegetation growth (USDA, 1981; Frey *et al*., 2014). Both the Springfield and Salem plateaus have been cut into by a number of rivers that have produced hilly areas with a range of channel slopes and watershed reliefs, though these are generally less than found in the St. Francois Mountain sub-region. Watersheds with shallow slopes and thick soils generally produce lower flood peaks due to larger near-surface water storage and reduced run-off speeds (Thomas and Leopold, 1978).

Vegetation and Land use

Vegetation is generally dominated by oak-hickory and shortleaf pine forests (Ethridge, 2009). More forest cover leads to more evapotranspiration, more rainfall interception, more surface friction, and protection from compaction by heavy raindrops that can reduce run-off rates during rainfall events (Lawrence, 1994). Accurate pre-settlement vegetation data is relatively scarce, however a study of palynology in the Ozarks by Smith (1984) found that a mixture of pine and oak forests were common under pre-settlement conditions. Schoolcraft (1821) describes the Ozark (Potosi to Springfield) vegetation as a mosaic of grassland, savannah, oak forest with open grass undergrowth, with densely wooded valley bottoms. Pioneers settling in the Ozarks during the 1800's cleared large portions of the thick forests for row crops and grazing (Jacobson and Primm, 1994). Better soils in river floodplains meant that they were first to be cleared, reducing the riparian buffer. Increasing soil erosion was inevitable from deforestation and removal of prairie grasses in the search of more land for agricultural practices (Rafferty, 1980).

During the late 1800's logging operations were increased to a dramatic extent in the Ozarks due to increased lumber demand. Accounts suggest that soil erosion was limited to the northern portion of the Ozarks, and hill slopes and steeper regions of the Ozarks were not subject to extensive erosion, likely due to the chert-rich soils (Jacobson and Primm, 1994). Extensive logging continued until the 1920's when agriculture had a revival (Rafferty, 1980; Jacobson and Primm, 1994). While agricultural production suffered during the 1980's, agricultural land cover and cattle populations have increased since the early 1970's (Jacobson and Primm, 1994., Karstensen, 2010). It is recognized that Ozark rivers have long experienced rates of bank erosion beyond the natural variability that would be expected since settlement (Jacobson and Primm, 1994., Flader, 2004., Martin and Pavlowsky, 2011).

The overall population of the Ozarks is approximately 1.7 million, and there are a couple of large cities, including Springfield with a population of 159,498 that sits mostly within the studied James River watershed (Homer, 2007). Impervious surfaces associated with urbanization can produce high peak flows due to faster conveyance of run-off and a lack of evapotranspiration and surface storage (Booth and Jackson, 1997). A general threshold that is often used for the effect of impervious area coverage on channel stability is 10% (Booth and Jackson, 1997). As the flood regime of a river is directly related to channel stability, this value can be useful in understanding the amount of urbanized area within a watershed that would be expected to have a strong effect on channel stability and flood discharges. The chosen study watersheds are classified as rural watersheds, with urbanized area percentages less than 10% (Harrington, 2012).

It has been suggested that growing populations and urban growth of cities located in the Ozark ecoregion will result in more detrimental land use change in the future (Karstensen, 2010), even though the introduction of soil management practices has generally improved watershed run-off conditions in the Ozarks in the past 40 year (Menau, 1997; Wortmann *et al*., 2008). In fact, soil erosion rates in Missouri as a whole decreased by half between 1985 and 2005 (MDNR, 2006). Additionally, forest regrowth in Missouri far exceeds forest removal, with area of regrowth rates having more than doubled between 1972 and 2005 (Moser *et al*., 2007). Totals based on the 2006 National Land Cover Dataset show that that the Ozarks are currently comprised of approximately

52% forest, 38% agricultural, and 10% urban land (Homer, 2007). However, current land use in the Ozarks varies across the region. Table 3 shows land use information for each watershed in the analysis, derived from the 2006 National Land Cover Dataset (Homer, 2007).

Climate

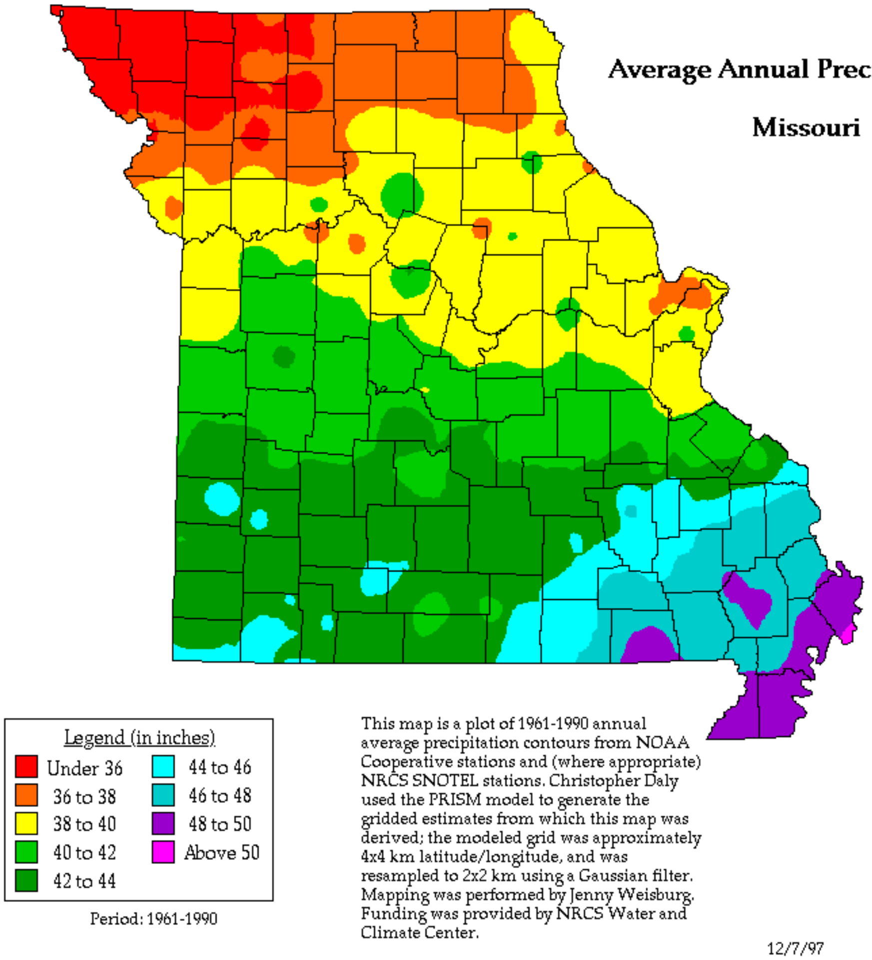
Ozark climate is continental in regime, and prevailing westerly winds drive commonly occurring storm systems in an easterly direction (Jacobson and Primm, 1994). While in the same general climatic region, the Ozarks generally experience higher temperatures and greater rainfall amounts than the northern portion of the state (Harrington, 2012). Generally speaking, winters are cold and summers are hot, though the weather is very variable. In the summer, temperatures can reach 90° F or higher on an average of approximately 55 days. Mean July maximum temperatures in the central Ozarks are relatively cooler than other parts of the ecoregion. In winter temperatures are below 32° for an average of approximately l00 days within the Ozarks (Decker, 2014).

Mean annual precipitation is approximately 40-45 inches in the Ozarks, though it varies across the eco-region. Figure 2 is a map of the 30-year mean annual precipitation (1961-1990) across the state of Missouri. Current maps of average annual precipitation across the state are unpublished. While outdated, this map displays the latitudinal variability in the average annual precipitation across the state. Seasonal variations in precipitation in the Ozarks are smaller than the north of the state as there is a greater influence of subtropical air masses coming from the Gulf of Mexico year round. Spring

Table 3. 2007 land use and 2009 road density in studied watersheds

Gage	% Forest	% Agriculture	% Urban	Road Density
Shoal Creek	30	62	8	2.47
Spring River	12	79	6	1.73
James River	41	50	7	3.31
Gasconade River	60	34	5	1.64
Jacks Fork	82	14	4	1.37
Eleven Point River	67	27	4	1.23
Meramec River (Upper)	65	28	5	1.66
Bourbeuse River	55	35	6	2.12
Current River	84	14	4	1.15
Meramec River (Lower)	58	33	7	1.94
Big River	72	20	7	2.06
St Francis River	65	31	4	1.31

Road density was calculated as the ratio between total road length within the watershed (km) and drainage area (km^2).



This map is a plot of 1961-1990 annual average precipitation contours from NOAA Cooperative stations and (where appropriate) NRCS SNOTEL stations. Christopher Daly used the PRISM model to generate the gridded estimates from which this map was derived; the modeled grid was approximately 4x4 km latitude/longitude, and was resampled to 2x2 km using a Gaussian filter. Mapping was performed by Jenny Weisburg. Funding was provided by NRCS Water and Climate Center.

Figure 2. Map of the 1961-1990 average annual precipitation in Missouri (Daly *et al*., 1994).

and summer precipitation largely comes in the form of thunderstorms, which are most frequent from April to July. It rains about 100 days a year, approximately half of which are days with thunderstorms which can produce intense rainfall events. The region experiences infrequent but extreme rainfall events which must be considered part of the normal climatic regime (Changnon and Kunkel, 2006). Flood events in smaller rivers resulting from heavy rains are expected once or twice in most years. Evaporation and transpiration is high during the summer months, sometimes leading to drought conditions if rainfall is infrequent (Decker, 2014).

METHODS

Gage selection

The selection of USGS gage records for analysis was based on four main criteria: (1) the majority of the watershed must lie within the boundaries of the Ozark ecoregion (Figure 1); (2) longest record length and continuity of gage operation (Hauth, 1974); (3) generally low urban influence (<10%); and (4) drainage area (A_d) of less than 10,000 square kilometers in an attempt to remove influence of large river dams (Graf, 2006). The longest operating, continuously recording flow gages were installed in the 1920s in Missouri. For this study, 12 gages with records of at least 90 years were selected for flood frequency analysis (Table 1). It is important to note that all watersheds lie entirely within the Ozark ecoregion boundary apart from the Spring River watershed, 30% of which lies within the Ozage Plains ecoregion (Table 2).

Data collection

Maximum annual flood time series were downloaded via the USGS Water Watch current stream flow data website (USGS, 2013). A full 90-year annual maximum peak flow time series was retrieved for each gage. These records were evaluated in 30-year intervals in two ways: 1) separated into three 30 year periods, and 2) thirteen separate 30 year time series' collected for each gage, the first spanning the years 1982-2012, with each successive time series set back by five years. Consequently, the next was 1977-2007, then 1972-2002, and so on until the record ran out in 1922 (Appendix A-2). A 30 year sample interval is often defined as the average climatic conditions for a region

(World Meteorological Organization, 2014). Therefore, each 30-year time series is inferred to represent the average climatic condition for the most recent year. Further, a 30 year period with no gaps is considered a time series of sufficient length to calculate flood discharges of various frequencies (Holmes, 2014). USGS procedures indicate that a 10 year time series is enough data to determine a discharge calculation for the 100-year flood, but the greater number of years of data the better, as a longer data set reduces sampling error and provides better model of the frequency relationship (Faber, 2010).

Watershed characteristics

Eco-region boundary data was obtained from the Environmental Protection Agency (EPA, 2013) website. Spring locations, USGS gage locations, elevation data, and geology percentages for each watershed derived from surficial geology data were obtained from the Missouri Spatial Data Information Service website (MSDIS, 2011). Land use percentages for each watershed were derived from the 2007 National Land Cover Database (Homer *et al.*, 2007). Drainage area was calculated using delineated watershed boundaries in *ArcMap 10.2*, produced from a 60 meter Digital Elevation Model (DEM). Gage height was also obtained using the 60 meter DEM, and relief was calculated by subtracting the gage height from the highest point in the delineated watershed. Main channel slope was calculated following the methods presented by Alexander and Wilson (1995).

Flood frequency analysis

The USGS software PeakFQ (2007) implements the most up to date and commonly used technique for calculating discharges for specific recurrence intervals (RIs) which is an estimate of the average interval time between floods of a certain magnitude (USGS, 1982; England, 2012). This technique was applied in the analysis of annual maximum flow time series data from the twelve USGS gaging stations, following procedures by Flynn *et al.* (2006). Flood frequency analysis was performed on a series of thirteen 30-year flood records for each gage. The overlapping technique of data collection lends itself to the analysis of changes in discharge for a range of RIs over time. Changes in calculated discharge over time for all RIs are displayed in Overlapping Magnitude-Frequency Analysis graphs (OM-FA). Each point represents one of the 13 *PeakFQ* discharge calculations (corrected for drainage area). Gage average discharge for each RI are also displayed on these graphs. The seven RIs are used in the analysis: the 1.5-, 2-, 2.33-, 10-, 25-, 50-, and 100-year floods. Three classes of floods are evaluated based on frequency and *PeakFQ* results for seven RIs for each gage record.

High frequency floods. High-frequency floods are representative of smaller, common rainfall events and are more susceptible to land use changes (Brooks *et al.*, 2003). Understanding the behavior of frequent flood events offers geomorphologists, biologists, and environmental engineers goals to aim for in terms of channel stability, habitat protection, and potential contaminated sediment erosion and transport. The mean annual flood for a given maximum annual series has an expected probability of occurring once every 2.33 years (Leopold *et al*., 1995). This flood flow (often referred to as the mean flood) is used in relating channel form variables to discharge and has inferred geomorphological significance (Knighton, 1998). The bankfull discharge is often referred to as the "geomorphically effective" flood, and has a reported RI of 1.5-years in the US (Leopold *et al*., 1995). Therefore, flood frequency analysis of the most frequent floods can be a very useful tool in the analysis of channel stability. It is important to note that some river channels can contain a flow with a discharge greater than the 1.5-year flood, and so the 2-year flood can also be used as the approximate bankfull discharge (Knighton, 1998). The 2-year flood is statistically the median flood flow. Because of the statistical relevance and the frequency of its occurrence, the 2-year flood is used by a number of flood management and restoration agencies, particularly when studying smaller of urban streams (Becker, 1986).

Moderate frequency floods. Moderate frequency flood events are represented by the 10- and 25-year flood events. These are flood flows that are not big enough and do not occur often enough to be considered the most geomorphically effective for the river channel. However, they are still responsible for considerable amounts of sediment erosion and transport in a river system (Knighton, 1998). Moderate frequency floods will overtop banks and be expected to erode and transport sediment out of channel bed and banks, and onto floodplains influencing floodplain form (Costa and O'Connor, 1995).

Low frequency floods. Low frequency flood events are the high magnitude over-bank flood events which can make significant and abrupt changes to channel and floodplain geomorphology (Kochel, 1988). Low-frequency floods are generally initiated by the most extreme rainfall events (Zhang and Schilling, 2006). These are represented in the analysis by the 50- and 100-year floods. The 50-year flood has an exceedance probability of 0.02, meaning that it has a 2% chance of occurring in any given year. The

100-year flood has an exceedance probability of 0.01. This means that there is a 1% change in any given year that a 100-year flood will occur. The 100-year flood is particularly important to evaluate since it is often used by engineers in levee design and by the Federal Emergency Management Agency (FEMA) for flood insurance rate and hazard mapping (FEMA, 2012). Therefore, evaluation of the largest floods on record is important for understanding flood risk, offering flood protection agencies the information needed to enforce economically viable and effective flood planning procedures.

USGS 100-year flood regression equation

The USGS produces regional regression equations for the estimation of discharges for a range of RIs. Alexander and Wilson (1995) present the most up-to-date generalized least-squares (GLS) regression equations for rural Missouri streams. The equation for the 100-year flood is as follows:

$$Q_{100} = 170A^{0.794}S^{0.471}$$

Where A is drainage area (mi^2) and S is main channel slope (ft/mi), calculated as “the difference in elevations at points 10 and 85 percent of the distance along the main channel from gage location to basin divide, divided by the distance between the two points” (Alexander and Wilson, 1995). The average standard error of estimate is 30%. Using this equation, a discharge estimation is are produced for the 100-year flood for each watershed. These discharges are then converted into Unit Discharge and compared to calculations produced from flood frequency analysis of the 1982-2012 period, in order to see how recent discharges differ from those produced and used by policy makers in 1995 (Alexander and Wilson, 1995).

Units

Discharge units for annual maximum peak flow time series and PeakFQ calculations are in cubic feet per second (cfs). Annual maximum peak flow discharge as well as USGS regression equation estimations were multiplied by 0.0283 to convert into cubic meters per second (m^3/s) for ease of data management. Additionally, in order to compare changes in discharge normalized for drainage area size, PeakFQ calculations were converted into specific discharge (per unit area). Discharge as cubic meters per second was multiplied by 1000, and divided by watershed drainage area to produce specific discharge, as liters per second per square kilometer ($l/s/km^2$).

RESULTS AND DISCUSSION

Multiple forms of analysis will be used to study trends in, sensitivity of, and discharge / drainage area relationships in annual maximum peak flow records. Food frequency analysis is presented after peak flow record analysis results. Recent trends in floods of a range of RIs are evaluated. Finally, flood frequency analysis calculations of the 100-year flood and 1995 USGS regression equations for the same RI flood are compared.

Annual maximum discharge trends

90-year trends. Average flood discharge has generally increased since 1922 in the Ozarks. Eleven of the twelve gage records indicate a positive increase in average flood peak discharge over the last 90 years in the Ozarks (Table 4). Four gage records, the Jacks Fork, Bourbeuse, Big, and Meramec (Upper) rivers, indicate statistically significant (<0.05 confidence) upward trends in average flood peak discharge over the study period (Figure 3 and Table 4). The trends in these gage records correspond to increases in discharge of 10.2, 7.7, 8.1, and 6.3% per decade, respectively (Table 4). Records for the Meramec (Upper), Eleven Point, St. Francis, James, Spring, Current, and Gasconade Rivers indicate 0.5, 2.9, 4.8, 5.1, 6.8, 4.5, 3.6% increases in discharge per decade respectively, though these are not significant to the 0.05 confidence level (Table 4). The Shoal Creek gage record is the only studied watershed that displays a downward trend with a 4.4% decrease in discharge per decade. The downward trend over the 90 year record is due to two large floods in 1941 and 1943 (Figure 3b).

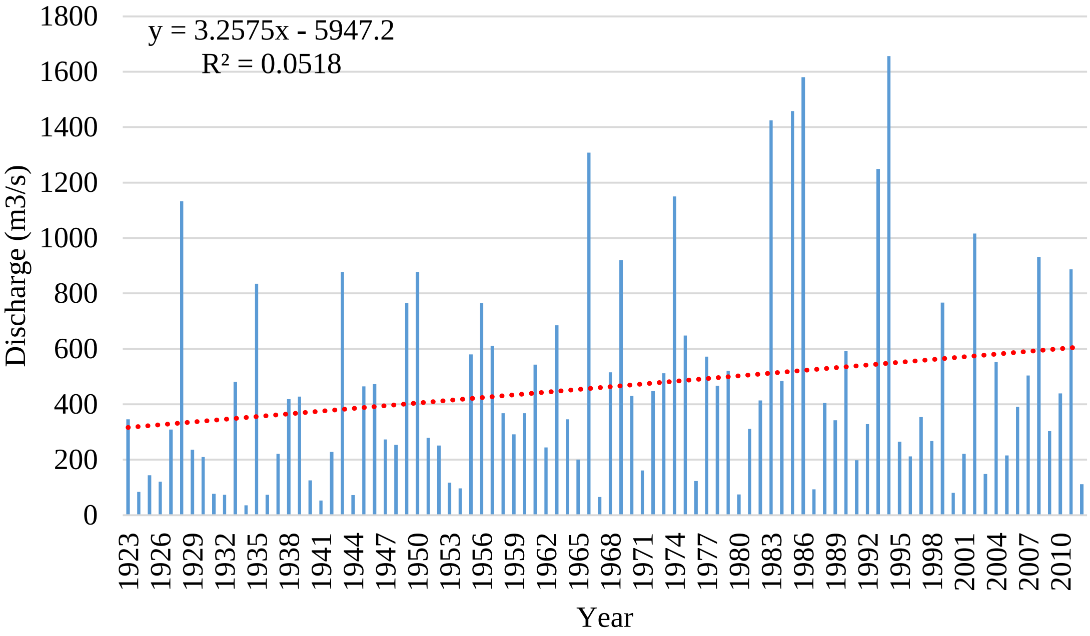


Figure 3a. Jacks Fork annual maximum peak flow record, with linear trend line

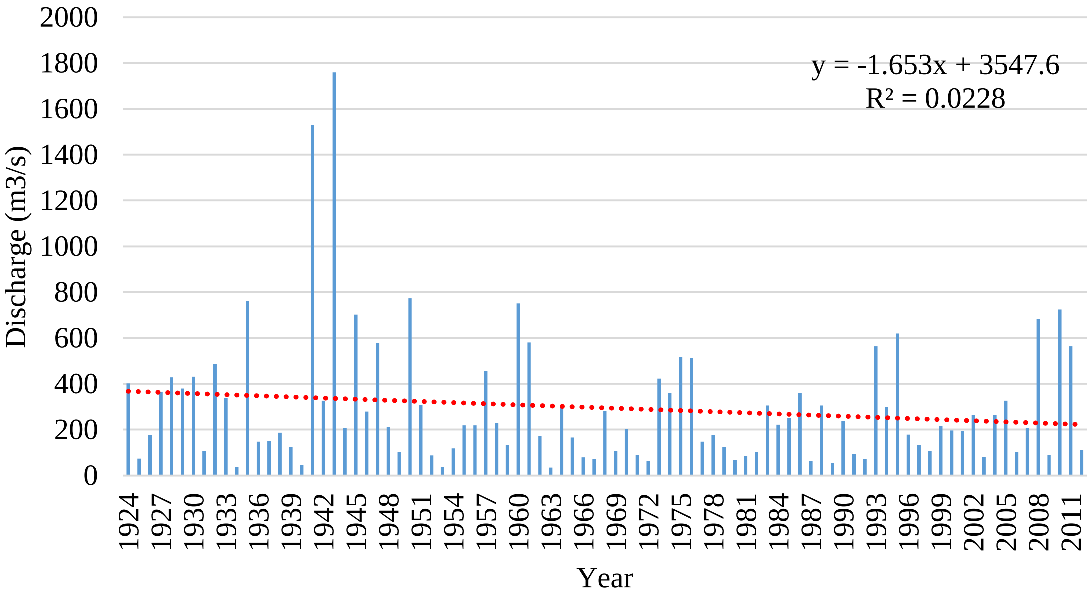


Figure 3b. Shoal Creek annual maximum peak flow record, with linear trend line.

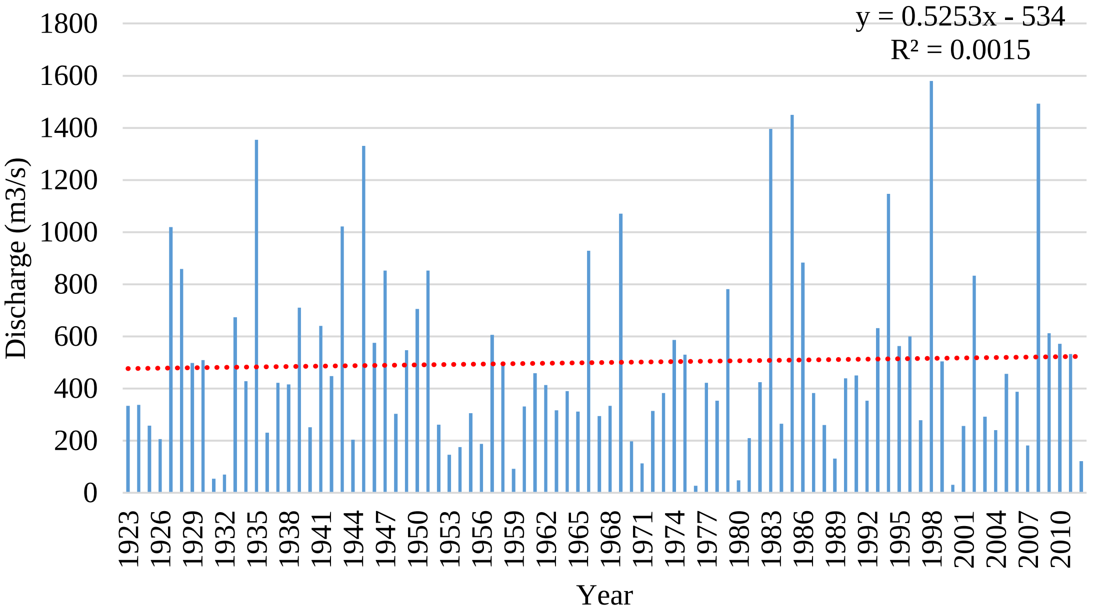


Figure 3c. Meramec (Upper) River annual maximum peak flow record, with linear trend line.

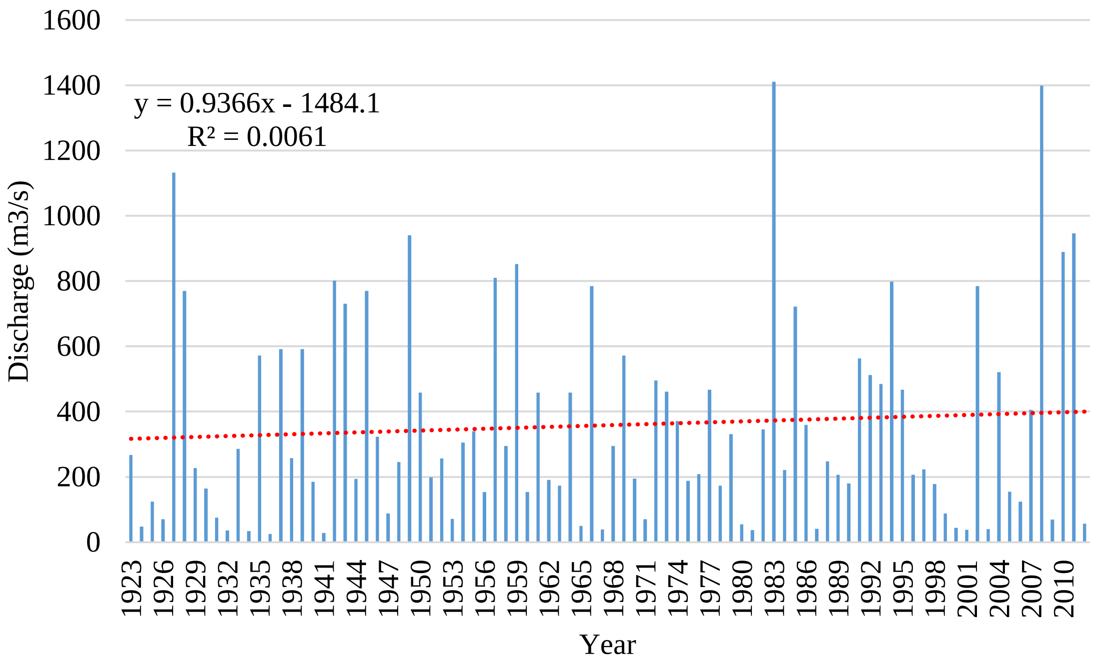


Figure 3d. Eleven Point River annual maximum peak flow record, with linear trend line.

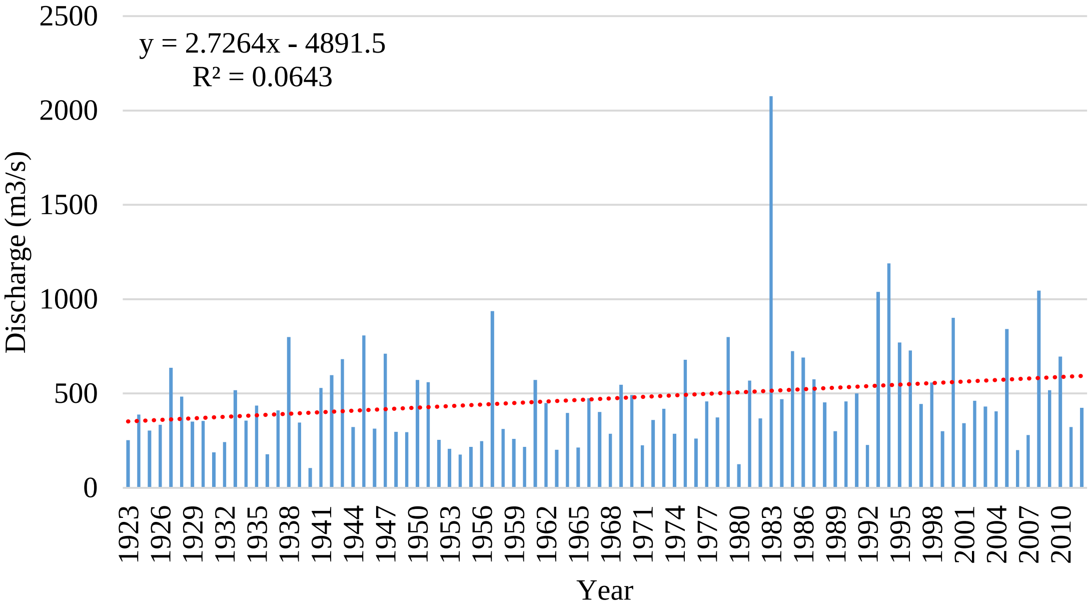


Figure 3e. Bourbeuse River annual maximum peak flow record, with linear trend line.

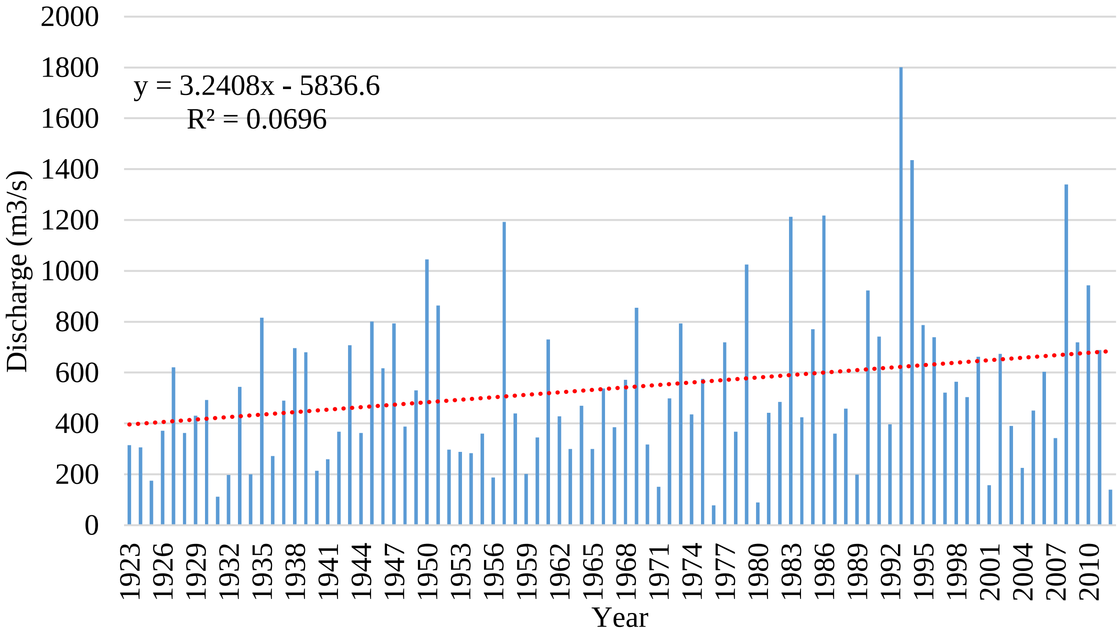


Figure 3f. Big River annual maximum peak flow record, with linear trend line.

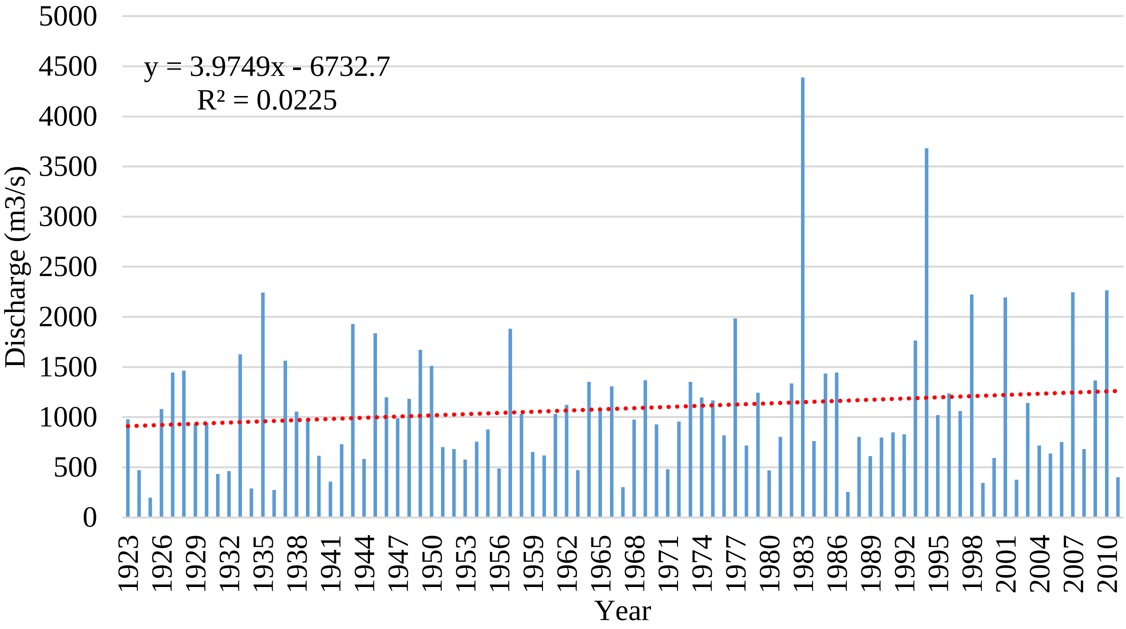


Figure 3g. St. Francis River annual maximum peak flow record, with linear trend line.

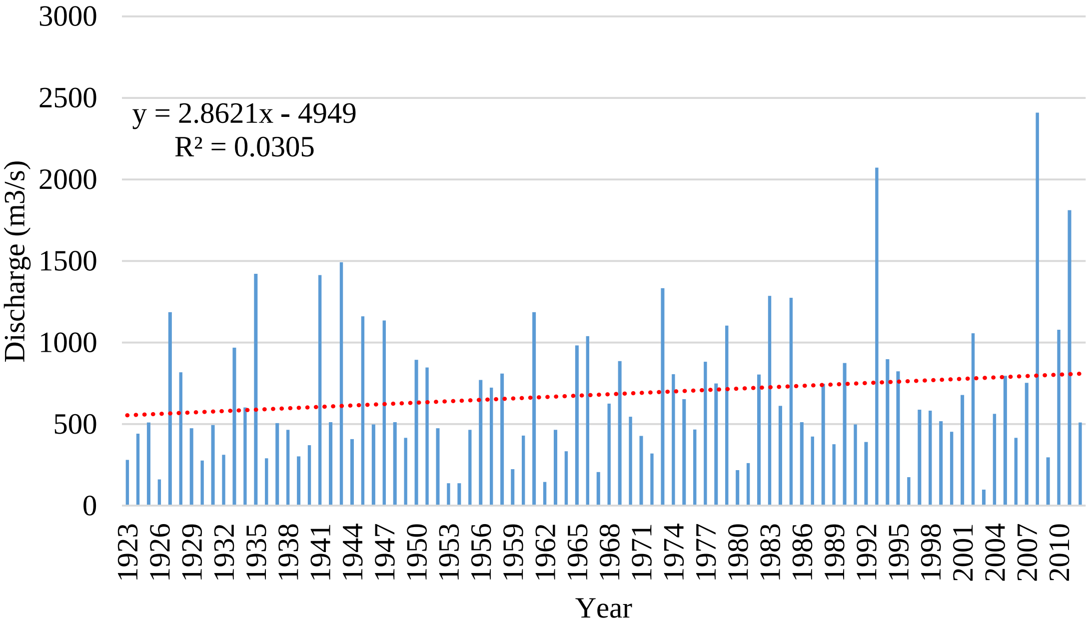


Figure 3h. James River annual maximum peak flow record, with linear trend line.

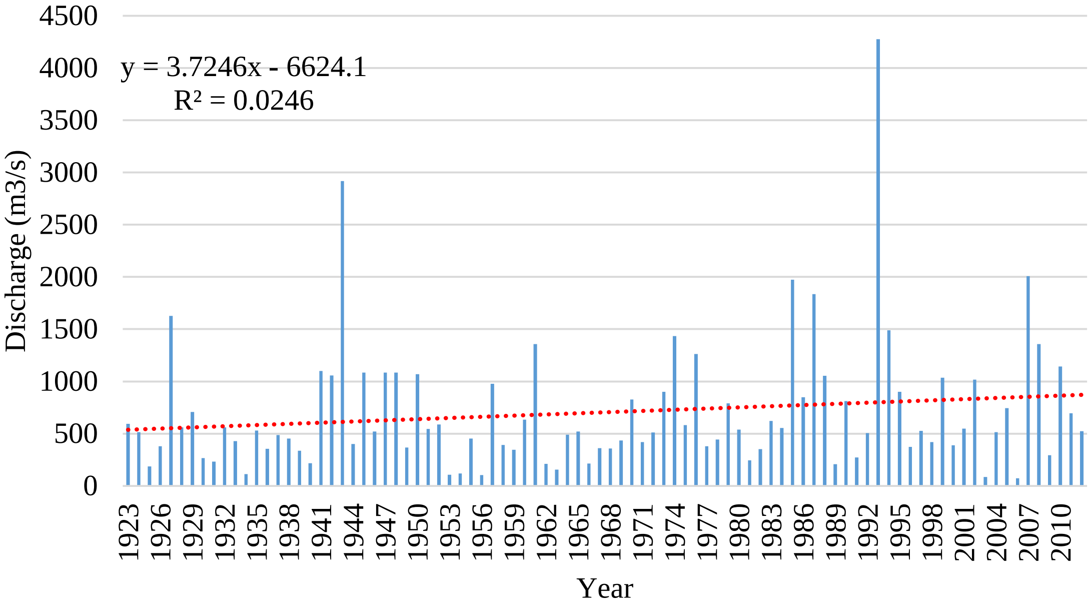


Figure 3i. Spring River annual maximum peak flow record, with linear trend line.

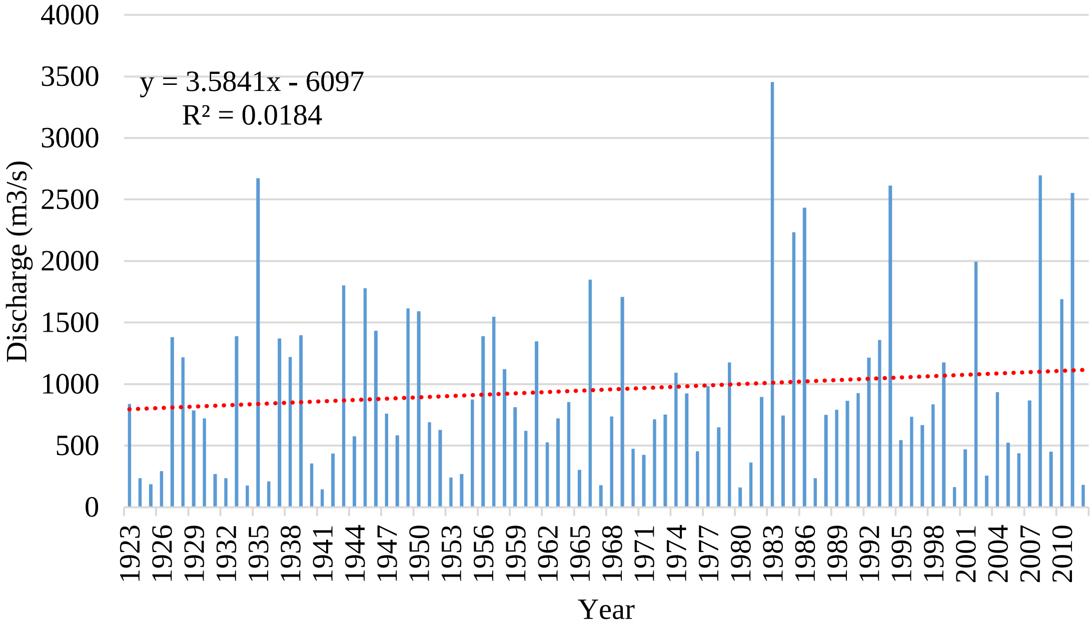


Figure 3j. Current River annual maximum peak flow record, with linear trend line.

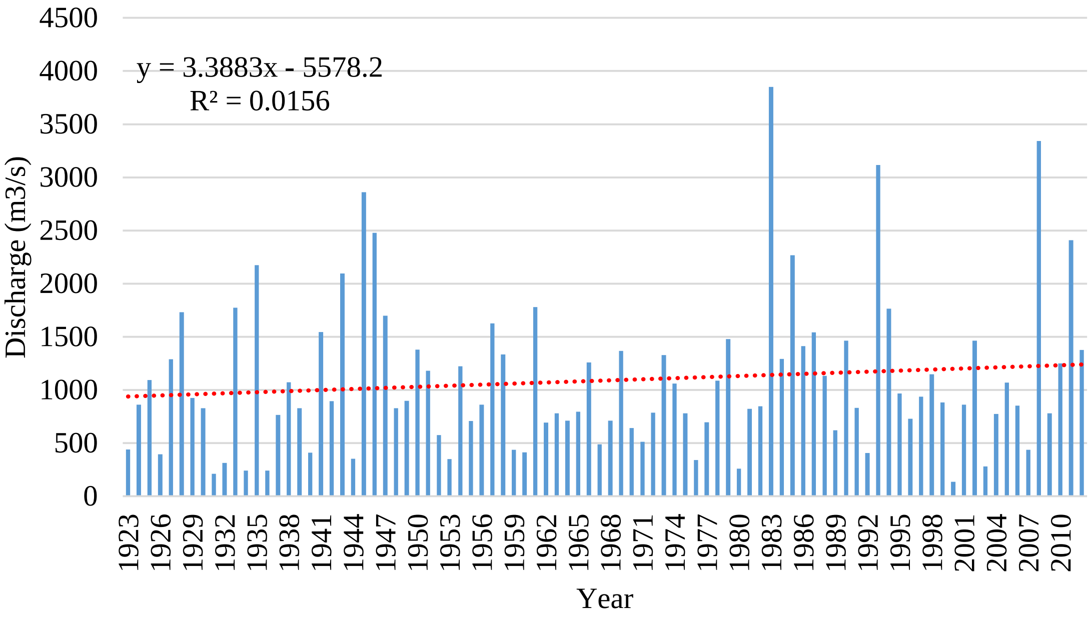


Figure 3k. Gasconade River annual maximum peak flow record, with linear trend line.

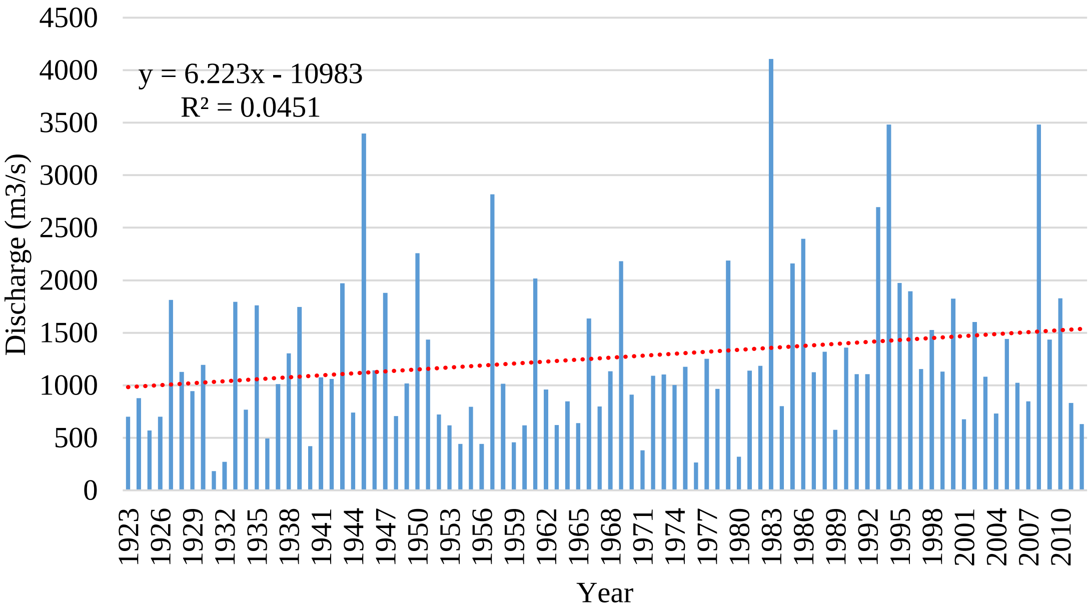


Figure 3l. Meramec River (Lower) annual maximum peak flow record, with linear trend line.

Table 4. 90-year annual maximum peak discharge trends

Gage Name	r^2	b_0 (y-intercept)	b_1 (slope)	p	Per cent change in discharge per decade[1]
Jacks Fork	0.05	-5947	3.26	0.03	10.2
Shoal Creek	0.02	3548	-1.65	0.16	- 4.4
Meramec River (Upper)	0.00	-43	0.28	0.85	0.5
Eleven Point River	0.01	-1484	0.94	0.46	2.9
Bourbeuse River	0.06	-4892	2.73	0.02	7.7
Big River	0.07	-5837	3.24	0.01	8.1
St. Francis River	0.02	-6733	3.97	0.16	4.8
James River	0.03	-4949	2.86	0.10	5.1
Spring River	0.02	-6624	3.72	0.14	6.8
Current River	0.02	-6097	3.58	0.20	4.5
Gasconade River	0.02	-5578	3.39	0.24	3.6
Meramec River (Lower)	0.05	-10983	6.22	0.04	6.3

[1] Per cent change in discharge per decade calculated by calculating the difference between the 1923 and 2012 mean flood discharges, divided by the number of decades in the record.

Flood record sensitivity. The three largest peaks floods were removed, replaced with the mean annual (2.33-year) flood value. The year of these flood occurrences in each gage record is displayed in Table 5. The per cent change relative to the mean annual flood at the start of the record (per cent change in discharge per decade), hereafter called the discharge change rate, was calculated for each gage. Removal of the three largest floods from the record generally leads to a reduction in the discharge change rate.

Despite decreasing rates with the removal of the three largest floods, increases in discharge can still be seen in ten of the twelve gage records. For example, the Big River record indicates an increase in mean annual flood discharge of 3.8% per decade (Figure 4). The Jacks Fork, Bourbeuse, Big, Spring, and Current River records indicate an increase in discharge of 3% (or higher) each decade without the three largest floods (Figure 4). It seems that increases in flood discharges presented in this study are not totally driven by the three largest floods, as evidenced by positive discharge change rates of up to 6% per decade for the record without the three largest floods (Figure 4).

The only record that shifts from positive to negative rate with the removal of the three largest floods is the Meramec River (Upper) record, which shifts from an increase of 1.1% per decade to a decrease of 1.9% per decade (Figure 4). This is because the 90-year trend was weak to begin with simply due to a number of relatively large floods early in the record and the three largest floods occurring later in the record (Figure 3c). The removal of the three largest floods increased the significance of the early floods, leading to an edited record discharge change rate that is unrepresentative of true flood behavior. Seven of the twelve gages, (Eleven Point, Spring, St Francis, Current, Gasconade, and Meramec (Lower), recorded their largest peak flow within the same three day period

Table 5. Year of the three largest floods on record (removed from trends for sensitivity analysis). 1 = largest flood, 2 = second largest flood, 3 = third largest flood.

Gage	1927	…[1]	1935	…	1941	…	1943	…	1950	…	1982	…	1985	…	1993	1994	…	1998	…	2007	2008	…	2011
Jacks Fork													2, 3		1								
Shoal Creek					2		1		3														
Meramec River (Upper)													3					1			2		
Eleven Point River	3										1										2		
Bourbeuse River											1					2					3		
Big River															1	2					3		
St. Francis River											1				2								3
James River															2						1		3
Spring River							2								1					3			
Current River			3								1										2		
Gasconade River											1				3						2		
Meramec River (Lower)											1					2					3		

[1]… indicates that there were no peak flows between the dates.

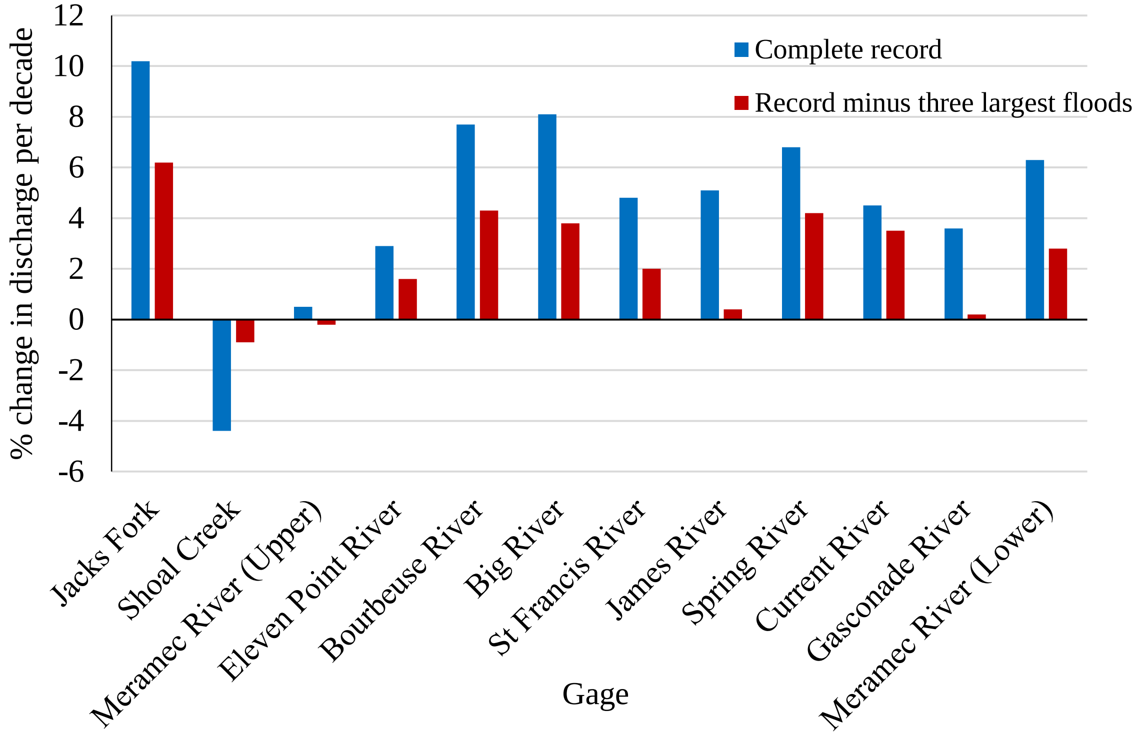


Figure 4. Difference in the discharge change rate between the complete record and the record with the three largest floods removed.

from December 3rd to 5th, 1982 (Table 5). The 1982 event was caused by a remarkably large heavy rainfall storm system that occurred during the winter months when watersheds are “shut down” in terms of evapotranspiration. This single event has had a lasting effect on many Ozark flood records.

The discharge change rate of the Shoal Creek record shifts in a positive direction once the three largest floods are removed. This is because the record captured two particularly large floods that occurred in 1941 and 1943 (Figure 3b). Subsequently, the discharge change rate between the true record and the cut record experienced a positive shift, even though the cut record discharge change rate remains negative at -3 m^3/s/decade (Figure 4). While flood peaks early in the record caused a downward trend in flood discharges over time, additional analysis is needed to understand the nuances of the record and to extract recent trends.

Across the twelve gages, the discharge change rate decreased by an average of 2.4% once the three largest floods were removed. This indicates that the studied flood records are highly sensitive to the largest floods, although this is to be expected when using annual maximum peak flow data (USGS, 1982). Leaving the largest floods out of the analysis would be unrepresentative of the true behavior of flooding in the Ozarks as extreme events are a natural part of the local climatic regime (Changnon and Kunkel, 2006). Further, climate change scenarios predict increased hydrologic extremes for the Midwest over the next century, and some studies report an increase in extreme floods over the past 30 years (Karl and Trenberth, 2003; Wuebbles and Hayhoe, 2004; Groisman *et al*., 2001; Groisman *et al*., 2005; Pryor and Schoof, 2008; Trenberth, 2011; Winkler *et al*., 2012).

Peak discharge - drainage area relationships

Regression equations vary among the three main periods of record, for both flood types. The median (2-year) flood and the mean of floods greater than the 10-yr RI (mean >10-yr flood) are calculated for each gage record for the first, second, and third periods of the 90 year record (1923-1952, 1953-1982, 1983-2012, respectively). Three discharge - drainage area regression equations are created for each flood frequency class. Hypothetically, a change in relationship slopes and/or intercepts over time indicates that there has been a change in the effectiveness of drainage area as a control on discharge.

2-year flood. Discharges for the median flood have generally increased in the largest watersheds in the Ozarks, but not those < 2000 km^2. An increase in discharge between the second and third period is observed in the median (2-year) flood relationships (Figure 5). The period during which drainage area is able to explain the most variability in the median flood discharge is the third period (r^2 of 0.79) (Figure 5). This indicates that over the past 30 years, drainage area has been a stronger control on the magnitude of small flood discharges in Ozark rivers, a period during which discharge has increased. Harrington (2012) reports that the relationship between the median flood and drainage area in the Ozarks was weaker than findings here suggest. Although, sample sizes and methods between the two studies differ. It is important to note that watershed factors (i.e. geology, soil thickness, land use, etc.) must play a role in determining smaller flood discharges (Harrington, 2012), though not in determining changes in discharge over

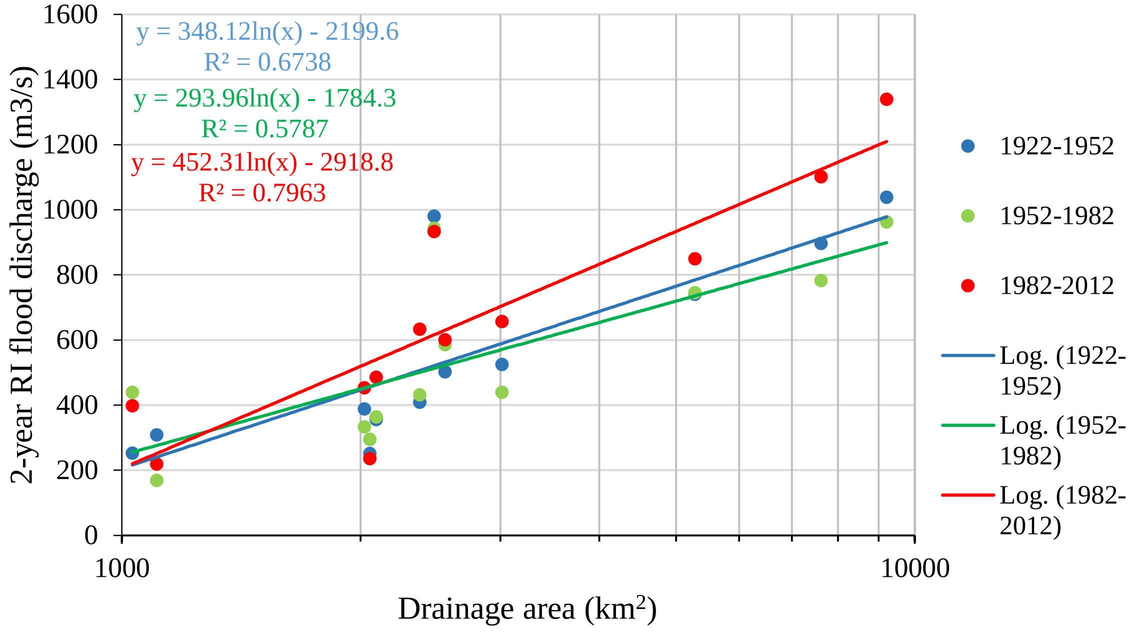


Figure 5. Relationships between the median (2-year) flood discharge and drainage area.

time, which must be a reflection of changing hydrology through land use, climatic change, or a combination of the two.

Small flood discharges have increased to a greater extent in larger basins in the Ozarks over the last 30 years. The median flood discharge - drainage area relationship changed very little between the first and second periods, but changed dramatically between the second and third periods (Figure 5). This is indicative of a change in the last 30 years, where median flood discharges have increased in larger watersheds while staying relatively unchanged in those approximately < 2000 km^2. This 2000 km2 threshold may be important to study further in the future, as it has huge implications for tackling channel stability management efforts in a changing system, no matter the reason behind the change.

<u>Mean >10-yr flood</u>. Greater discharges can be seen in the most recent 30 year period, as evidenced by the 1982-2012 relationship slope relative to the earlier periods (Figure 6). The greater slope and y-intercept values for the third period relationship indicates that there has been a large increase in the discharges of large flood events over the last 30 years, and that this increase has been most effective in larger basins (drainage area >2000 km^2). Drainage area is able to explain 69% of the variability in flood peak discharge in the third period, the highest of all three periods (Figure 6). It seems that drainage area becomes a greater control on large floods during periods of higher discharge (Figure 6). This seems logical, as a watershed of a certain size cannot produce an infinite amount of run-off and must therefore inherently limit a flood’s size. While drainage area does provide a major control on the absolute magnitude of flood peaks, other factors such as land use cover and climate can add significant variability to

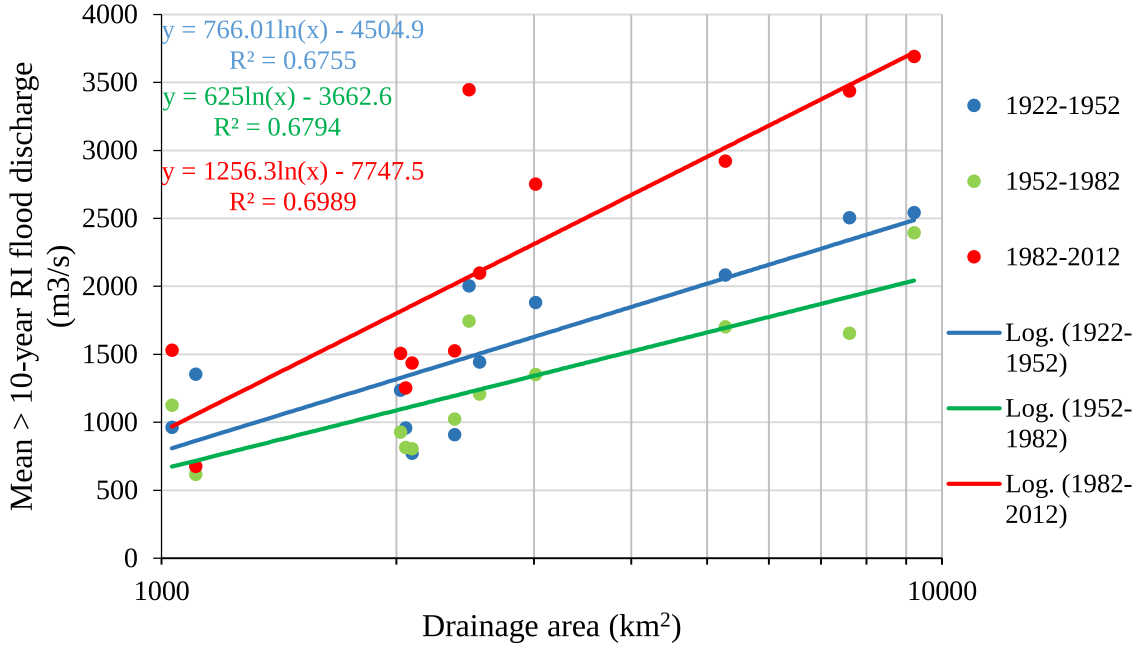


Figure 6. Relationships between the mean >10-yr flood discharge and drainage area.

discharge – drainage area relationships.

Increases in discharge between the second and third periods are high due to low discharges during the former. High flood discharges during the first period is potentially a reflection of watershed disturbances during the late 1800s and early 1900s (Jacobson and Primm, 1994). Lower discharges during the second period could therefore reflect dryer conditions of record and/or the improvement of watershed conditions post-timber boom.

Over half of the floods above the 10-year flood have occurred within the most recent 30 year period of the full 90 year record (Figure 7). This finding, along with the observed behavior in the three flood categories, correlates to previous findings across the Midwest that suggest that large flood events have increased in magnitude over recent time (Knox, 2006; Pinter *et al*., 2008; Villarini *et al*., 2011). In the literature, increases in large flood discharges are strongly correlated to an increase in heavy precipitation event intensity across the Midwest (Angel and Huff, 1997; Changnon and Kunkel, 1995).

Changes in variability over time

A simple way of viewing changes in variability over time is to compare the coefficient of variability (CV) (as the normalized variability) of the annual maximum peak flow record between the three thirds of the 90-year record (1923-1952, 1953-1982, and 1983-2012). The 1983-2012 period has a higher amount of variability than the two previous 30-year periods. The CV value of 72% for the 1983-2012 period is greater than both the 1923-1952 and 1952-1982 period values of 67% and 59% respectively. This indicates that there has been more variability in flood records across the Ozarks over the last 30 years. If increases in flood discharges can indeed be attributed to climatic factors

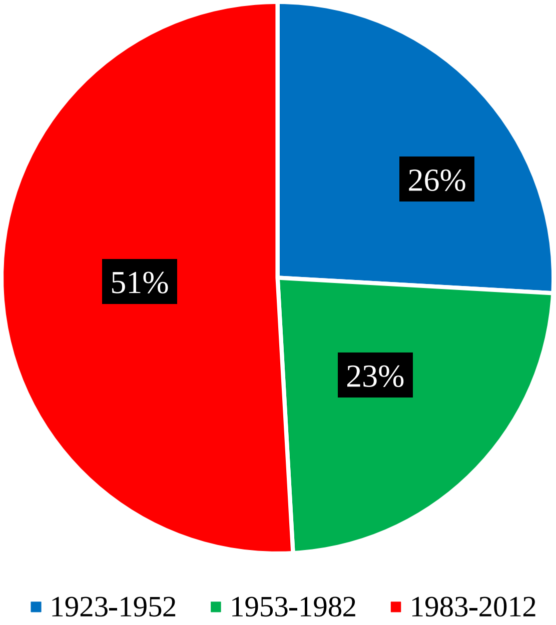


Figure 7. Temporal distribution of largest floods (> 10-year flood)

as previously mentioned, then is stands to reason that the higher amount of variability in the recent record can also attributed to climate change introducing greater extremes. This would support findings related to increased large flood discharges over the last 30 years that are likely to be correlated to recent increases in heavy precipitation event intensity (Angel and Huff, 1997; Changnon and Kunkel, 1995; Knox, 2006; Pinter *et al*., 2008; Villarini *et al*., 2011).

Flood frequency analysis

Overlapping magnitude-frequency analysis (OM-FA) trends.

High frequency floods. The three small flood RIs (1.5-, 2-, and 2.33-year events) behave similarly in a single record, but behave differently between different gage records. Major changes in the records occur following the period ending in 1982. That is to say, the main shift small flood events in the Ozarks occurred during the 1980s. Seven gage records display decreases in small flood discharges from the start of the record up until the periods ending in either 1977 or 1982. These are the Shoal Creek, Meramec (Upper), Eleven Point, Bourbeuse, Spring, Gasconade, and Meramec River (Lower) records (Figures 8b-e, i-j, and l). The James, Big, and Current River records indicate very little change in discharge, while the St. Francis River and Jacks Fork records indicate increases up until 1977. Overlapping magnitude-frequency analysis (OM-FA) graphs for the Meramec (Upper), Bourbeuse, Big, James, Spring, Current, Gasconade, and Meramec River (Lower) records all indicate a large upward shift in high frequency flood magnitudes from the periods ending in 1982 to the period ending in 2002 (Figures 8c, e-f, and h-l), after which there is very little change until 2012. Small flood discharges from

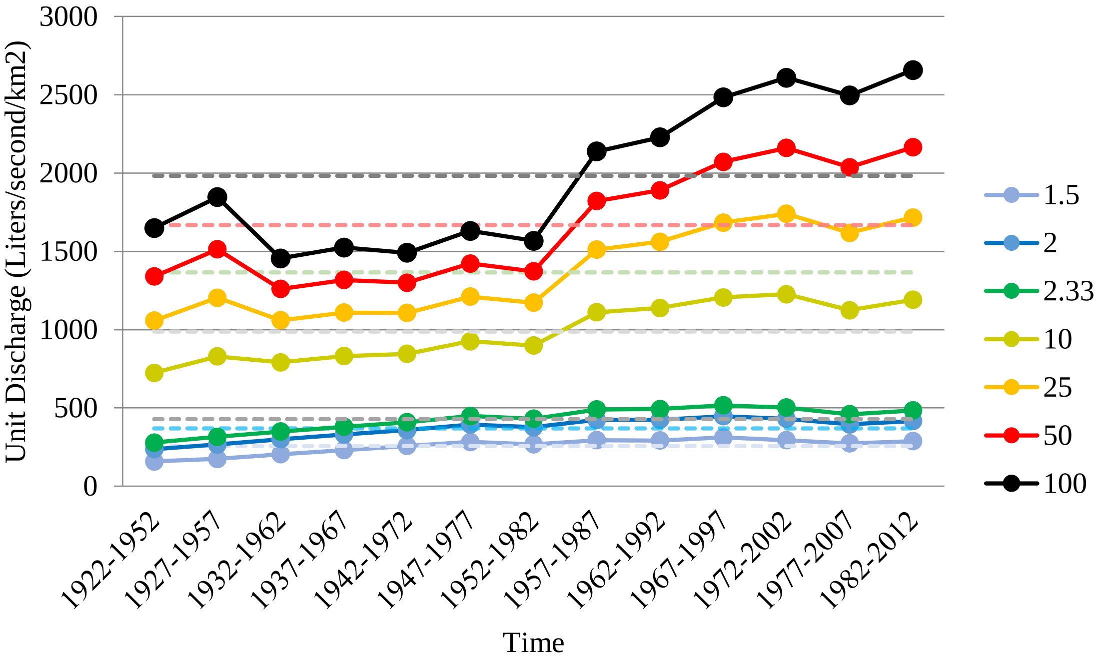


Figure 8a. OM-FA output for the Jacks Fork record.

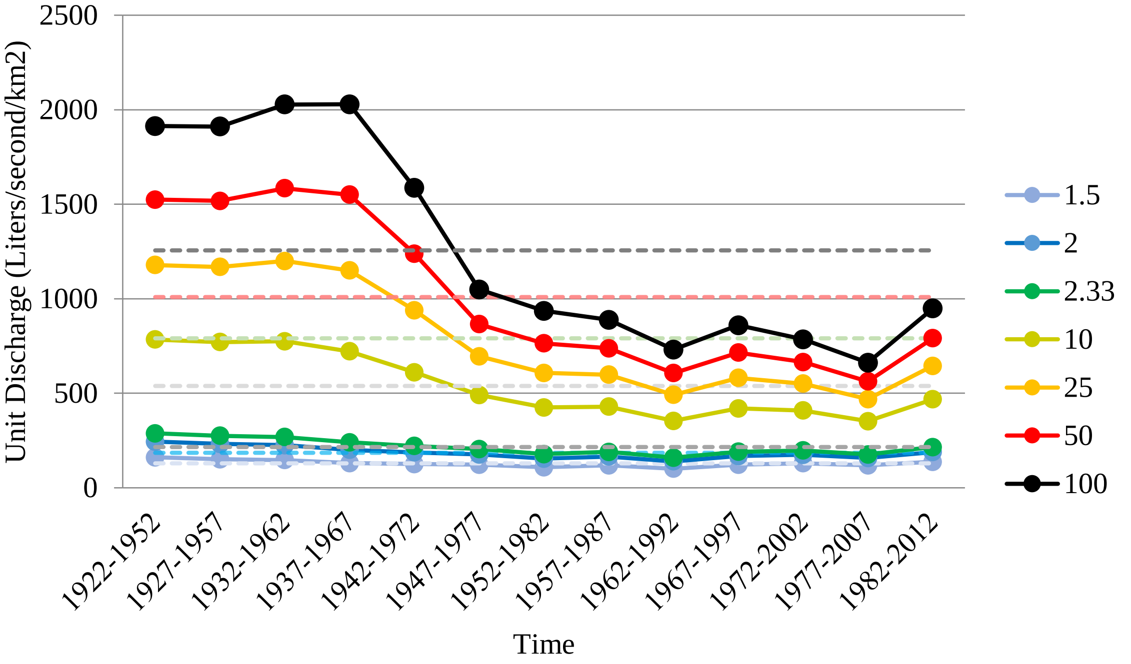


Figure 8b. OM-FA output for the Shoal Creek record.

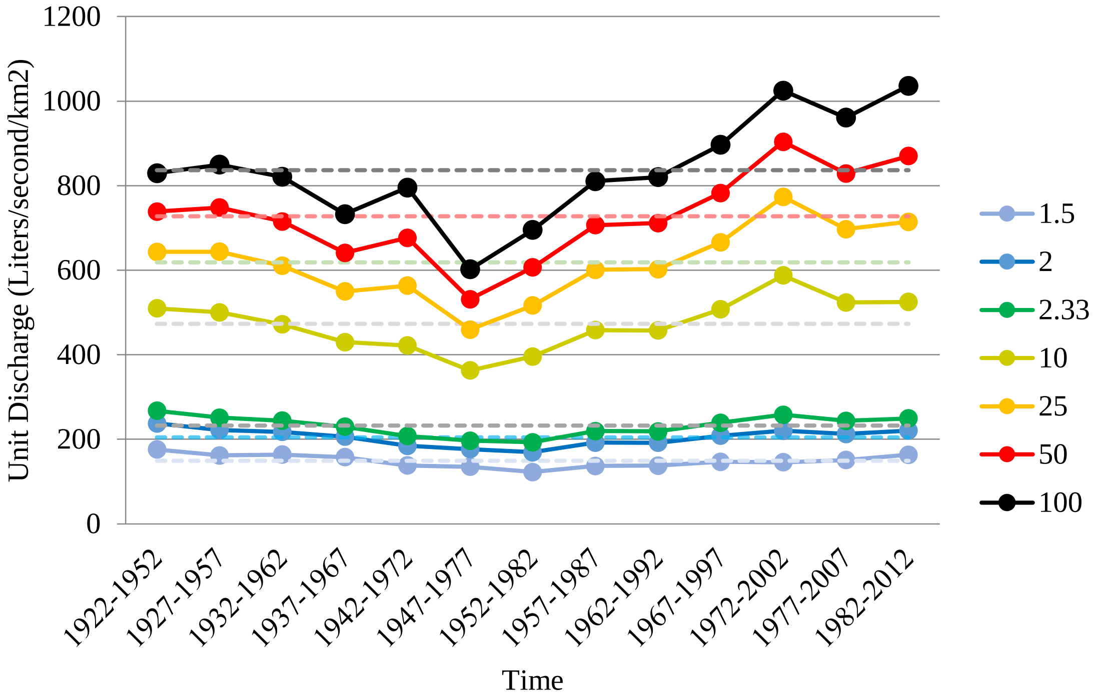


Figure 8c. OM-FA output for the Meramec River (Lower) record.

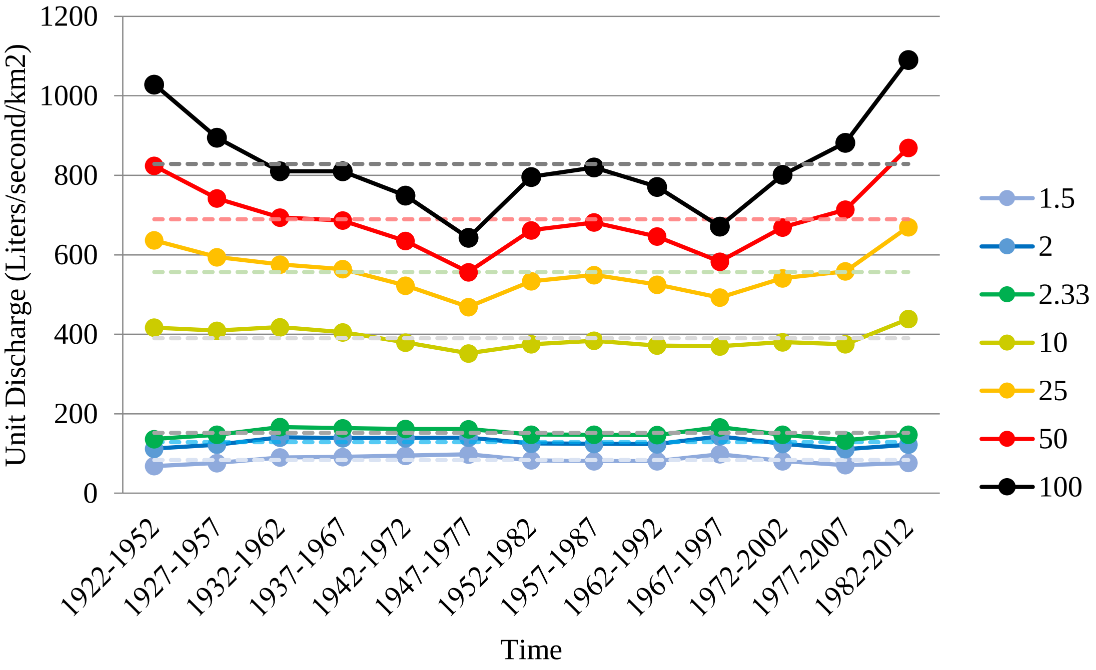


Figure 8d. OM-FA output for the Eleven Point River record.

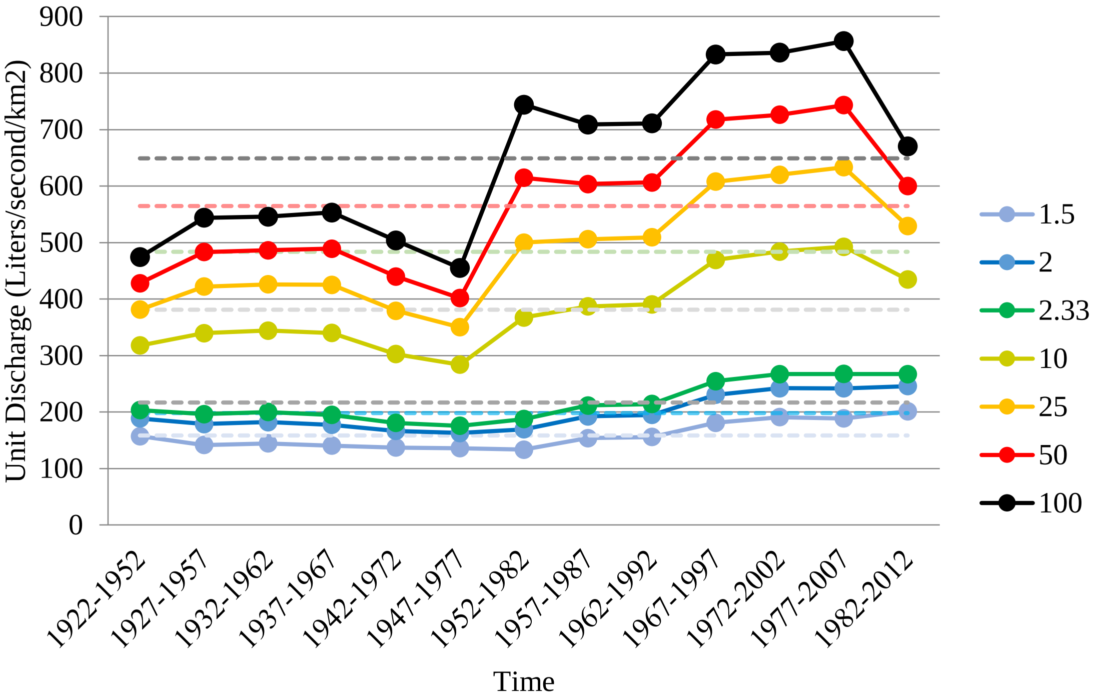


Figure 8e. OM-FA output for the Bourbeuse River record.

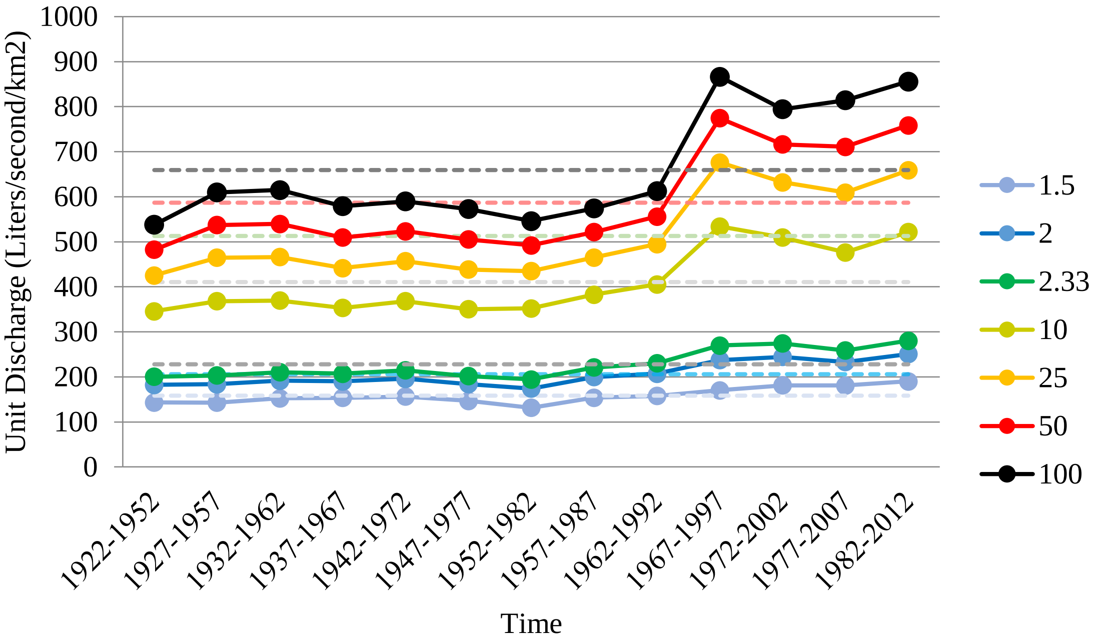


Figure 8f. OM-FA output for the Big River record.

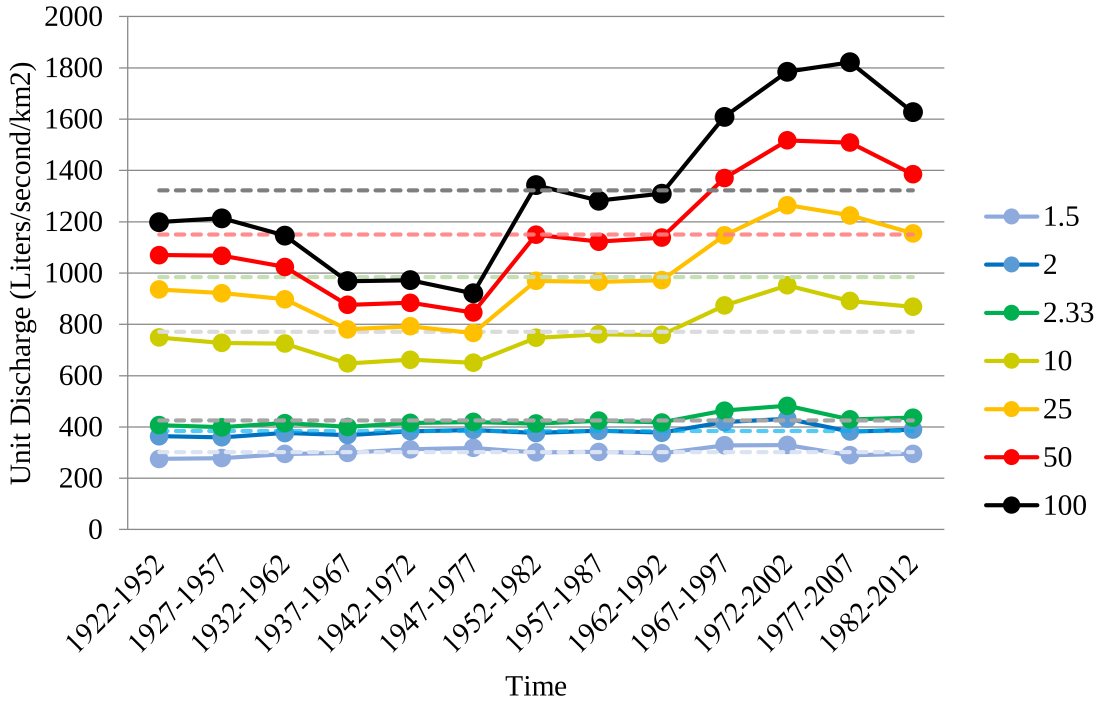


Figure 8g. OM-FA output for the St. Francis River record.

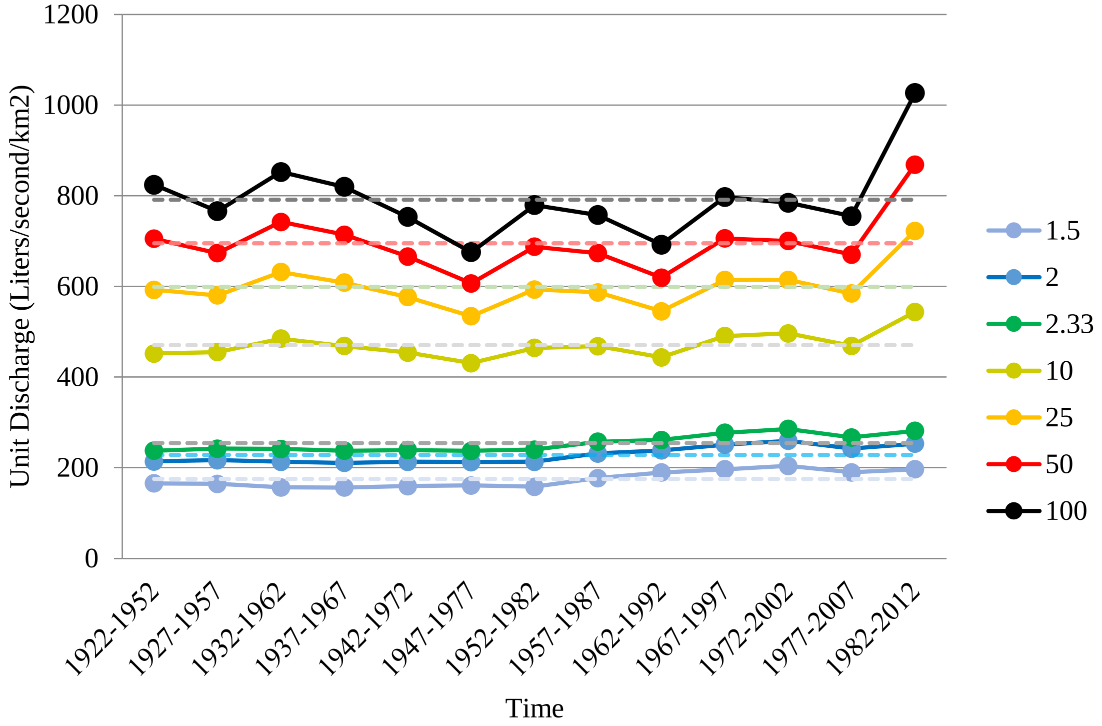


Figure 8h. OM-FA output for the James River record.

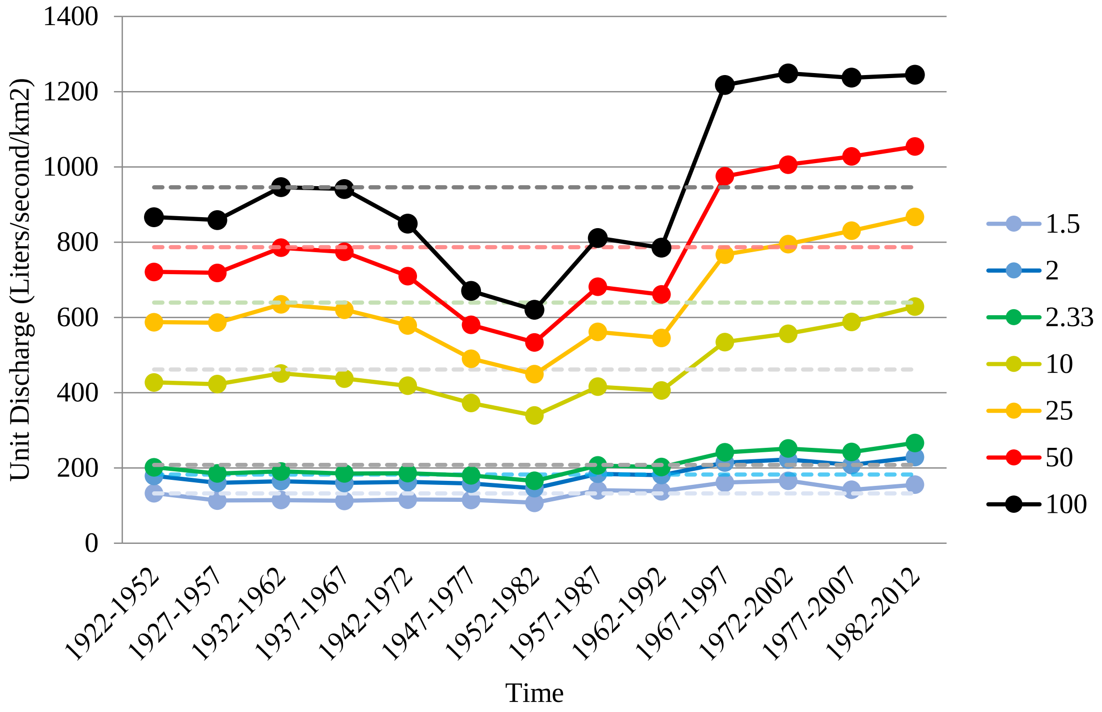


Figure 8l. OM-FA output for the Spring River record.

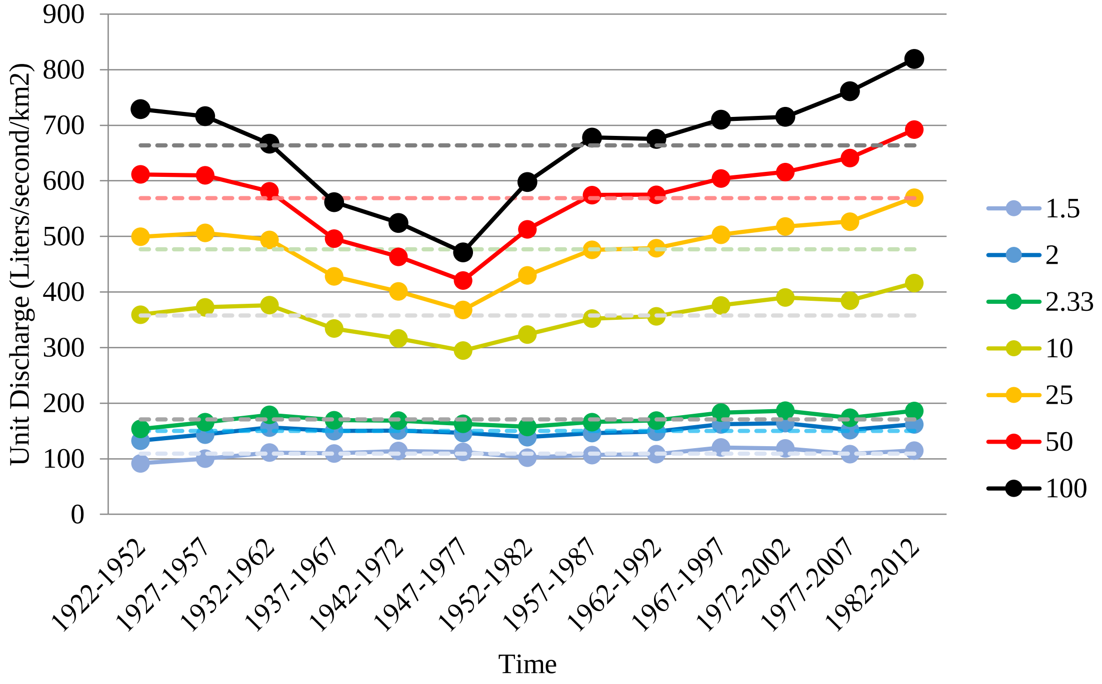


Figure 8j. OM-FA output for the Current River record.

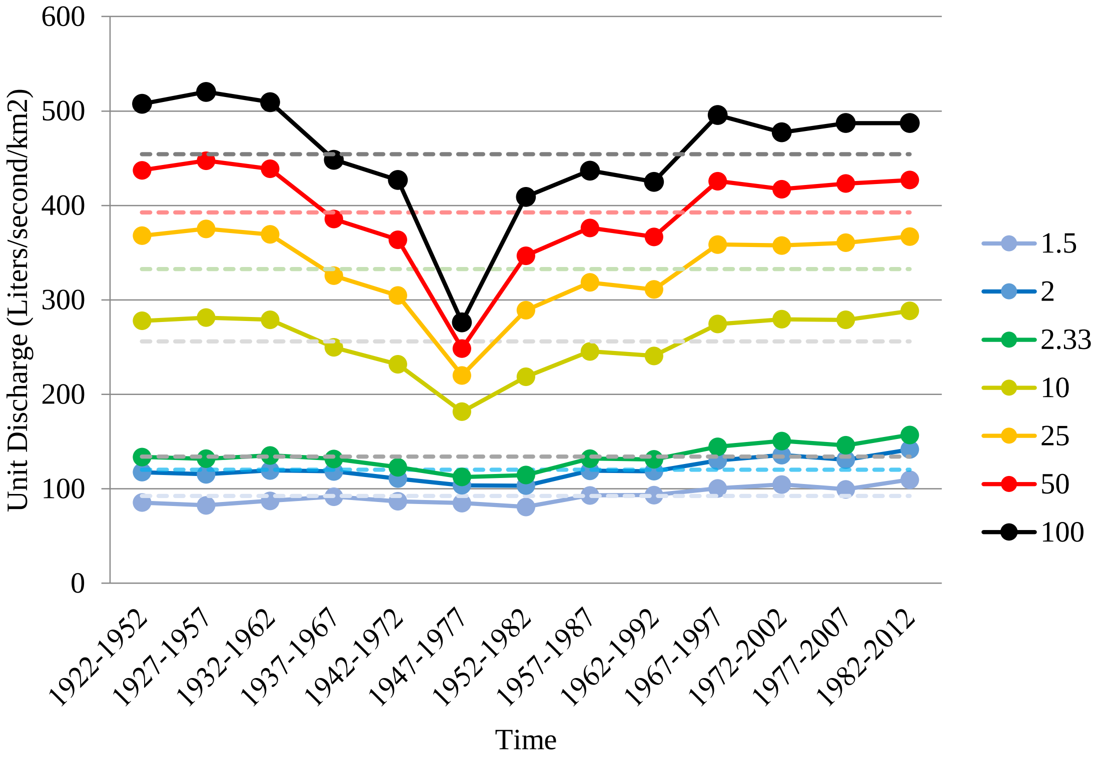


Figure 8k. OM-FA output for the Gasconade River record.

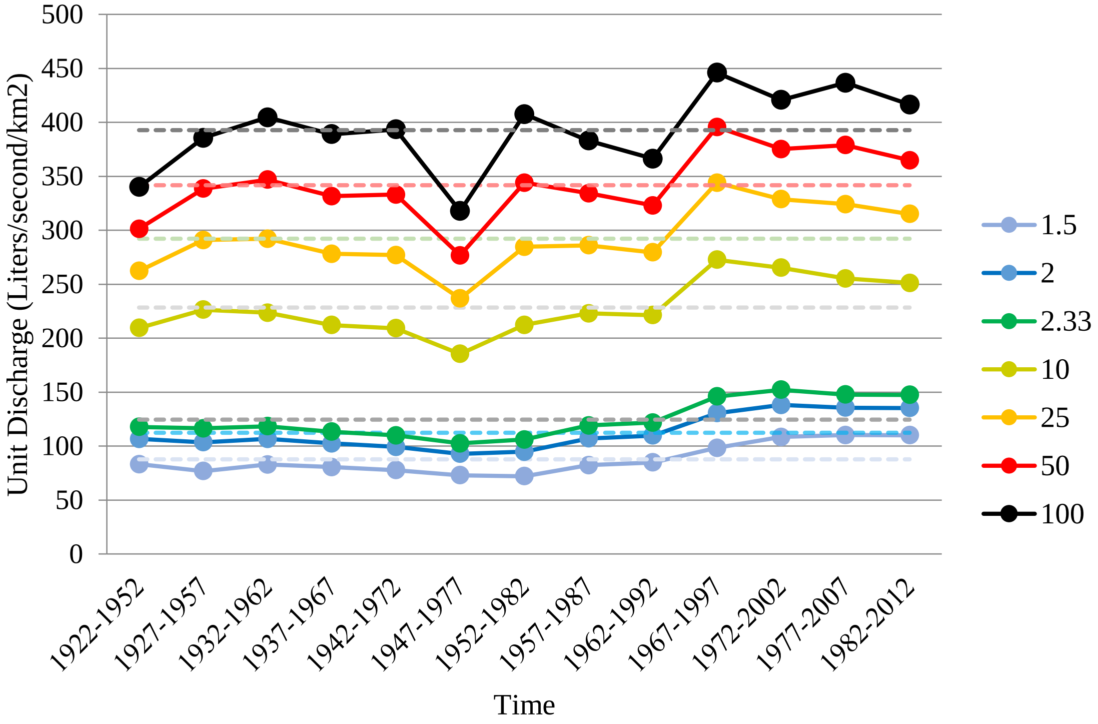


Figure 8l. OM-FA output for the Meramec (Lower) River record.

the Jacks Fork and Eleven Point records remained level with slight increases until the period ending in 1997, and have since decreased. Shoal Creek discharges steadied after 1982, but have increased slightly since 1992 (Figure 8b). Small flood discharges in the St. Francis River record remained steady all the way through to 1992, after which there was fluctuation (Figure 8h). Generally speaking, the periods ending in the late 70s and early 80s indicate the lowest small flood discharge calculations.

Moderate frequency floods. Moderate floods behave in a similar fashion to the low frequency, high magnitude floods. That is the timing of the shifts in discharge are the same for both sets of RIs, though the magnitude of the change differs between them. The magnitude of recent changes in moderate frequency flood discharges is discussed below.

Low frequency floods. Large flood behavior is comparable to small and moderate flood behavior trends in that large flood calculations from a single gage record are similar, though there are differences between watersheds. There seems to be a consistent theme of drastic increases in the 50- and 100- year RI discharge calculations during the 1980s and 1990s. Nine of the twelve studied gage records display this behavior: the Jacks Fork, Meramec (Upper), Bourbeuse, Big, St. Francis, Spring, Current, Gasconade, and Meramec (Lower) records (Figures 8a, c, e, f, g, and i-l). To a lesser extent, the Eleven Point and the James River records both increase in discharge following the period ending in 1977, after which discharge calculations seem to fluctuate up and down (Figures 8d and 8h). In gage records where large flood discharges have increased since the late 1970s and early 1980s, discharge values either continue at a similar rate of increase or level off before the end of the record in 2012. Generally, after the period ending in 2002 large flood discharges have leveled out and changed very little in the Jacks Fork, Meramec

(Upper), Big, St. Francis, Spring, Current, Gasconade, and Meramec (Lower) Rivers. The exception is the Bourbeuse record, which indicates a dramatic decrease in discharge between the periods ending in 2007 and 2012 (Figure 8e). This is because of the data collection method used, which meant that the 1983-2012 period did not capture the largest flood in the Bourbeuse River record in 1982. This produced the apparent decrease in discharge between the 2007 and 2012 periods (Figure 8e). Even though the Bourbeuse record is highly sensitive to some of the largest floods in the record, the 2012 discharge calculations for both the 50- and 100-year floods are still greater than the gage average (Figure 8e). Findings indicate that the biggest changes in discharge seem to have occurred over the last 30 years.

Recent trends. Comparing maximum annual discharge values between the 1962-1992 time series (as a base for average flood behavior 30 years ago) to the 1982-2012 time series (as an indicator of current flood behavior) will produce a percentage of change in discharge of each RI from 30 years ago until now. A positive result would indicate that flood magnitude is currently greater than it was 30 years ago, while a negative result would suggest a decrease in magnitude over recent time. Of course, some of this change must be attributed to random variability in the record. Approximate standard error values from the USGS report “Factors Influencing the Occurrence of Floods in a Humid Region of Diverse Terrain” suggest that a change in discharge greater than (approximately) 25%, 30%, and 35% for small, moderate, and large flood RIs respectively can be considered a significant increase, especially over just 30 years (Benson, 1962).

High frequency floods. In general, discharges of the 1.5-, 2-, and 2.33-year flood have increased over the last 30 years. Discharges have increased in the range of 8-52% over the last 30 years at ten of the twelve gages in the 1.5-year flood (Table 6). The Eleven Point and St. Francis records are the only ones that display decreases in the 1.5-year flood over the last 30 years. Additionally, the Eleven Point River record displays the only decreases in the 2-year flood. Increases in discharge in the range of 3-56% have occurred at the other eleven gages in the 2-year flood (Table 6). No gage records indicated decreases in 2.33-year flood discharges, though the Eleven Point River results indicate that the 2012 discharge calculation saw no change in the 2.33-year flood (Table 6). Results from Shoal Creek indicate that there has been a considerable increase in median flood discharge in the last 30 years despite an overall decreasing trend over time (Figure 3b). The Eleven Point River and St. Francis River records display the only decreases in the 1.5-year flood. Watershed for these gaga records are located in the south central Ozarks on the fringe of the Ozark climatic zone. Their location means that there is potential for capturing different storm patterns and intensities from adjacent climate zones. A detailed watershed level study into land use and weather patterns is needed to fully understand trends in each individual watershed.

The significance of the observed increases is difficult to measure as the expected variability between FFA for two separate time periods is unknown. Although, the approximate error for small flood discharges in a humid region is about 25% (Benson, 1962). It is important to note that error values by Benson (1962) are only approximations of the error expected in humid region flood records. A large portion of the difference between the 1982 and 2012 FFA discharge calculations can be attributed to the random

Table 6. Recent change in frequent flood recurrence intervals. Per cent difference in discharge calculations between period ending 2012 and period ending in 1982.

Gage	1.5-Year	2-year	2.33-year
Jacks Fork	8	11	13
Shoal Creek	27	22	21
Meramec River (Upper)	33	30	29
Eleven Point River	-8	-2	0
Bourbeuse River	51	45	42
Big River	44	44	44
St. Francis River	-2	3	6
James River	24	19	17
Spring River	45	56	61
Current River	12	17	18
Gasconade River	36	37	37
Meramec River (Lower)	52	43	39

variability of flood records (Benson, 1962), but the uniformly positive changes in small flood discharges between the two calculations points away from random variability, and towards a significant change in small flood behavior over the last 30 years.

Moderate frequency floods. Significant increases in magnitude are observed at eleven of the twelve gages for the 10-year flood (in the range of 10-85%), and at ten of the twelve gages for the 25-year flood (in the range of 6-93%) (Table 7). Moderate frequency flood events, much like low frequency events, are predominantly controlled by the occurrence of high-intensity storms (Konrad, 2003). Indeed, the trends in discharge over time in the moderate frequency floods are comparably closer to the behavior of the small flood discharges than to the behavior of the large flood discharges, as can be seen in the OM-FA graphs (Figures 8a-m). Changes in magnitude of the moderate to large flood events may be better indicators of climatic change than smaller floods which are generally less reliant on intense heavy rainfall events (Holmes, 2014). Despite the skewed nature of the record, increases in discharges of floods in the Shoal Creek record can still be seen over the past 30 years.

Low frequency floods. Increases are observed in eleven of the twelve gage records for both the 50- and 100-year flood discharges over the past 30 years. Some gages indicate increases in discharge greater than 40% in both RIs (Jacks Fork, Meramec (Upper), and Big), and the Spring River record displays an increase over 98% in the 50-year flood, and 101% in the 100-year flood, over just the last 30-years (Table 8). With low levels of land-use change over recent time, and land use alteration unlikely to cause such drastic increases in large-flood discharges, climate must certainly be the main

Table 7. Recent change in moderate frequency recurrence intervals. Per cent difference in discharge calculations between period ending 2012 and period ending in 1982.

Gage	10-year	25-year
Jacks Fork	32	46
Shoal Creek	10	6
Meramec River(Up)	33	38
Eleven Point River	17	25
Bourbeuse River	18	6
Big River	48	51
St. Francis River	16	19
James River	17	22
Spring River	85	93
Current River	29	33
Gasconade River	32	27
Meramec River (Down)	18	11

Table 8. Recent change in low frequency recurrence intervals. Per cent difference in discharge calculations between period ending 2012 and period ending in 1982.

Gage	50-year	100-year
Jacks Fork	58	70
Shoal Creek	4	1
Meramec River(Up)	43	49
Eleven Point River	31	37
Bourbeuse River	-2	-10
Big River	54	57
St. Francis River	20	21
James River	26	32
Spring River	98	101
Current River	35	37
Gasconade River	23	19
Meramec River (Down)	6	2

influence on the observed increases. Current calculations of large flood discharges are higher than the respective gage average discharges in the majority of gage records (Table 8). The most recent 50-year flood discharge calculations for the Jacks Fork, Big, St. Francis, James, Spring, and Current River records are greater or equal to the 100-year flood average discharge (Figures 8a and 8f-j). Essentially, the discharge in the 50-year flood has increased at these six gages to the extent that the gage average 100-year flood is now equal to the 50-year flood in terms of frequency. Current FFA 100-year flood discharge calculations for the Jacks Fork, Meramec (Upper), Eleven Point, Big, Spring, and Current River records are all greater than the approximate error value of 35% (Benson, 1962), although current discharge calculations for the St. Francis and James River records are also high (21% and 32% respectively) (Table 8).

Only the Bourbeuse River record indicates a decrease in discharge between periods ending in 1982 and 2012. A minor decrease in discharge of 2% for the 50-year flood and 10% for the 100-year flood are seen in the Bourbeuse River record, though the 1983-2012 FFA discharge calculations for the 50- and 100-year floods are still greater than the gage average discharges (Figure 8e). Therefore, despite recent decreases current large flood discharges in the Bourbeuse River are still higher than the gage average discharge. Much like the Shoal Creek record for the moderate flood discharges, discharge calculations for the 1983-2012 record are lower than the gage average for the 50- and 100-year flood but are greater than the gage average discharges.

Flood record inflection

It seems as though there has been large increases in discharge for all flood frequency classes since 1982. However, it is important to understand that not all records started changing in 1982. The recent change in flood discharges began at different points in the records, which can be seen in the OM-FA graphs, using the amount of change over 30 years is simply a useful way of generalizing recent changes. Table 9 indicates the inflection point (start year of the 30-year period in which recent changes began to occur) based on visual inspection of the OM-FA graphs.

Increases in high frequency floods in the Shoal Creek and St. Francis River only began in 1997, though two gages indicate increases since 1982 (Bourbeuse River and Meramec River (Lower)) (Table 9). Decreases in high frequency flood discharges occurred over just a 10-year period. For the high frequency flood class, the median date when change began is 1987, five years earlier than the 1992 median for moderate and low frequency floods (Table 9). This seems obvious, as changes in lower frequency flood events would be expected to take longer to show up in a flood record due to their infrequency. As already mentioned, moderate and low frequency flood events behave almost identically, and therefore display similar inflection points. Five gage records indicate an inflection point of 1982 (Meramec (Upper), Bourbeuse, St. Francis, Current, and Gasconade Rivers) in the moderate/low frequency floods, but many increases have not began until much more recently (Table 9). In fact, the inflection point in the Shoal Creek and James River records is 2012, indicating a large portion of the increases over the past “30 years” has actually only occurred in the last five.

Table 9. Point of inflection of recent change (start of period in which recent increases in discharge began to occur) in gage records.

	Flood frequency class		
	High	Moderate	Low
Jacks Fork	1987	1987	1987
Shoal Creek	1997	2012	2012
Meramec River (Upper)	1987	1982	1982
Eleven Point River	2002*	2002	2002
Bourbeuse River	1982	1982	2012*
Big River	1987	1997	1997
St. Francis River	1997	1982	1982
James River	1987	2012	2012
Spring River	1987	1997	1997
Current River	1987	1982	1982
Gasconade River	1987	1982	1982
Meramec River (Lower)	1982	1997	1997
Median	1987	1992	1992
Miniumum	1982	1982	1982
Maximum	2002	2012	2012

*Record indicates a decrease in discharge

While examining the change in discharge between periods ending in 1982 and 2012 may miss some of the important nuances of changes in the record, it does give a good value to work with to look at general trends across multiple gage records. Differences in the inflection point of discharge changes between gages indicate that flood behavior across the Ozarks has not been spatially, or temporally, consistent.

Correlation analysis

A Pearson's correlation coefficient matrix is created to see if there is any relationship between recent changes in flood discharges and regional, hydrologic, geologic, and land use factors across the Ozarks. To minimalize the output only changes in the 2-year (2yr%), 10-year (10yr%), and 50-year (50yr%) RI floods between the 1952-1982 and the 1983-2012 periods are used, representing the high, moderate, and low frequency flood classes respectively. Regional, hydrologic, geologic and land use variables used include latitude (Lat), longitude (Long), drainage area (Ad), basin relief (R), main channel slope (S), forest land use % (For%), agricultural land use % (Agr%), urban land use % (Urb%), road density (RoadD), and carbonate (limestone and dolomite) bedrock % (Carb%). Due a sample size of just 12 watersheds, factors that show a correlation to changes in flood discharges are plotted and fitted with trend lines to study the strength of the relationship further.

There is a strong positive relationship between 10yr% and 50yr% ($r = 0.9$), indicating that moderate and low frequency floods behave very similarly in gage records (Table 10). On the other hand, there is only a slight relationship between 2yr% and 10yr% ($r = 0.59$) and no relationship between 2yr% and 50yr% which demonstrates that

Table 10. Pearson r correlation matrix for relationships between regional, geologic, and land use variables and changes in the 2-, 10-, and 50-year RI flood discharges since 1982.

	2yr%	10yr%	50yr%	Lat	Long	A_d	R	S	For%	Agr%	Urb%	RoadD	Carb%
2yr%	1.00												
10yr%	0.59	1.00											
50yr%	0.23	0.90	1.00										
Lat	0.62	0.06	-0.23	1.00									
Long	0.23	0.28	0.23	-0.53	1.00								
A_d	0.34	-0.03	-0.24	0.33	-0.19	1.00							
R	-0.08	-0.08	-0.10	0.33	-0.68	0.52	1.00						
S	-0.54	-0.38	-0.19	0.03	-0.77	0.22	0.71	1.00					
For%	-0.42	-0.32	-0.16	0.19	-0.85	0.12	0.58	0.93	1.00				
Agr%	0.37	0.32	0.18	-0.25	0.86	-0.11	-0.56	-0.90	-1.00	1.00			
Urb%	0.55	-0.01	-0.22	0.21	0.47	0.07	-0.22	-0.63	-0.61	0.57	1.00		
RoadD	0.28	-0.18	-0.26	0.04	0.49	-0.11	-0.35	-0.53	-0.59	0.57	0.82	1.00	
Carb%	0.35	0.31	0.27	-0.41	0.87	0.03	-0.47	-0.65	-0.72	0.73	0.66	0.62	1.00

Significance: p = 0.1 = r >0.476, p = 0.02 = r >0.634

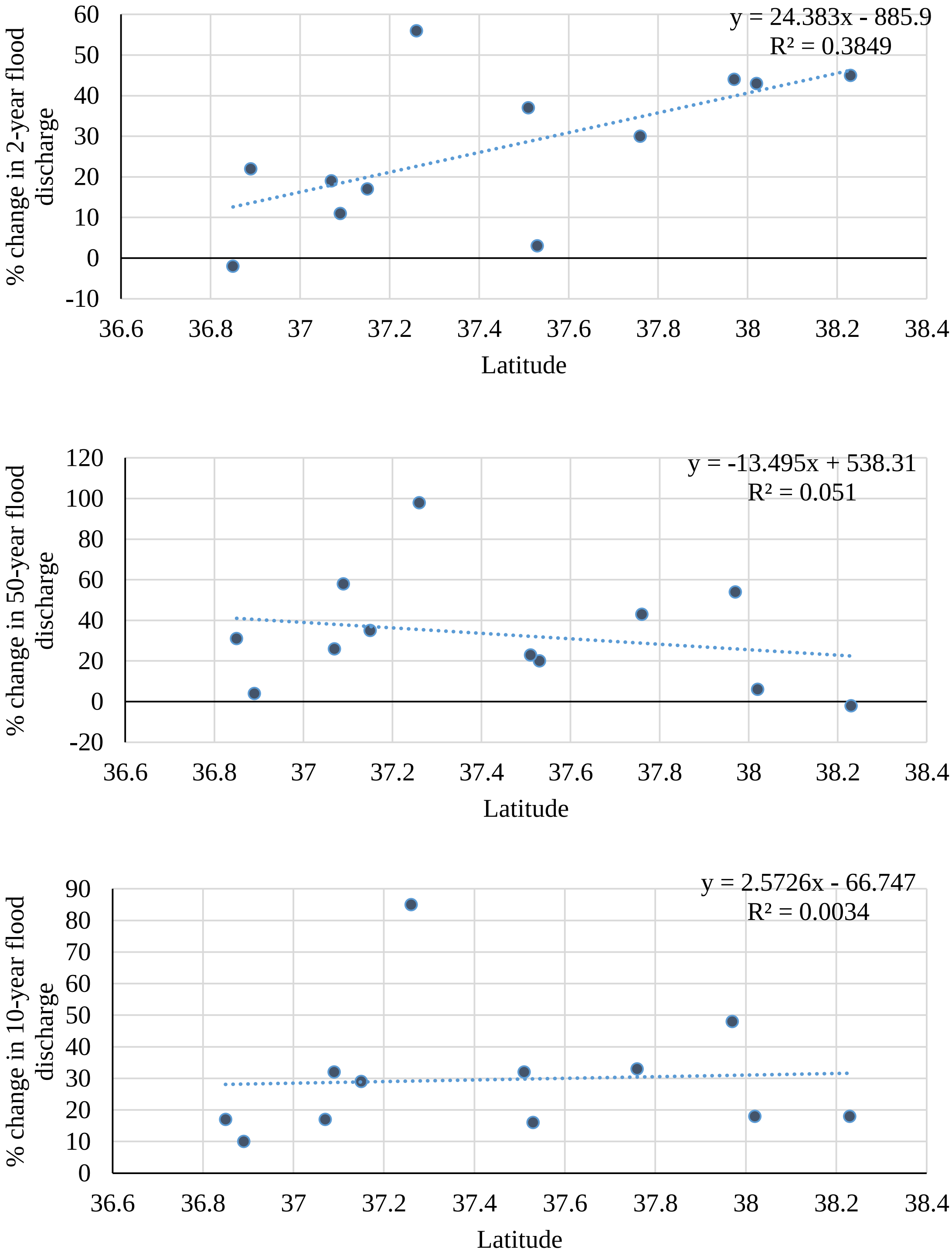


Figure 9. Relationship between latitude and changes in flood discharges across the Ozarks: a = 2-year flood, b = 10-year flood, c = 50-year flood.

high frequency flood events are behaving differently to low frequency (larger flood) events.

It is unlikely that recent changes in moderate and low frequency flood discharges have been driven by land use change or geologic watershed factors, though they may still play a minor role. There are no significant relationships between 10yr% or 50yr% and any of the regional, geologic, or land use variables. Conversely, 2yr% has significant (to the 0.1 confidence level) relationships with latitude (r = 0.62), main channel slope (r = -0.54), and urban area % (r = 0.55) (Table 10). A significant, strong, positive relationship between 2yr% and latitude indicates that greater increases in small flood discharge are expected towards the north of the study area (Figure 9). Latitude seems to be unrelated to any other variable in the analysis. Indeed, most of the variability in land use and geologic watershed variables occurs along an east-west axis (Table 10). Therefore, it is possible that increasing small flood discharges to the north of the Ozarks is related to changes in precipitation factors across the region in the last 30 years, though more study of this phenomenon is needed. The lack of relationship between latitude and 10yr% and 50yr% further confirms that small flood discharges are being controlled by different spatial mechanisms to larger flood discharges.

A significant positive relationship between urban area % and 2-yr% suggest that watersheds with greater urban area covers have seen larger increases in 2-year flood discharges. Upon closer inspection, the relationship between the two variables seems non-linear and more complex (Figure 10). A polynomial trend line is fitted to the data to show a relationship where urban area % seems to positively correlate with the change in the 2-year flood discharge up to a certain point (around 6% urban area), after which a

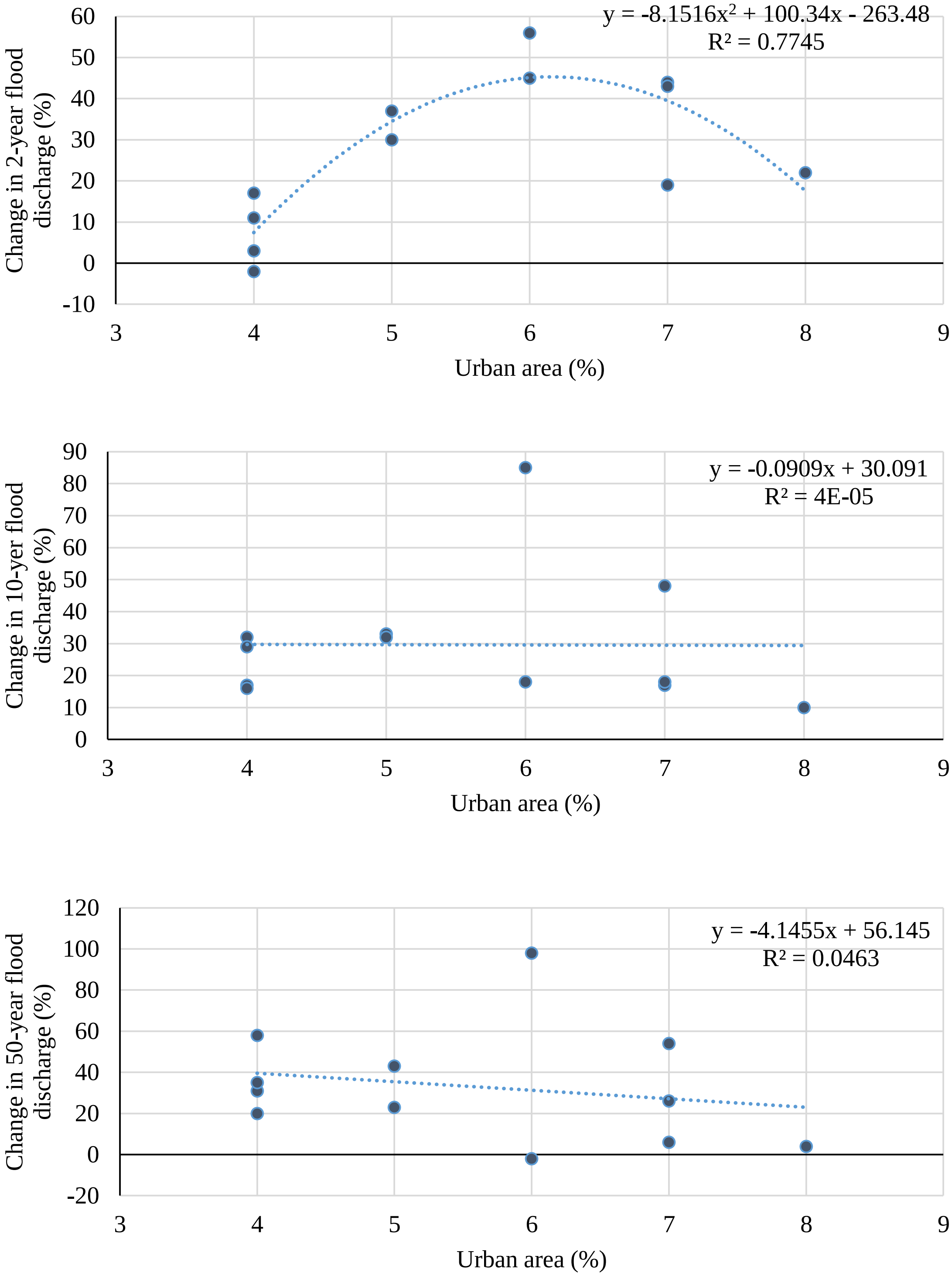


Figure 10. Relationship between urban area and changes in flood discharges across the Ozarks: a = 2-year flood, b = 10-year flood, c = 50-year flood.

further increase in urban area % seems to lower the amount of change in discharge (Figure 10). This relationship suggests that urban area has affected changes in the 2-year flood to a minor extent across the Ozarks, though perhaps a better indicator of the effect of land use changes on flood discharges is to use a value of the amount of change in urbanized land use over the past 30 years. Reliable historical land use data is needed in order to study this relationship further. The 10-year and 50-year flood relationships with urban area show no correlation at all (Figure 10).

In order to drive the increases in discharge observed in this study, even a weak correlation between urban land use % and changes in moderate to large flood flows would be expected, though this is not the case. It seems as though changes in smaller flood discharges have likely been affected by the amount of impervious surface in the watershed to some extent, while changes in larger flood discharges see very little influence from urban area, and have been driven by changes in climate.

The negative relationship between per cent change in the 2-year flood discharge and main channel slope cannot be explained, as lower slopes are expected to produce higher discharges (Thomas and Leopold, 1978). More research into slope relationships with changes in small flood discharges is needed to understand this finding.

USGS discharge estimate comparison

The USGS produces regression equations for each state which can be used to predict flood discharges. Comparing discharge calculations from up to date FFA and discharges produced by regression equations from 1995 gives an idea of the under, or over, prediction of large floods in the Ozarks. A discharge of the100-year flood for each

Table 11. 1983-2012 FFA and USGS GLS regression equation discharge estimates for the 100-year flood in specific discharge (l/s/km^2), with per cent difference and average standard error of prediction.

Gage	1983-2012	USGS	% Difference
Jacks Fork	2658	1964	35
Shoal Creek	948	1377	-31
Meramec River (Upper)	1036	966	7
Eleven Point River	1091	811	35
Bourbeuse River	670	1009	-34
Big River	856	794	8
St Francis River	1627	1269	28
James River	1026	812	26
Spring River	1245	914	36
Current River	819	719	14
Gasconade River	487	465	5
Meramec River (Lower)	417	419	0
		Average =	11 %

of the studied watersheds was produced using USGS regression equations and a discharge calculation for the 100-year flood for the period ending in 2012 was produced using the flood frequency analysis technique in this study (Table 11). The standard error of estimate for the GLS regression equation is 30%, as the amount of variation between the equation estimate and the station data used to derive the equation.

Ten of the twelve gage records indicate higher discharge calculations for the last 30 years than predicted by the USGS equations (Table 11). Only the Jacks Fork (35%), Eleven Point River (35%), and Spring River (36%) FFA discharge calculations exceed the USGS estimate by more than the 30% standard error of prediction (standard error) (Table 11).This indicates under predictions of 100-year flood discharges for these three rivers based on up-to-date FFA. The Shoal Creek and Bourbeuse River FFA discharge calculations are 31% and 34% lower than the corresponding USGS estimates, indicating that USGS estimations over-predict the 100-year flood discharge for these two rivers (Table 11). Current FFA discharge calculations for the Meramec (Upper), Big, Gasconade, and Meramec (Lower) River records are all <10% greater than USGS estimates, which lies well within the standard error.

If the FFA calculations were purely error driven, then both positive and negative results would be expected, however, the majority of FFA calculations are greater than USGS estimates. This is not a perfect comparison, but it does give a general idea as to where current discharge calculations are headed, and displays that the 100-year flood is being under-predicted in rivers across the Ozark Highlands. Updated regression equations have been produced in the past 15 years for 40 US states, but not yet for Missouri

(Koenig, 2014). Regression equations for the Ozarks must be updated if they are to be used in flood protection schemes or management practices.

Implications

Increases in flood discharges has been a common theme across the Ozarks over the past 30 year, with some records indicating increases of up to 44%, 93%, and 101% for the 2.33-, 25-, and 100-year flood discharges, respectively. In light of these findings, it is important to understand their potential implications in economic, social, and environmental terms.

From a geomorphological perspective, a significant increase in flood discharge will trigger a geomorphic response in the river channel. Concern will arise if the flood discharges increase to a point which creates a state of imbalance. Increasing bed and bank erosion leading to channel widening in affected rivers is a likely outcome as the river channel attempts to find a new state of equilibrium with the increasing flood discharges (Knighton, 1998). This is of particular concern in rivers that display a large increase in the small flood RIs (the bankfull 1.5- year flood, the median 2-year flood, and the geomorphic 2.33-year flood), as these are the flows that are frequent enough to have the greatest long-term cumulative effect on river stability (Knighton, 1998).

Increased channel erosion is an issue in many watersheds for many reasons. Bed and bank erosion tends to increase the amount of coarse sediment available for transport. This can build up and choke channel sections during low-flow conditions that can lead to a reduction in channel depth. In turn this can produce a greater risk of small flood events by reducing channel capacity (Kondolf *et al*., 2002). Additionally, bank erosion of floodplain deposits can also increase fine sediment inputs into a river channel which may be detrimental to water quality. For example, high turbidity from high suspended sediment loads can reduce sunlight penetration into a water column, limiting algae growth and reducing aquatic habitat quality (Wang, 1974).

Higher rates of erosion can also increase the risk of contaminated sediment release from contaminated sites or the erosion of nutrient rich soils (Massey, 1984). This is the case for the Big River, which drains an area of southeastern Missouri, well known for its history of intensive lead mining. The river picks up contaminated sediment from mine tailing and waste sites, and transports it further downstream to be deposited into floodplains and bars during smaller flood events. Increased bank erosion due to higher flood discharges creates conditions for contaminated sediment to be reworked and once more become available (Czamezki, 1985; Young, 2011). Heavy metals (primarily lead) have been found in high concentrations in the Big River which has raised concerns for aquatic life (Gale and Wixson, 1986). For example, there has been a major concern and focus on the effects of lead contamination on freshwater mussel populations in the Big River (Gale *et al*., 2002; Brumbaugh *et al*., 2007). An increase in flood discharges means there is potential for mussel and other freshwater biota to be adversely affected by habitat alteration and deteriorating water quality.

Land use influence on Ozark Highland floods

It is well established that land use has an effect on flood discharges. It is therefore imperative that land use change relating to the observed increases in flood discharges over the last 30 years is discussed. Research by Karstensen (2010) offers some insight into recent land cover changes in the Ozarks, between 1973 and 2000. The study reports that the percentage of forested area in the region decreased from 58.5% to 56.2% over the 27 year study period. An increase in agricultural land use has also occurred despite decreases in crop yields, as well as an increase in urban land use. This is contradictory of general assumptions that forested area has increased since the 1920's (Jacobson and Primm, 1994), based on trends in upland and rural areas of the Ozarks. Consequently, it is likely that the 2.3% decrease in forested area between 1973 and 2000 was constrained to growing urban regions. It is unlikely that a decrease in forested area of less than 3% as indicated by Karstensen (2010) would have the drastic effect on flood hydrology indicated by the findings for rural watersheds presented here. Furthermore, the most urbanized watershed in the study has an urban area coverage of 8%, less than the 10% impervious surface threshold for channel stability (Booth and Jackson, 1997). This, along with no correlation found between the 10-year an 50-year RI flood discharges for the most recent period, would suggest that urbanization has had a very small effect on larger floods over the past 30 years, and a moderate effect at most on small flood discharges.

The influence of land use changes on flood discharges is likely to increase in the future with population increases and ongoing urbanization (Markus and McConkey, 2009), though it is unlikely that recent changes observed in this study are due to past and recent land use alteration. Soil conservation practices and the restoration of riparian corridors have generally improved watershed conditions in the Ozarks since the 1930s, which may explain why there is a decrease in flood discharges in the middle of the 90-year record (Menau, 1997; DNR, 2006; Wortmann *et al.*, 2008). Though of course decreased discharges in the middle of the record may also be a reflection of a droughts across the Midwest in the 1950s and 1970s (Singh and Mishra, 2011).

Climate change influence on Ozark Highland floods

While flow relationships with watershed factors have been studied in the Ozarks, these were primarily for in-channel flows (Harrington, 2012). Despite using watersheds from one ecoregion, geological watershed factors do vary to some extent across the Ozarks. Regional and geologic watershed factors seem to play a minor role in the flood changes observed in this study. For example, Shoal Creek watershed is 99% limestone and the Boubeuse River and Meramec River (Lower) watersheds are primarily sandstone and dolomite, but they display similar increases in discharge since 1982. Of the regional control on flood discharges, only latitude has a small correlation with changes in the 2-year flood, which may be an indicator of a climatic control. The behavior of discharges in select watersheds towards the edges of the Ozark region (i.e. Spring River and St. Francis River) may indicate where Ozark climate boundaries exists. More research is needed into regional trends in flood discharge changes across the eco-region.

The increases in discharge for multiple flood RIs presented in this study provides support for previous research into the impact of climate on flooding trends in the US Midwest. Knox (2006) suggested a shift towards more frequent large flood events since 1950. Increasing rainfall amounts and intensities are strongly related to observed increases in flood discharges over the last 50 years (Changnon and Kunkel, 1995; Angel and Huff, 1997; Karl and Knight, 1998; Changnon and Kunkel, 2006; Pinter *et al*., 2008; Tomer and Schilling, 2009; Villarini *et al*., 2011). Many of these studies suggest anthropogenic climate change as the driver for these observed increases in precipitation, with land use change also playing a role. The most recent report from the Intergovernmental Panel on Climate Change states that it is very likely, with a high degree of certainty, that most of the observed increase in globally averaged temperature since the mid-20th century has been caused by the emissions of heat-trapping gases by human activity (IPCC, 2013). Dirmeyer and Kinter (2009) warn that extreme widespread flooding over the central US may become more apparent in a warming climate. Climate models have been useful in the prediction of future changes to the hydrological cycle across the Midwest. Multiple climate models report an increase in heavy precipitation events across the Midwest into the mid-century (Karl and Trenberth, 2003; Wuebbles and Hayhoe, 2004; Groisman *et al*., 2001; Groisman *et al*., 2005; Pryor and Schoof, 2008; Trenberth, 2011; Winkler *et al.*, 2012). Further increases in these events are likely to exacerbate the risk of large flood occurrences in the Ozarks, where records are already indicating increases in discharges as presented here.

It seems unlikely that regional (geologic) factors control the variability in changes in flood discharges across the Ozarks. Also, with increased understanding of the importance of watershed quality and the implementation of watershed management plans, it is unlikely that the observed increases in flood discharges in the studied rural watersheds would be related to detrimental land use changes. Rather, the significant increases in flood discharges across the Ozarks observed in this study are likely to be a reflection of climatic change across the Midwest, a phenomenon that has already been linked to increasing magnitude and frequency of floods across the region (Changnon and Kunkel, 1995; Angel and Huff, 1997; Groisman *et al*., 2001).

CONCLUSIONS

This study fills a gap in our understanding of changes in flood behavior over time in the Ozark Highlands with the study of annual maximum peak flow records. The longest USGS peak flow records available from the Ozark Highlands were analyzed using a range of techniques including flood frequency analysis. Flood discharges for a range of recurrence intervals have generally increased in magnitude over the past 30 years. The findings have implications for future land use management, flood protection, and climate change understanding.

1) Floods in watersheds draining 1,000 to 10,000 km^2 in the Ozarks have increased.
    a. For eleven of the studied watersheds, discharges of the 2-year flood have increased by an average of 30%. A geomorphic response following increases in small flood discharges are likely to prove challenging for management efforts towards the improvement of channel stability, aquatic habitats, and water quality.
    b. Flood frequency analysis shows increases in discharge that are particularly evident for moderate to low frequency floods. Current discharge calculations for 25-year floods are equal to the long-term average 50-year flood discharges in the Meramec (Upper), Eleven Point, Big, St. Francis, James, Spring, Current, and Gasconade rivers. In other words, a flood discharge with a recurrence interval of 50 years based on the full record actually now has a frequency of just 25-years in these rivers, according to recent calculations.

    c. For eleven of the studied watersheds, discharges of the 100-year flood have increased by an average of 39%, though three records indicate increases of 1.5-2x over the past 30 years.
    d. The overlapping time series analysis method used in this study has allowed for the detection of recent changes in flood discharges, even though the Shoal Creek record displays a decreasing trend over time, in part due to two large floods in 1941 and 1943.
2) Increases in the discharge of flood events are more pronounced in larger watersheds, primarily those greater than 2,000 km^2. This behavior is more pronounced for low frequency flood events which can be attributed to the fact that a greater area can produce a greater amount of run-off during the extreme rainfall events that produce large flood flows. This information is vital for flood risk reduction efforts in large watersheds, and suggests that smaller watersheds may have a lower risk of low frequency flood increases in a changing climate.
3) Changes in high frequency flood discharges seem more susceptible to urban area %, though the affect seems minimal. The amount of urban area in the watershed seems to have no affect on changes in moderate to low frequency flood discharges, though land use change cannot be completely ruled out as an influential factor.
4) Trend lines for the 90-year annual maximum peak flow time series' show an upward trend in discharge in eleven out of the twelve gage records. It is possible that recent increasing precipitation trends in the Midwest are responsible for these increases in flood trend records (Pryor and Schoof, 2008). Also, records are highly sensitive to large flood events, even though these events do not seem to completely drive

observed increases in flood discharges over the past 30 years. When the three largest floods were removed, increasing trends decreased on average by 3% per decade. However, increases in discharge over time could still be seen in ten out of the twelve gage records without the three largest floods.

5) USGS regression equations seem to under predict current 100-year flood discharges based on flood frequency calculations for the last 30 years for ten of the twelve studied rivers. Only Shoal Creek and Bourbeuse River 100-year flood frequency discharge calculations are lower than the USGS estimates indicating over-predictions by the USGS for these two rivers. Findings here suggest that regression equations for Missouri and, more specifically, the Ozark Highlands must be updated soon if they are to be of use in current flood protection schemes or management practices.

It is likely that increases in flood magnitudes over the last 30 years in the Ozarks are due to a combination of observable increases in measures of precipitation, including rainfall intensity and total annual rainfall, and possibly land use changes. It is often difficult to separate the hydrologic influences of climate and land use on basin flooding (Garbrecht *et al*., 2004; Tomer and Schilling, 2009), though the observed results strongly indicate that climatic change is the dominant factor. If precipitation amounts continue to increase, the rate of increase in flood discharges will be dependent on land use changes as the synergistic effect of climate and land use are greater than their individual effects (Hu *et al.*, 2005; Hejazi and Markus, 2009). Adapting to these changes will be prove to be environmentally, socially, and economically challenging (Murdoch *et al*., 2000; Kundzewicz, 2008; Wilby and Keenan, 2012; IPCC, 2013).

Increases in severe weather (including storm intensity and overall precipitation amounts) are expected with a changing climate (IPCC, 2013). Winkler *et al*. (2012) neatly summarize the findings and implications of a changing climate for the Midwest. The largest expected impacts in the Midwest are increases in precipitation intensity and an overall increase in winter precipitation amount by the middle of the century (Groisman *et al*., 2001; Wuebbles and Hayhoe, 2004; Groisman *et al*., 2005; Pryor and Schoof, 2008; Winkler *et al*., 2012; IPCC, 2013). If fall and winter precipitation amounts continue to increase as expected, there may be a shift towards more frequent and larger cold-season flood events due to low evapotranspiration, a leaf-off canopy causing low interception, and more frozen ground reducing infiltration leading to high run-off rates (USDA, 1989).

Conclusions about recent increases in flood discharges observed here can be useful for future studies. It shows for the first time the magnitude of recent increases in flood discharges in the Ozark Highlands. Additionally, values of recent increases in discharge for multiple RIs offer a benchmark for future flood analysis to improve on, when longer records are available. The presented overlapping time series analysis method seems an appropriate tool to visualize the temporal trends and inflections in flood records over human timescales. This technique can be applied for any flood records that contain at least 90 years of continuous and reliable data collection. Also, the length of each period and length of time lag for the overlapping analysis can be altered to fit specific research needs. Continued reliable data collection is needed in order to extend the temporal resolution of flooding data to aid future flood research. Detailed hydrological analysis that utilizes historical flow data and land use alteration is needed to better understand the driving factors of the changes observed in this study (Hu *et al*., 2005).

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APPENDIX

Appendix A-1. Additional watershed information

Gage Number	Gage Name	Ad	Gage Height (ft asl)	Max Relief (ft)	Av. Slope %	Lat	Long
07066000	Jacks Fork	1031	616	992	5.9	37.15	91.36
07187000	Shoal Creek	1106	884	682	2.3	37.02	94.5
07013000	Meramec River (Upper)	2023	682	765	4	37.999	91.36
07071500	Eleven Point River	2054	793	1105	4.5	36.65	91.2
07016500	Bourbeuse River	2093	489	726	3.4	38.44	91
07018500	Big River	2375	434	1282	4.6	38.4	90.64
07037500	St Francis River	2476	371	1394	5.9	37.19	90.5
07052500	James River	2556	922	813	3.5	36.81	93.46
07186000	Spring River	3015	834	1280	1.2	37.45	94.57
07068000	Current River	5278	321	1082	4.5	36.62	90.85
06933500	Gasconade River	7615	658	1330	6.6	37.93	91.98
07019000	Meramec River (Lower)	9811	404	1443	4.6	38.51	90.59

Land cover and watershed information based on 2006 National Land Cover Dataset and a 60m DEM

Appendix A-2. Jacks Fork OM-FA PeakFQ discharge estimations in Liters/second/km^2

Period	1.5	2	2.33	10	25	50	100
1922-1952	159	237	279	724	1058	1340	1649
1927-1957	175	267	316	829	1204	1514	1846
1932-1962	205	301	349	791	1060	1260	1455
1937-1967	231	330	380	832	1109	1317	1525
1942-1972	257	358	408	846	1107	1300	1491
1947-1977	283	394	449	926	1211	1422	1631
1952-1982	268	377	431	899	1172	1373	1568
1957-1987	294	424	490	1111	1511	1822	2139
1962-1992	292	425	493	1139	1561	1891	2228
1967-1997	312	447	517	1206	1684	2072	2483
1972-2002	294	431	503	1227	1740	2161	2609
1977-2007	273	395	459	1125	1619	2037	2496
1982-2012	288	417	485	1190	1717	2165	2658

Appendix A-2. Shoal Creek record OM-FA PeakFQ discharge estimations in Liters/second/km^2

Period	1.5	2	2.33	10	25	50	100
1922-1952	161	244	288	785	1179	1525	1914
1927-1957	151	232	275	771	1168	1517	1911
1932-1962	147	225	269	775	1200	1584	2028
1937-1967	130	201	240	722	1149	1551	2029
1942-1972	126	187	221	611	939	1238	1587
1947-1977	122	176	204	490	695	865	1049
1952-1982	108	154	178	425	608	764	935
1957-1987	118	165	190	429	598	738	889
1962-1992	101	139	159	354	492	606	731
1967-1997	122	167	191	419	581	715	860
1972-2002	129	174	197	409	551	665	785
1977-2007	119	157	176	352	469	563	662
1982-2012	138	189	215	468	645	791	948

Appendix A-2. Meramec River (Up) record OM-FA PeakFQ discharge estimations in Liters/second/km^2

Period	1.5	2	2.33	10	25	50	100
1922-1952	176	238	267	510	643	739	829
1927-1957	162	222	251	500	644	748	850
1932-1962	164	218	244	472	610	715	821
1937-1967	158	206	230	430	550	641	733
1942-1972	138	185	208	422	563	677	796
1947-1977	135	177	197	363	459	531	602
1952-1982	122	170	193	396	517	606	695
1957-1987	137	192	219	458	601	707	811
1962-1992	138	192	219	457	603	712	820
1967-1997	147	208	239	507	666	783	896
1972-2002	145	220	258	588	774	904	1025
1977-2007	151	213	244	524	697	829	961
1982-2012	163	220	249	525	715	870	1036

Appendix A-2. Eleven Point River record OM-FA PeakFQ discharge estimations in Liters/second/km^2

Period	1.5	2	2.33	10	25	50	100
1922-1952	68	112	137	417	636	824	1029
1927-1957	76	122	147	409	594	742	895
1932-1962	90	140	167	418	576	694	810
1937-1967	91	139	164	405	564	686	810
1942-1972	95	139	162	380	523	635	749
1947-1977	98	140	161	352	469	556	643
1952-1982	83	125	148	375	534	662	796
1957-1987	81	124	147	384	549	681	820
1962-1992	81	124	146	372	525	646	771
1967-1997	98	143	166	370	492	583	671
1972-2002	81	124	147	380	541	669	802
1977-2007	71	111	133	375	559	714	882
1982-2012	76	122	148	439	670	870	1091

Appendix A-2. Bourbeuse River record OM-FA PeakFQ discharge estimations in Liters/second/km^2

Period	1.5	2	2.33	10	25	50	100
1922-1952	157	189	203	318	381	428	474
1927-1957	142	179	196	340	422	483	544
1932-1962	144	182	200	344	426	486	546
1937-1967	141	177	195	340	425	489	553
1942-1972	137	167	181	303	379	440	503
1947-1977	136	163	176	284	350	402	455
1952-1982	133	169	187	367	500	615	744
1957-1987	154	192	211	387	506	603	709
1962-1992	156	195	214	391	509	606	711
1967-1997	181	230	255	469	608	718	833
1972-2002	191	242	267	484	620	726	836
1977-2007	189	242	268	493	633	743	857
1982-2012	201	246	267	434	529	600	670

Appendix A-2. Big River record OM-FA PeakFQ discharge estimations in Liters/second/km^2

Period	1.5	2	2.33	10	25	50	100
1922-1952	143	182	201	346	425	483	538
1927-1957	143	184	203	368	465	537	609
1932-1962	152	192	210	370	466	540	615
1937-1967	154	190	207	353	442	510	579
1942-1972	156	196	214	368	457	523	590
1947-1977	147	184	202	350	438	505	573
1952-1982	132	174	194	352	435	492	546
1957-1987	154	200	221	383	465	522	574
1962-1992	158	207	230	405	495	556	612
1967-1997	170	237	270	534	676	775	866
1972-2002	181	244	274	510	632	716	794
1977-2007	181	233	259	477	609	711	814
1982-2012	190	251	280	522	659	759	856

Appendix A-2. St. Francis River record OM-FA PeakFQ discharge estimations in Liters/second/km^2

Period	1.5	2	2.33	10	25	50	100
1922-1952	275	364	407	749	936	1070	1199
1927-1957	278	360	399	728	922	1067	1213
1932-1962	295	376	415	725	898	1024	1146
1937-1967	299	368	400	648	781	876	969
1942-1972	313	383	416	662	792	884	972
1947-1977	319	388	420	651	766	846	921
1952-1982	301	376	413	748	970	1149	1343
1957-1987	303	385	425	761	966	1123	1282
1962-1992	297	378	417	759	972	1138	1309
1967-1997	329	419	464	873	1147	1370	1609
1972-2002	329	432	483	952	1265	1518	1785
1977-2007	290	382	429	891	1225	1508	1822
1982-2012	295	390	436	869	1155	1385	1627

Appendix A-2. James River record OM-FA PeakFQ discharge estimations in Liters/second/km^2

Period	1.5	2	2.33	10	25	50	100
1922-1952	166	214	237	452	593	705	824
1927-1957	164	217	242	455	580	673	766
1932-1962	157	213	241	485	632	742	853
1937-1967	156	211	237	469	608	714	820
1942-1972	160	213	239	454	577	666	753
1947-1977	161	213	237	431	534	607	675
1952-1982	158	213	240	464	593	687	779
1957-1987	177	231	257	468	587	673	757
1962-1992	190	238	261	443	545	619	692
1967-1997	197	251	277	491	614	706	797
1972-2002	204	260	286	496	614	700	785
1977-2007	190	242	267	469	585	670	755
1982-2012	196	253	281	544	722	869	1026

Appendix A-2. Spring River record OM-FA PeakFQ discharge estimations in Liters/second/km^2

Period	1.5	2	2.33	10	25	50	100
1922-1952	133	178	202	427	587	721	866
1927-1957	113	161	185	422	586	718	859
1932-1962	114	165	191	451	634	785	946
1937-1967	112	160	185	437	620	774	941
1942-1972	116	162	186	418	579	710	849
1947-1977	115	158	180	372	490	580	670
1952-1982	107	146	165	339	449	534	620
1957-1987	141	184	206	416	561	681	811
1962-1992	138	181	202	405	545	661	785
1967-1997	161	214	241	534	767	975	1217
1972-2002	166	222	251	557	795	1006	1248
1977-2007	142	208	242	588	830	1028	1237
1982-2012	155	229	266	628	867	1054	1245

Appendix A-2. Current River record OM-FA PeakFQ discharge estimations in Liters/second/km^2

Period	1.5	2	2.33	10	25	50	100
1922-1952	92	133	154	359	499	612	729
1927-1957	100	144	166	373	506	610	716
1932-1962	111	156	179	376	494	581	667
1937-1967	110	150	170	334	428	496	562
1942-1972	114	151	169	316	401	463	524
1947-1977	112	146	163	295	368	420	471
1952-1982	102	139	157	324	430	513	598
1957-1987	107	146	166	352	476	575	678
1962-1992	108	149	169	357	479	575	675
1967-1997	120	162	183	376	503	604	710
1972-2002	119	164	187	390	518	616	715
1977-2007	109	152	174	385	527	641	761
1982-2012	115	162	186	416	570	692	819

Appendix A-2. Gasconade River record OM-FA PeakFQ discharge estimations in Liters/second/km^2

Period	1.5	2	2.33	10	25	50	100
1922-1952	85	118	134	278	368	437	508
1927-1957	83	115	132	281	375	447	520
1932-1962	87	119	135	279	369	439	509
1937-1967	92	119	132	250	326	386	448
1942-1972	87	111	123	232	305	364	427
1947-1977	85	104	112	182	220	248	276
1952-1982	81	103	115	219	289	347	409
1957-1987	93	119	132	246	319	376	437
1962-1992	93	119	131	241	311	367	425
1967-1997	101	130	144	274	359	426	496
1972-2002	105	136	151	280	358	417	477
1977-2007	100	131	146	279	361	423	487
1982-2012	110	142	157	288	367	427	487

Appendix A-2. Meramec River (Down) record OM-FA PeakFQ discharge estimations in Liters/second/km^2

Period	1.5	2	2.33	10	25	50	100
1922-1952	83	107	118	210	262	301	340
1927-1957	77	104	116	226	291	339	386
1932-1962	83	107	118	224	292	347	405
1937-1967	81	103	113	212	278	332	389
1942-1972	78	99	110	209	277	333	393
1947-1977	73	93	102	185	237	277	318
1952-1982	72	95	106	212	285	344	408
1957-1987	82	107	119	223	286	334	383
1962-1992	85	110	122	221	280	323	366
1967-1997	98	131	146	273	344	396	446
1972-2002	108	138	152	265	329	375	421
1977-2007	110	136	148	255	324	379	437
1982-2012	110	135	148	251	315	365	416

Appendix A-3. Median (2-year) flood discharge values for each of the three periods.

Gage	1922-1952	1952-1982	1982-2012
Jacks Fork	245	426	386
Shoal Creek	279	152	198
Meramec (Up)	192	164	224
Eleven Point	122	143	115
Bourbeuse	170	174	232
Big	170	182	267
St Francis	396	381	377
James	197	229	235
Spring	174	146	218
Current	116	61	66
Gasconade	140	141	161
Meramec (Down)	118	103	145

Appendix A-3. Mean >10-yr flood percentile flood discharge values for each of the three periods.

Gage	1922-1952	1952-1982	1982-2012
Jacks Fork	934	1092	1484
Shoal Creek	1224	557	611
Meramec (Up)	611	458	745
Eleven Point	466	397	609
Bourbeuse	369	385	686
Big	382	431	642
St Francis	809	702	1392
James	564	473	821
Spring	624	488	913
Current	420	164	322
Gasconade	695	322	554
Meramec (Down)	329	217	451

Appendix A-4. Difference in the per cent change in discharge per decade of annual maximum peak flow records with the three largest floods removed.

Gage	Complete record	Record minus three largest floods	Difference
Jacks Fork	10.2	6.2	-4
Shoal Creek	-4.4	-0.9	3.5
Meramec River (Upper)	0.5	-0.2	-3
Eleven Point River	2.9	1.6	-1.3
Bourbeuse River	7.7	4.3	-3.4
Big River	8.1	3.8	-4.3
St Francis River	4.8	2	-2.8
James River	5.1	0.4	-4.7
Spring River	6.8	4.2	-2.6
Current River	4.5	3.5	-1
Gasconade River	3.6	0.2	-3.4
Meramec River (Lower)	6.3	2.8	-3.5