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# SMALLMOUTH BASS FEEDING DYNAMICS AND GROWTH IN HEADWATER STREAMS OF THE INTERIOR HIGHLANDS

By

BRANDON PLUNKETT

Submitted to the Faculty of the Graduate College of
Arkansas Tech University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE IN FISHERIES AND WILDLIFE SCIENCE

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# ABSTRACT

# SMALLMOUTH BASS FEEDING DYNAMICS AND GROWTH IN HEADWATER STREAMS OF THE INTERIOR HIGHLANDS

Smallmouth Bass have been extensively studied, but knowledge of the effects of temperature and hydrologic regime on populations in the Interior Highlands of Arkansas remains lacking. In 2018, I monitored diet characteristics of Smallmouth Bass, located in streams prone to dryness and representing a range of water temperatures, and presence of potential competitors. Diet characteristics of Smallmouth Bass, Green Sunfish, and Creek Chub were studied in the Boston Mountains ecoregion of Arkansas during the summer of 2018. Temperature was not significantly related to Smallmouth Bass stomach fullness. There was a significant association between species and prey selection ($X^2 = 27.475$, df = 4, $P < 0.001$). Crayfish were the primary diet item of Smallmouth Bass in the seven streams sampled in the Boston Mountains. Based on the 2018 study, food availability was not a major limiting factor relative to Smallmouth Bass productivity. Therefore, competition is not likely to explain poor productivity in Boston Mountain headwaters. In 2019, I expanded the scope of the project to search for relationships between Smallmouth Bass growth and hydrologic regime. My objectives were to compare growth rates of Smallmouth Bass among three ecoregions and to characterize the relationship between hydrologic regime and annual growth rates of Smallmouth Bass. I sampled Smallmouth Bass from five streams each in the Boston Mountain, the Ouachita Mountain, and the Ozark Highland ecoregions of Arkansas during the summer of 2019. Annual growth was estimated for each captured fish by measuring annuli on the whole otolith and then the sectioned otolith for individual fish deemed age-2 or older. Smallmouth Bass caught in the Boston Mountains had a higher growth coefficient ($K = 0.53$), than those captured in the Ouachita Mountains ($K = 0.41$)

and Ozark Highlands ($K = 0.2$).  Individual annual growth was significantly affected by both flow and age.  I found an inverse relationship between the coefficient of variation of flow and individual annual growth of age-2 Smallmouth Bass from 2014 through 2018.  Fluctuations in hydrologic regime may be influencing predatory success or evolved strategies of Smallmouth Bass in our study.  Climate change could cause increases in stream temperatures and hydrologic fluctuations which may alter metabolic costs and prey availability.  Thus, focusing on why Smallmouth Bass annual growth decreases with fluctuations in mean flow should be a primary concern for future studies in the Interior Highlands of Arkansas.

# CHAPTER 1:  INTRODUCTION

The Smallmouth Bass *Micropterus dolomieu* is a popular sportfish native to Arkansas.  It occurs in cool, clear streams usually containing rock and gravel substrate (Robison and Buchanan 1984).  However, it can be found in muddy streams, indicating some ability to tolerate high turbidity (Cleary 1956; Webster 1954).  The Interior Highlands of Arkansas, represent the southern extent of the native range of Smallmouth Bass (Tovey et al. 2008).  This region contains streams of variable annual flows which can affect the distribution and resource availability of native fishes (Gagen et al. 1998; Homan 2005).  Water temperature has direct effects on Smallmouth Bass growth, and indirect effects through food resources, oxygen saturation, and competition from other species (Armour 1993).

Recently, there has been scientific interest in how potential increases in water temperature and changes in hydrologic regime associated with climate change might affect native Smallmouth Bass (Middaugh et al. 2016).  Productivity of riverine fishes can be impacted by changes in flow regime or other environmental variables related to hydrology (Cushman 1985).  Additionally, the Arkansas Game and Fish Commission is interested in Smallmouth Bass growth variability across ecoregions in Arkansas (Quinn et al. 2012).  This study tries to address the lack of knowledge of how the native Smallmouth Bass of Arkansas will respond to increased temperatures and changing flow regimes.

Chapter Two focuses on characterizing the diet of Smallmouth Bass and potential competitors in headwater streams of Arkansas prone to intermittency.  Pool isolation is thought to lead to increased resource competition (Peterson and Payley 1993; Lonzarich et al. 1998) and possible increased predation rates on fishes confined to pools (Gagen et al. 1998).  Smallmouth Bass feed on crayfish and fishes, with an increase in feeding on insects during the summer

(Johnson et al. 2009). Creek Chub *Semotilus atromaculatus* and Green Sunfish *Lepomis cyanellus* often occur alongside Smallmouth Bass in similar pool structures while feeding on smaller fishes, invertebrates, and crayfish (Taylor 1997). The Boston Mountains ecoregion of Arkansas included streams known to encounter periods of dryness and pool isolation (Hines 1975; Homan 2005), so I monitored potential changes in diet associated with increased water temperatures while documenting presence of other piscivores throughout the summer of 2018.

Chapter Three focuses on how environmental factors, especially differences in hydrologic regime, may be influencing the growth of Smallmouth Bass, including possible subspecies, in this southern portion of their range. Although increased temperature associated with climate change is important to evaluate, potential changes in flow regime can also have substantial effects on stream ecology (Wenger et al. 2011). Smallmouth Bass growth has been found correlated with variable flows (Paragamian and Wiley 1987; Eggleton and Peacock 2020). Thus, growth rates of possible subspecies of Smallmouth Bass thought to exist separately in the Boston Mountains, Ouachita Mountains, and Ozark Highlands were measured. Each subspecies is thought to inhabit a different ecoregion, which have differing environmental variables. Chapter Three examined aspects of the hydrologic regime, calcium concentration, and subspecies as potential determining factors relative to annual growth.

# CHAPTER 2: SMALLMOUTH BASS FEEDING DYNAMICS IN HEADWATER STREAMS OF THE INTERIOR HIGHLANDS

## ABSTRACT

Arkansas represents the southern extent of the Smallmouth Bass *Micropterus dolomieu* native range and includes intermittent streams and pool isolation. Reduced riffle and run habitat, potential competitors, and increasing temperatures in summer could contribute to low production of Smallmouth Bass in these headwater streams. I monitored potential diet changes of Smallmouth Bass in relation to habitat characteristics and presence of other piscivores. I sampled Smallmouth Bass from seven, similarly-sized streams in the Boston Mountain ecoregion of Arkansas during the summer of 2018. In addition to Smallmouth Bass (≥ 150 mm), I targeted Green Sunfish *Lepomis cyanellus* (≥ 100 mm) and Creek Chub *Semotilus atromaculatus* (≥ 100 mm) by electrofishing three designated pools in each stream on two occasions. Total length and wet weight were measured, and I extracted stomach contents by pulsed gastric lavage. Stomach contents were preserved in an ethanol solution for later measurement of diet weight and volume. Smallmouth Bass mainly consumed crayfish but also consumed more fishes compared to Green Sunfish and Creek Chub. There was a significant association between species and prey selection of fishes caught ($X^2 = 27.475$, df = 4, $P < 0.001$). Stream temperature was not significantly related to Smallmouth Bass stomach fullness. Further studies should expand the size range of sampled Smallmouth Bass to incorporate diet characteristics of younger individuals. Smallmouth Bass production in Boston Mountain streams was not likely limited by prey abundance as I did not find evidence of competition. However, if streams become warmer with less surface flow in the future, competition could become more important for Smallmouth Bass in the Interior Highlands of Arkansas.

# INTRODUCTION

Low productivity of Smallmouth Bass in intermittent streams of the Boston Mountains (Homan 2005) of Arkansas could be associated with a combination of limited prey availability and thermal stresses. Middaugh and colleagues (2016) hypothesized that Smallmouth Bass growth rate may decline in Arkansas with increased temperature associated with climate change (NOAA 2021). This study addresses the possible implications of climate change influencing diet of Smallmouth Bass in intermittent streams.

Arkansas represents the southern extent of the Smallmouth Bass native range and includes widespread pool isolation in intermittent streams. Thus, movement of Smallmouth Bass can be limited to pools during low water periods where low water riffles act as barriers (Brown et al. 2009). Hafs and colleagues (2010) found that most of the Smallmouth Bass in this type of drainage network position themselves in larger pools which tend to hold water throughout the dry period of summer.

Riparian cover and other habitat characteristics can result in temperature variability within a pool (Wehrly et al. 2003). Rutherford and others (2004) found that water temperatures were 4-5 °C warmer for stream segments with no riparian cover. Conversely, stream segments with higher levels of canopy closure had lower temperatures than more exposed segments (Larson and Larson 1996). Mundahl (1990) attributed fish survival in isolated pools to riparian shade and rock cover providing microclimates with lower temperatures. Salmonids and other species experience decreased thermal stress during summer months when there is riparian vegetation influencing the thermal regime (Malcolm et al. 2004). Often persistence of isolated pools in intermittent streams is contingent on groundwater input during dry conditions (Labbe 2000). Higher proportions of groundwater influx contribute to temperature and oxygen stability in stream systems (Brunke and Gonser 1997). Thus, groundwater seeps can provide thermal refuge for Smallmouth Bass during hot and cold seasons (Whitledge et al. 2006).

High water temperature can cause stream fishes to undergo mortality or behavioral changes (Caissie 2006). For example, increasing stream temperature above thermal optima can lead to decreases in growth for native stream fishes (Poole and Berman 2001), and Armour (1993) documented maximum growth for Smallmouth Bass at 25-26°C. Water temperature influences distribution, migration, spawning date, and growth rate of Smallmouth Bass (Brown et al. 2009). Hafs (2007) reported that Smallmouth Bass, confined to remnant pools in the Boston Mountains, were exposed to water temperatures that occasionally exceeded 30°C, and Homan (2005) showed low Smallmouth Bass production in this drainage compared to other regions. However, the potential influence of high water temperature on diet characteristics of Smallmouth Bass in Arkansas headwaters have not been published.

Knowledge of potential diet changes of Smallmouth Bass in intermittent pools may provide insight on effects of increasing temperature from climate change. Adult Smallmouth Bass change their diet in response to prey availability as they are opportunistic predators (Scott and Crossman 1973; Carter et al. 2010). Optimal prey sizes for Smallmouth Bass include 20 to 30% total length for fish and 12-19% for crayfish (Carter et al. 2010). Size and abundance of prey for Smallmouth Bass could decrease as time progresses in isolated pools.

Girondo (2011) concluded that fishes in isolated pools of Boston Mountain streams exhibited high mortality rates which affected community structure and may influence diet composition of associated Smallmouth Bass. Differences in monthly diets for Smallmouth Bass, in groundwater dominated streams versus those from streams more influenced by runoff, have been documented (Middaugh 2017), but trends in diet composition relative to trends in water temperature have not been reported for isolated pools in intermittent streams. Furthermore, increasing temperatures may change competitive interactions as summer progresses.

Drought and increasing water temperatures within isolated pools can cause increases in competition and predation due to decreases in habitat refugia (Magoulick and Kobza 2003). Predatory fish such as Creek Chub *Semotilus atromaculatus* and Green Sunfish *Lepomis cyanellus* often occur alongside Smallmouth Bass in similar pool structures while feeding on smaller fishes, invertebrates, and crayfish (Taylor 1997). Spotted Bass *Micropterus punctulatus* prefer deeper water than Smallmouth Bass, but both species are known to occur in the same Arkansas waterbodies (ADPCE 1987; Johnson et al. 2009). A reduction in habitat heterogeneity may increase interspecific competition between black basses and green sunfish feeding on similar prey (Johnson et al. 2009). Streamflow discharge typically decreases in headwater streams of the lower Boston Mountains as the summer months progress (Homan et al. 2005) which contributes to loss of connectivity between pools. Pool volume was a significant variable predicting species richness (Taylor 1997) and therefore potentially impacts Smallmouth Bass diet.

This study was designed to characterize the diets of Smallmouth Bass during the growing season along a Boston Mountain headwater stream network in areas prone to drying. Another objective was to monitor potential Smallmouth Bass diet changes in relation to the presence of competing species such as Green Sunfish, Spotted Bass, and Creek Chub. My third objective was to search for relationships between aspects of thermal regime and measures of diet among these piscivorous species.

I hypothesized that Smallmouth Bass diet would reflect declining prey richness in pool habitats as temperature increases. I also hypothesized that higher water temperature would be associated with decreased stomach fullness and an increased diet overlap for the piscivorous species. Finally, I hypothesized that Smallmouth Bass would show greater diet overlap and lower stomach fullness when found in pools with other piscivores.

## METHODS

### *Study Area*

I studied Smallmouth Bass feeding dynamics in the Boston Mountain ecoregion in Arkansas. The North, Middle, and East Forks of the Illinois Bayou have isolated pools during the late summer (Homan et al. 2005; Hafs et al. 2010) for watersheds averaging 5,085 ha. Therefore, criteria for site selection involved watershed sizes of 5,085 ± 1,271 (25%) ha, draining a predominately forested area; road access within 200 meters; and drainage to the Arkansas River. Three pools were selected at each stream where maximum water depth was 0.75 ± 0.25 m within one kilometer upstream or downstream of access. Selected streams included Big Piney Creek, Hurricane Creek, Indian Creek, Moccasin Creek, East Fork Illinois Bayou, Middle Fork Illinois Bayou, and North Fork Illinois Bayou (Table 2.1; Figure 2.1).

### *Fish Collections and Diet Analyses*

I sampled up to 30 adult Smallmouth Bass (>150 mm) from each stream, twice between late June and mid-August, as well as Green Sunfish and Creek Chub (≥ 100 mm). I used backpack electrofishing (Smith Root model LR-20) and dip nets to collect fishes. Total length and wet mass of fishes were measured in the field for all three species. Two passes were made, starting from the downstream end of each pool and finishing at the upstream end.

Stomach contents were extracted from Smallmouth Bass and co-occurring piscivores by gastric lavage. Pulsed gastric lavage (Kamler and Pope 2001) was performed by inserting a plastic tube through the mouth and into the stomach of the fish, then stomachs were flushed with water while massaging the stomach (Middaugh 2017). Van Den Avyle and Roussel (1980) found that only one out of 266 dissected black bass stomachs still contained food after using gastric lavage. Gut contents were stored in 70% ethanol in the field for later identification. Once a stomach had been flushed, a passive integrated transponder (PIT) tag was inserted into each fish via a specialized hypodermic needle for future identification of recaptures individually. Stomach contents were categorized as fish, crayfish, or other aquatic invertebrates. The categorized items were not separated additionally by family, genus, or species.

### *Measurement of habitat parameters*

I measured maximum depth, mean depth, canopy cover, temperature, and turbidity at each pool. Pool lengths and widths were measured with a laser range finder (Homan et al. 2005). I measured canopy cover by using a densiometer for each pool in the center of the stream at the upstream and downstream ends of the pool. I measured turbidity on each sampling occasion near the center of each pool’s upstream end. Temperature was measured by placing a HOBO Pendant temperature logger in the deepest area of the pool. The temperature loggers recorded temperature for each pool in intervals of 30 minutes. Each temperature logger was attached to half cinder blocks to keep them in place throughout the summer. Instantaneous temperature was recorded in a shaded area where possible, at each pool after electrofishing was completed.

### *Statistical Analyses*

Percent stomach fullness was calculated by dividing total wet weight of stomach contents by total fish weight and multiplying by 100. I used ordinary least squares regression to search for relationships between stomach fullness and temperature. Principle component analysis was used to examine stream similarity, diet overlap, prey occurrence trends for each species, and diet composition with or without other target species present. Additionally, I used Pearson's chi-squared test to evaluate potential association between predator species and diet items. I set alpha level at $\alpha \leq 0.05$ to assess statistical significance.

## RESULTS

### *Fishes Caught*

One hundred and fifty-one fish of the three target species were sampled during the summer of 2018. Of these, 82 were Smallmouth Bass, 32 were Green Sunfish, and 37 were Creek Chub (Table 2.2). The number of diet items collected were 65 for Smallmouth Bass, 29 for Green Sunfish, and 32 for Creek Chub (Table 2.3). Sampled Smallmouth Bass were usually larger than both Green Sunfish and Creek Chub (Figure 2.2-2.3). Captured Green Sunfish and Creek Chub showed more overlap in total length between each other than Smallmouth Bass (Figure 2.2).

### *Diet Analyses*

Principle component analysis of prey selection showed a lack of stream effect as all waterbodies exhibited overlap (Figure 2.4). Furthermore, there was substantial diet overlap among all three target species based on principal components analysis (Figure 2.5). Smallmouth Bass mainly consumed crayfish, Green Sunfish consumed crayfish and other invertebrates, and Creek Chub mainly consumed other invertebrates (Table 2.3). Smallmouth Bass exhibited the broadest range of diet selection, as it encompassed the range of both Green Sunfish and Creek Chub diets (Figure 2.5). Also, principle component analysis showed similar prey selection with or without potential competitors in the same pool (Figure 2.6). The first principle component (percent crayfish in Smallmouth Bass stomachs) accounted for 46% of the variance, and the second principle component (percent fish in Smallmouth Bass stomachs) accounted for 33% of the variance (Figure 2.4-2.6). The eigen values for the first and second principle components were 1.09 and 1.03, respectively. I used a chi square test for association to identify a possible association between predator and prey type. There was a significant association between predator species and prey type ($X^2 = 27.5$, df = 4, $P < 0.001$).

I log-transformed the data for regression of temperature and stomach fullness because stomach fullness was not normally distributed. Stomach fullness of Smallmouth Bass decreased with increased temperature (Figure 2.7). However, Green Sunfish Creek Chub stomach fullness increased with increased temperature (Figure 2.7). There were no significant relationships between temperature and stomach fullness for Smallmouth Bass, Green Sunfish, and Creek Chub (Figure 2.7).

## DISCUSSION

Crayfish were the primary diet item of Smallmouth Bass in the seven Boston Mountain streams and were found in stomach contents throughout the entire study. Smallmouth Bass stomach contents were not as limited to certain diet items as were Green Sunfish and Creek Chub. Diets of Smallmouth Bass contained primarily crayfish and fish, which is consistent with other studies (Zimmerman 1999; Dauwalter and Fisher 2008; Johnson et al. 2009; Middaugh and Magoulick 2019). Green Sunfish and Creek Chub exhibited similarities to Smallmouth Bass in their diet contents containing aquatic invertebrates other than crayfish (Figure 2.5). The observed diet overlap among sampled piscivores does not constitute evidence of significant food partitioning (Probst et al. 2011) but there could be existing habitat partitioning among the sampled species.

Lengths of sampled Smallmouth Bass generally exceeded those of Creek Chub and Green Sunfish (Figure 1.03). Orth and Roell (1993) reported significant diet overlap between Smallmouth Bass and Rock Bass *Ambloplites rupestris* in the New River, West Virginia. Surber and Seaman (1949) and Sanderson (1988) found that other Centrarchids negatively affected Smallmouth Bass densities and growth. Larger Green Sunfish and Creek Chub may be able to compete for similar food resources with Smallmouth Bass. Thus, I may have found greater diet similarities between the three species if I had analyzed diets of Smallmouth Bass caught below 150 mm. For example, Pert (2002) and others found age-0 Smallmouth Bass to consume predominately aquatic insects and crayfish like the Green Sunfish and Creek Chub in this study.

My study was limited by aspects of habitat in small streams of the Boston Mountains. I was unable to properly capture fishes in certain sites due to poor capture efficiency associated with low conductivity or depth. If the study continued, I would recommend using a barge electrofisher (Dauwalter and Fisher 2008) in deeper pools and have more than two people for netting. Similar to Peterson (2004) and others, I encountered wood and substrate structures which potentially reduced capture efficiency.

Smallmouth Bass growth and food intake may increase due to climate change (Wuellner et al. 2010) due to longer growing seasons, thus prey may become more limiting which could intensify interspecific competition. Changes in thermal and flow regimes could influence prey availability and growth potential of Smallmouth Bass (Middaugh et al. 2016). When concluding the study in 2018, I decided to analyze other factors besides diet which could influence the condition of Smallmouth Bass in streams of Arkansas. I proposed to expand the scope of my project to search for relationships between Smallmouth Bass growth and environmental factors in three ecoregions where Smallmouth Bass occur in Arkansas.

TABLE 2.1. The GPS Coordinates (UTM Zone 15 North) and watershed area of each sampled Boston Mountain headwater stream during the summer of 2018.

| Stream | Easting | Northing | Watershed Area (ha) |
|---|---|---|---|
| Big Piney Creek | 464383 | 3958709 | 4766 |
| East Fork Illinois Bayou | 514562 | 3940330 | 5154 |
| Hurricane Creek | 486944 | 3957969 | 4999 |
| Indian Creek | 489200 | 3944415 | 4869 |
| Middle Fork Illinois Bayou | 508301 | 3948657 | 5465 |
| Moccasin Creek | 487281 | 3940169 | 4921 |
| North Fork Illinois Bayou | 498186 | 3947437 | 4636 |

TABLE 2.2. The number of fish captures at each sampling location for each target species in Boston Mountain headwater streams during the summer of 2018.

| | Species | | | |
|---|---|---|---|---|
| Stream | Smallmouth Bass | Green Sunfish | Creek Chub | Total |
| Big Piney Creek | 12 | 2 | 5 | 19 |
| East Fork Illinois Bayou | 14 | 3 | 12 | 29 |
| Hurricane Creek | 3 | 3 | 8 | 14 |
| Indian Creek | 14 | 7 | 0 | 21 |
| Middle Fork Illinois Bayou | 23 | 15 | 0 | 38 |
| Moccasin Creek | 1 | 2 | 7 | 10 |
| North Fork Illinois Bayou | 15 | 0 | 5 | 20 |
| Total | 82 | 32 | 37 | 151 |

TABLE 2.3. The number of each prey type observed in diets of sampled Smallmouth Bass, Green Sunfish, and Creek Chub in Boston Mountain headwater streams during the summer of 2018.

| | Prey Type | | | | |
|---|---|---|---|---|---|
| Species | Crayfish | Fish | Other Invertebrate | Empty | Total |
| Creek Chub | 8 | 1 | 23 | 6 | 38 |
| Green Sunfish | 12 | 2 | 15 | 2 | 31 |
| Smallmouth Bass | 33 | 18 | 14 | 17 | 82 |
| Total | 53 | 21 | 52 | 25 | 151 |

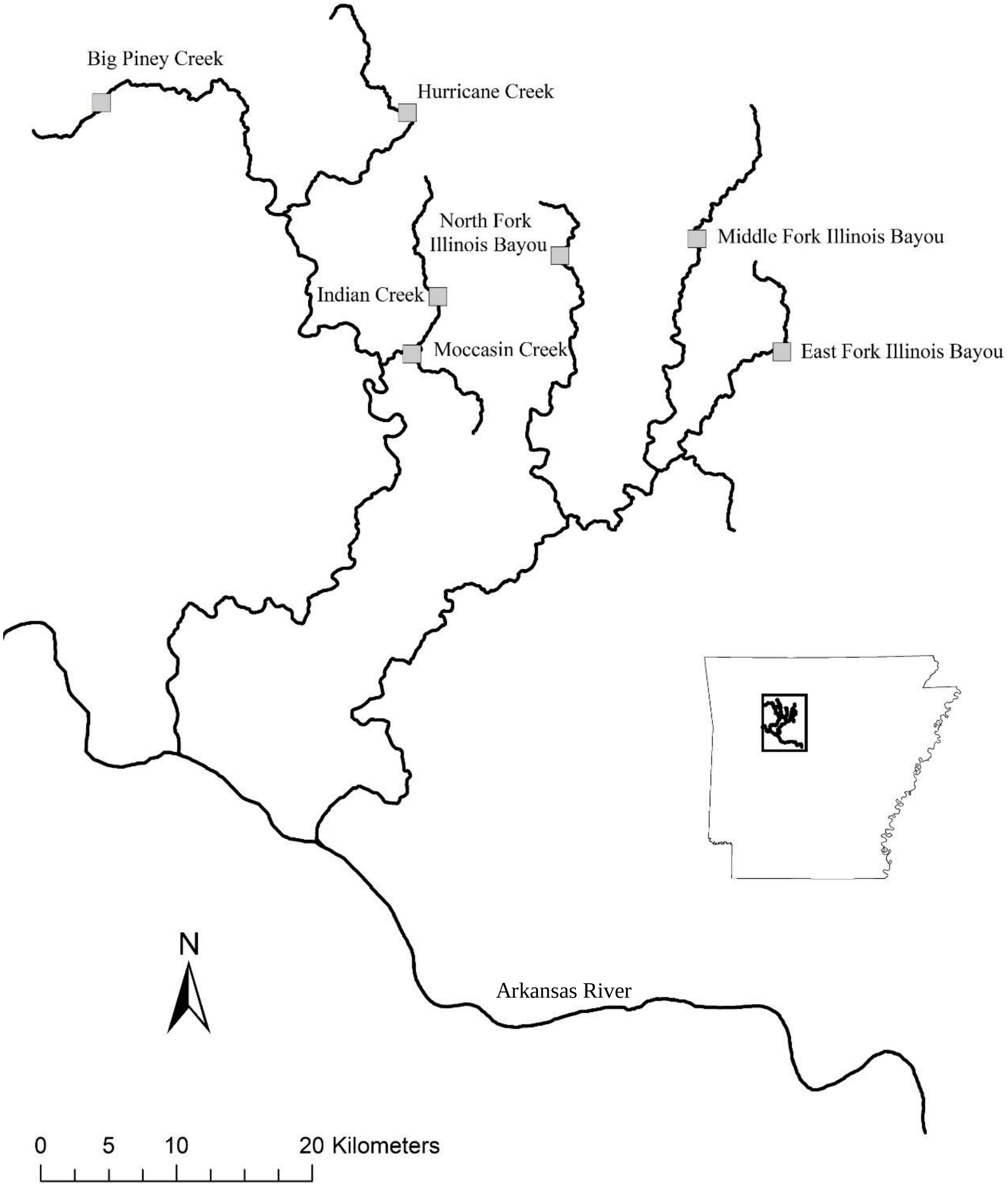

FIGURE 2.1. Distribution of seven study sites representative of headwater streams in the Boston Mountains of Arkansas. These streams drain into the Arkansas River via the Illinois Bayou and Big Piney Creek with watershed area ranging from 3,600 to 5,500 ha.

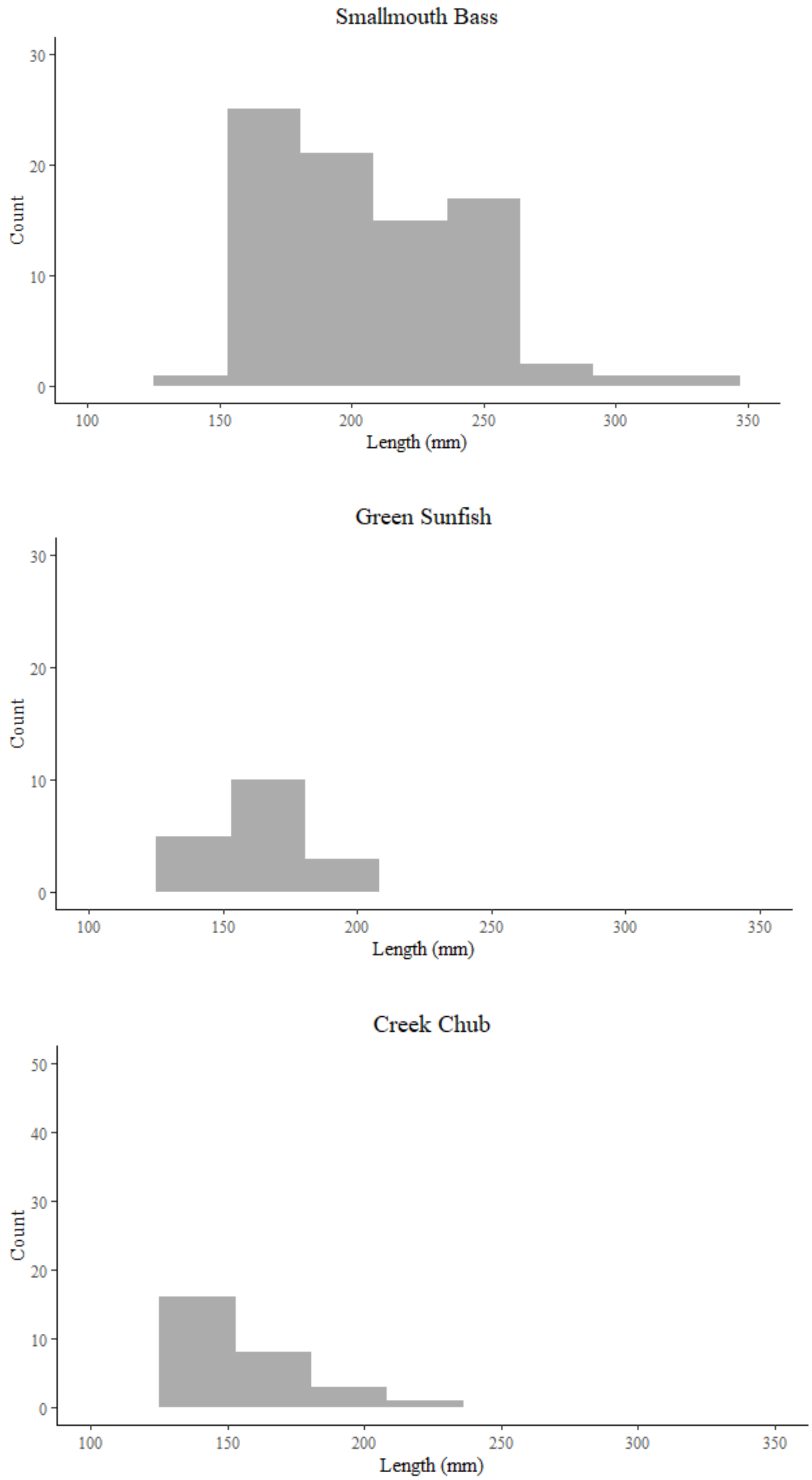

FIGURE 2.2. Length frequency histograms for all Boston Mountain fishes caught in the summer of 2018 based on 10 mm length groups.

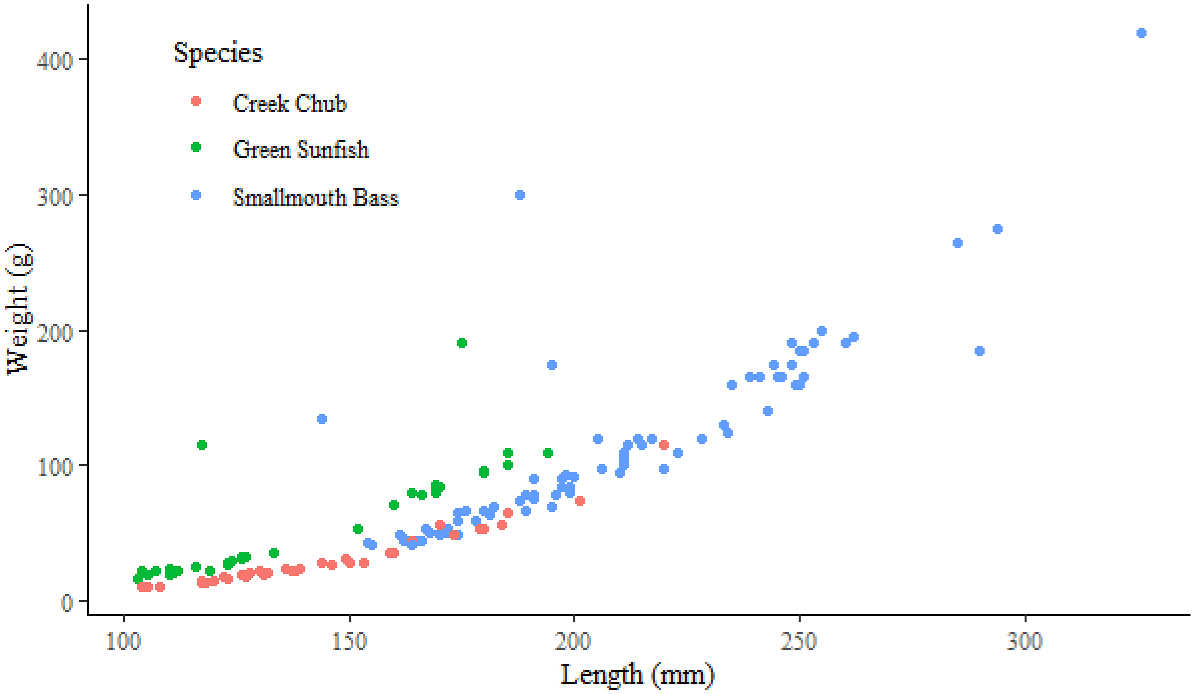

FIGURE 2.3. Scatterplot of total length versus weight of Smallmouth Bass, Green Sunfish, and Creek Chub caught in the Boston Mountains during the summer of 2018.

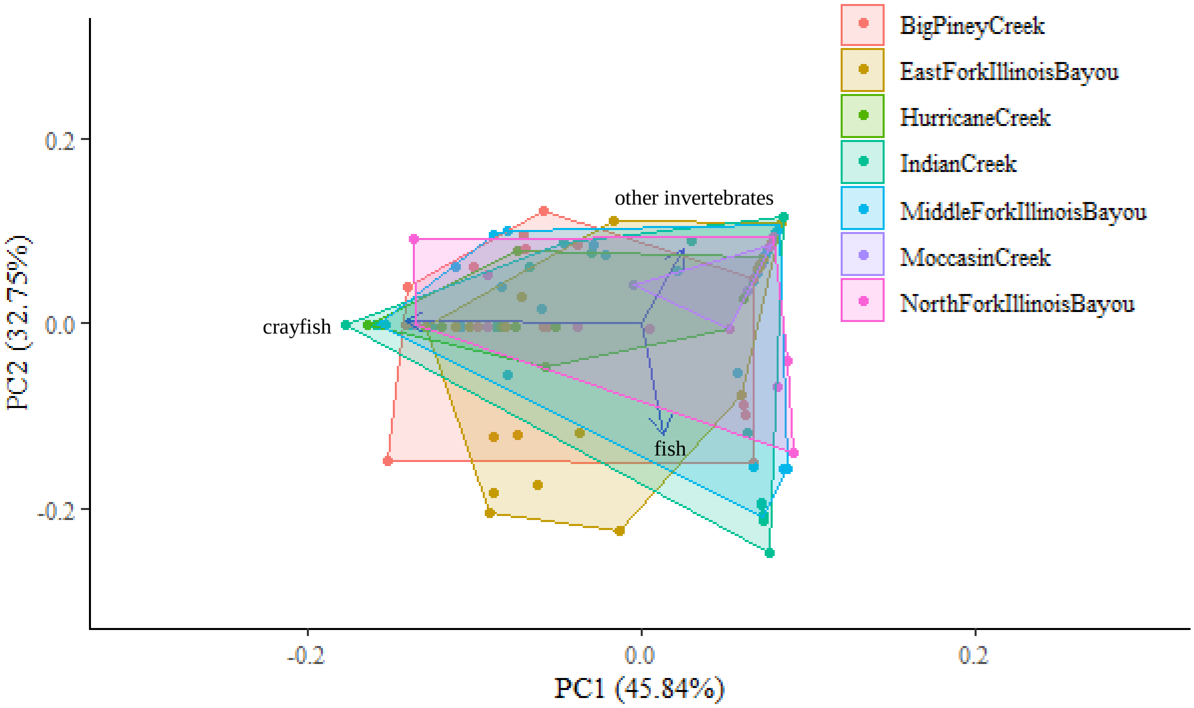

FIGURE 2.4. Principle component analysis showing overlap of prey occurrence in stomach contents of Smallmouth Bass, Green Sunfish, and Creek Chub caught in the summer of 2018 in my sampled streams.

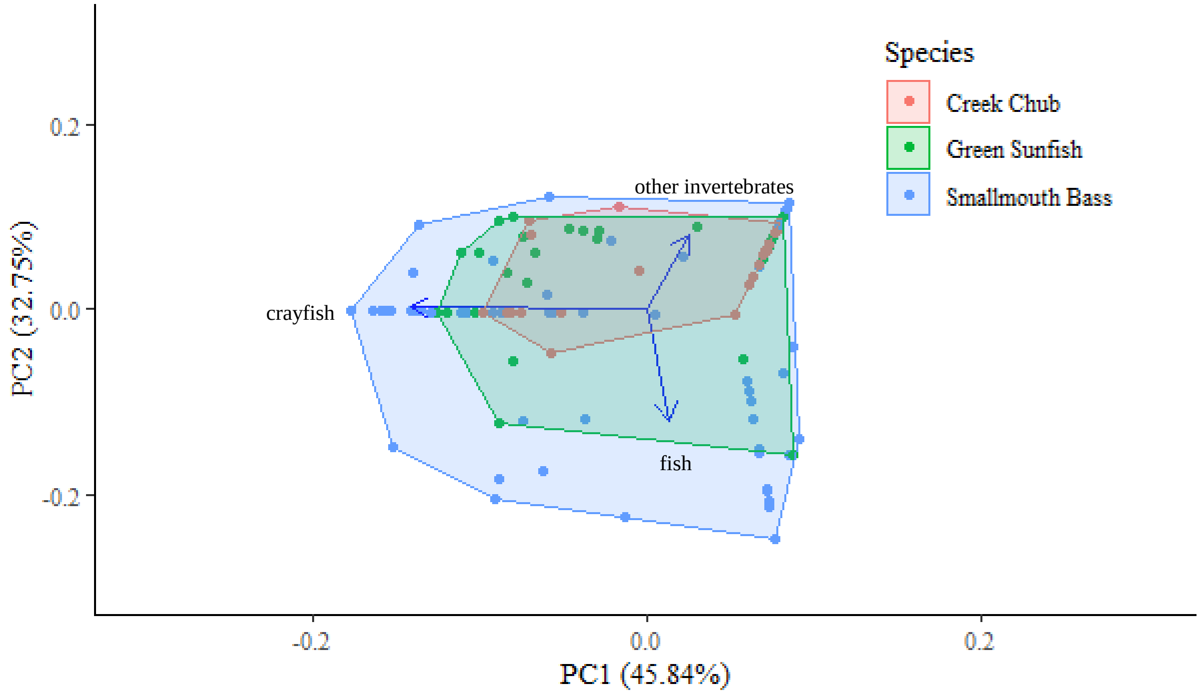

FIGURE 2.5. Principle component analysis showing overlap of prey occurrence found in stomach contents of Smallmouth Bass, Green Sunfish, and Creek Chub caught in summer of 2018.

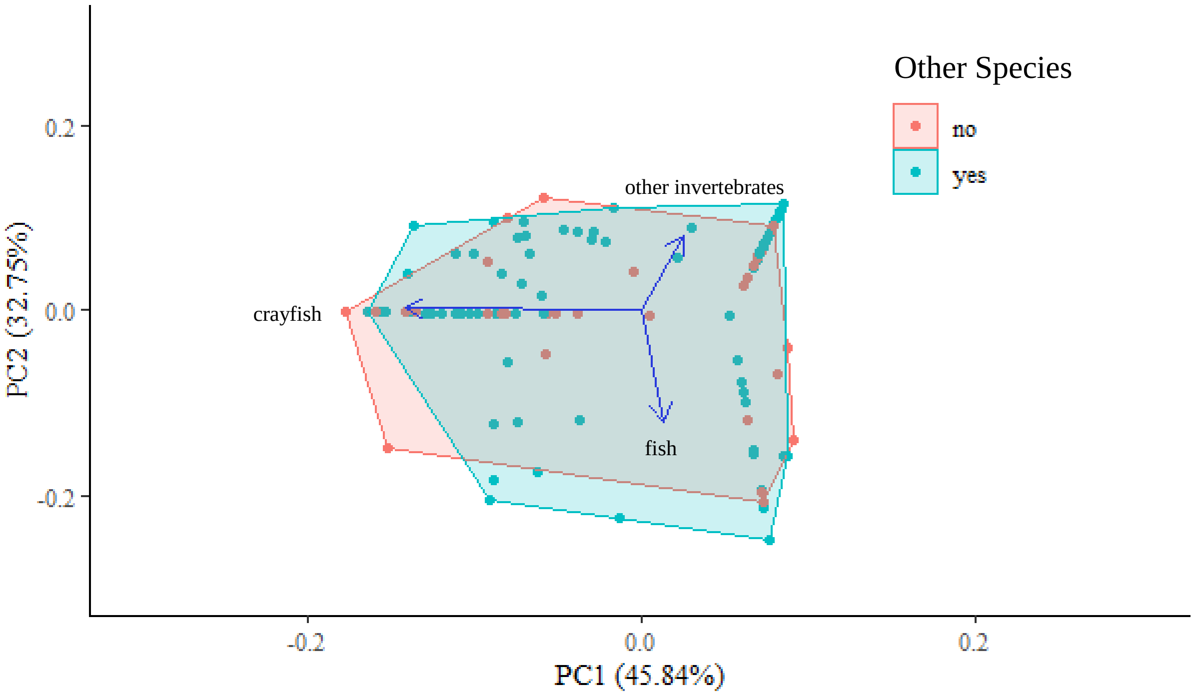

FIGURE 2.6. Principle component analysis showing diet overlap when there was a potential competitor present or not for Smallmouth Bass, Green Sunfish, or Creek Chub caught in summer of 2018.

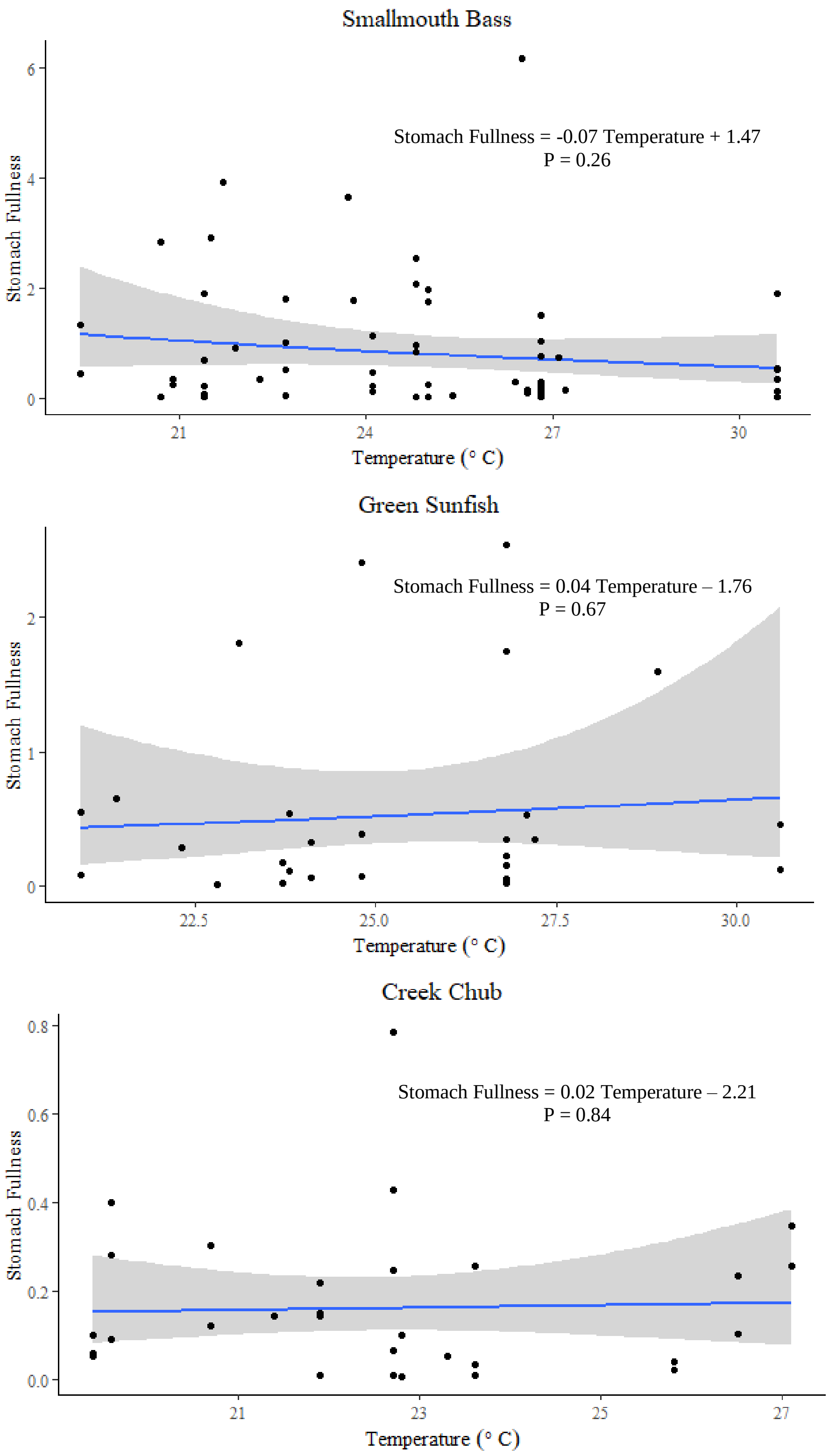

FIGURE 2.7. Relationship between stomach fullness and temperature for Smallmouth Bass, Green Sunfish, and Creek Chub caught in the summer of 2018 with the 95% confidence interval (shaded in blue). Empty stomachs were not included.

# CHAPTER 3: COMPARISON OF SMALLMOUTH BASS ANNUAL GROWTH RATES AMONG THREE ECOREGIONS IN ARKANSAS

## ABSTRACT

Growth data are lacking on the endemic Neosho Smallmouth Bass *Micropterus dolomieu velox* of the Boston Mountains and the Ouachita Smallmouth Bass lineage of the Ouachita Mountains. This study was initiated to compare annual growth rates of the more widespread northern Smallmouth Bass *Micropterus dolomieu dolomieu* with these two more endemic lineages. The three lineages occur in three ecoregions which provide a range of hydrologic regimes. I sampled Smallmouth Bass from five streams each in the Boston Mountains, the Ouachita Mountains, and the Ozark Highlands of Arkansas during the summer of 2019. Sites were selected from streams containing historical United States Geological Survey (USGS) discharge data and watershed size between 5,600 and 107,200 ha. Annual growth was estimated for each captured fish by measuring annuli on the whole otolith and later using sectioned otolith for individual fish deemed age-2 or older. Smallmouth Bass caught in the Boston Mountains had a higher growth coefficient ($K = 0.53$), than those captured in the Ouachita Mountains ($K = 0.41$) and Ozark Highlands ($K = 0.20$). Individual annual growth was significantly affected by both flow ($F = 8.85$, df = 2, $P < 0.01$) and age ($F = 419.09$, df = 1, $P < 0.01$). There was an unexpected inverse relationship between individual annual growth of Smallmouth Bass and mean flow ($F = 10.85$, df = 1, $P < 0.01$) from 2014 through 2018. Increased mean annual flow may have disrupted life history strategies and foraging success of our sampled Smallmouth Bass. If climate change could lead to increased fluctuations in hydrologic regime, then future studies should address the possible consequences for the endemic Smallmouth Bass subspecies of Arkansas.

# INTRODUCTION

Arkansas streams include portions of the northern Smallmouth Bass *Micropterus dolomieu dolomieu,* Neosho Smallmouth Bass *Microtperus dolomieu velox,* and the Ouachita Smallmouth Bass lineages. Each variant of the Smallmouth Bass occurs in a different ecoregion (Stark and Echelle 1998). The northern Smallmouth Bass occurs in lakes and streams of the Ozark Highlands, the Neosho Smallmouth Bass in the Boston Mountains and lower Ozark Highlands, and the genetically distinct Ouachita Smallmouth Bass lineage in the Ouachita Mountains (Hubbs and Bailey 1940; MacCrimmon and Robbins 1974; Stark and Echelle 1998). Location of the various subpopulations exposes them to different environmental variables and they represent genetic differences which could influence growth rates (Kleinssaser et al. 1990). However, published age and growth characteristics of the subpopulations in Arkansas are lacking. Brewer and Long (2015) argued for more age and growth data for Neosho Smallmouth Bass and the Ouachita Smallmouth Bass lineage. Additionally, the Arkansas Game and Fish Commission (AGFC) is interested the current status of major Smallmouth Bass fisheries (AGFC 2012). Their management plan calls for growth studies on Smallmouth Bass at multiple sites in each ecoregion of Arkansas (AGFC 2012).

Annual growth rates are likely associated with environmental variables found within each ecoregion; thus, developing a better understanding of existing relationships can facilitate managing these fishes (Summerfelt and Hall 1987). Habitat quality may provide insight on potential growth (Karr 1991) of the Smallmouth Bass in each ecoregion. Growth of fishes has been linked to fluctuations in hydrologic regime in many studies (Brown 1960; Elwood and Waters 1969; Sigler et al. 1984), and endemic species of Smallmouth Bass appear to be adapted to natural flow regimes (Brewer and Long 2015). The size of fishes in riverine habitats during highwater events is an important factor to examine (Filipek et al. 1991). Low and high flow events can inhibit growth of juvenile Smallmouth Bass (Paragamian and Wiley 1987; Brewer and Orth 2014). Peterson and Kwak (1999) predicted that changes in stream flow and increased temperatures, as a result of climate change, could increase growth of Smallmouth Bass in riverine ecosystems due to longer growing seasons. Studies (Kaushal et al. 2010.; Mosheni et al. 2003) predict climate change will increase stream temperatures and potentially affect biotic processes. Taylor and others (2018) recognized a general need to better understand ecological mechanisms affecting growth of endemic Smallmouth Bass.

In addition to flow regime, significant ecoregion differences in water quality potentially influence Smallmouth Bass growth rates in Arkansas. Kane and Rabeni (1987) studied Smallmouth Bass acidity tolerance, but there is a lack of information on potential effects of calcium in more alkaline waters. I will examine the possible relationship between calcium concentration and annual growth of Smallmouth Bass populations in each ecoregion, as the Ozark Highlands are known to have more alkaline waters (Haggard et al. 2007). Higher turbidity could also have negative effects on Smallmouth Bass growth due to reduced ability to locate prey as they are sight predators (Brown et al. 2009).

Establishing a baseline comparison of Smallmouth Bass growth rates among the three major ecoregions where Neosho Smallmouth Bass, Ouachita Smallmouth Bass lineage, and northern strain Smallmouth Bass are known to occur could facilitate future management decisions. For example, climate change may eventually influence the distribution of native Smallmouth Bass of Arkansas (Middaugh and Magoulick 2018). Resource managers will need to better understand how Smallmouth Bass growth is currently impacted by environmental variables to prepare for possible challenges associated with range expansions or retractions (Brewer and Orth 2014).

The objectives of this study were: to compare age structure and growth rates of Smallmouth Bass among ecoregions and to characterize the relationship between hydrologic regime and annual growth rates of Smallmouth Bass.

## METHODS

### *Study Area*

I sampled Smallmouth Bass from five streams each in the Boston Mountains, Ouachita Mountains, and Ozark Highlands of Arkansas. I randomly selected sites from streams containing a United States Geological Survey (USGS) gauging station and watershed size between 5,600 and 107,200 ha. I also selected one additional site per ecoregion to include streams Homan (2005) studied to quantify stream dryness and growing season Smallmouth Bass production in the same three ecoregions. The selection process involved classifying USGS gauging stations by ecoregion within ArcGIS for watershed sizes between 5,600 and 107,200 ha offering a minimum of five years of historical data to characterize hydrologic regime (Figure 3.1). Sites were removed from the selection process when access was impeded by private property. Selected sites for the Boston Mountains were Big Creek, Big Piney Creek, Illinois Bayou, Mulberry River, and Richland Creek (Figure 3.1). My selected sites for the Ouachita Mountains were Alum Fork Saline River, Caddo River, Cossatot River, Ouachita River, and the South Fourche LaFave River (Figure 3.1). The selected sites for the Ozark Highlands were Bear Creek, Illinois River, North Sylamore Creek, Osage Creek, and War Eagle Creek (Figure 3.1). Sampling occurred between mid-June and mid-August.

### *Fish Collections*

I established two one-kilometer sites on each stream; one upstream and one downstream of each selected USGS gauging station. I attempted to collect 20 Smallmouth Bass at each site by hook and line. Incidental captures of Largemouth Bass *Micropterus salmoides* and Spotted Bass *Micropterus punctulatus* were sampled, as well. I used soft-plastic baits, artificial minnows, and crayfish imitators with spinning rods following Middaugh (2017). Total length and wet weight were measured for each Smallmouth Bass, Largemouth Bass, and Spotted Bass caught. I clipped and collected the upper lobe of the caudal fin on each fish and stored it in ethanol for possible future genetic studies by Dr. Lori Eggert and Joseph Gunn in the Biological Department of the College of Arts and Science at the University of Missouri.

Aside from tissue extraction in the field, whole fish were placed in a cooler with ice and returned to the laboratory for otolith removal to back calculate length-at-age (Quist et al. 2012) for each Smallmouth Bass, Largemouth Bass, and Spotted Bass. After otolith extraction, fish were preserved in a buffered formalin solution and stored for future morphometric and meristic assessment (Dakota Nash, Fisheries and Wildlife undergraduate, Arkansas Tech University). All preserved fish had buffered formalin injected into their stomachs to preserve contents for possible future comparison of diet characteristics to those from 2018 samples (Chapter 2).

### *Fish Age Estimation and Growth Increment Determination*

Sagittal otoliths were removed from Smallmouth Bass, Largemouth Bass, and Spotted Bass in the lab, and I initially measured annual growth for each captured fish on the whole otoliths by examining them under a dissecting microscope. Then, I produced digital pictures of each whole otolith using a camera attached to a dissecting microscope. After uploading the digital image, I estimated the age of each fish and used the direct proportion (“Dahl-Lea”) method for estimating annual growth (Schramm et al.1992; Maceina et al. 2007; Hecke et al. 2016) by marking distance between otolith rings with the RFishBC package in R version 3.6.2 (R Studio Team 2016). I used sectioned otoliths for further confirmation of ages for individual fish deemed age-2 or older based on whole otolith measurements. Otoliths were sectioned by cracking with thumb pressure and forceps (Zale et al. 2012).

### *Hydrologic Data Classification*

Streamflow characteristics for all 15 sampling locations were obtained from the USGS (waterdata.usgs.gov/ar/nwis/rt). I only used data from 2014 through 2018, because Big Creek's historical gauge data began in 2014. I wanted a full growing season for back-calculation, so I only used gauge recordings until the year 2018. Daily mean flow (Q)(expressed as $L/s{\cdot}ha^{-1}$) was characterized as discharge reported for 15-minute intervals from the USGS gaging station centered at each sampling location from May 1 through September 30 of each year (nominal growing season).

### *Additional Habitat Sampling*

I recorded stream temperature between 10:00 and 14:00 during each sample in a shaded area, as close as practical to, the USGS gauging station. Additionally, I measured turbidity and conductivity at each site after fish collection ceased. Linear distance was measured by hip chain or Trimble Geo 7x GPS unit later in the summer for each one-kilometer site following Homan and others (2005). I did not measure wetted linear distance because none of my sampling sites had complete linear dryness during sampling.

After fish sampling had been completed for the summer, I returned to all sample sites, within one week in September, to collect samples for water quality analysis. Water quality sampling involved recording temperature, conductivity, salinity, and pH on site. Additionally, I collected water samples for later measurements of calcium concentration, alkalinity as $CaCO_3$, and pH by a certified commercial lab (Environmental Enterprise Group, Inc. Russellville, AR).

### *Statistical Analyses*

I calculated the von Bertalanffy growth equation with the FSA package in R version 3.6.2 (Ogle 2016; R Studio Team 2019) to assess Smallmouth Bass growth from each ecoregion. Then, to compare relative weights of Smallmouth Bass among ecoregions, I used a One-Way Analysis of Variance (ANOVA) and post-hoc Tukey HSD for pairwise comparisons. I calculated the coefficient of variation for Q for each nominal growing season for each stream from 2014 through 2018. Then, I created a linear mixed effects model, with the lme4 package in R version 3.6.2 (R Studio Team 2016), to account for repeated measures of back-calculated annual growth and Q data from each year. My independent variables were coefficient of variation for Q by year, age of Smallmouth Bass during same year, and the year itself was my random effect. I used estimated individual annual growth as my dependent variable. Statistical significance for my analyses was set at $\alpha \leq 0.05$.

## RESULTS

### *Growth Comparisons of Smallmouth Bass Among Ecoregions*

I captured 186 Smallmouth Bass during the summer of 2019 from 13 of my 15 selected streams (Table 3.2). Back-calculated lengths-at-age of Smallmouth Bass of the Boston Mountains averaged (±SE) 112 ± 3.69 mm at age-1; 192 ± 3.02 mm at age 2; 247 ± 3.61 mm at age 3; 274 ± 7.25 mm at age 4; 277 ± 9.45 mm at age 5; 303 mm for age 6; and 316 mm at age 7 (Table 3.3). Back-calculated lengths at age of Smallmouth Bass of the Ouachita Mountains averaged (±SE) 115 ± 4.00 mm at age 1; 202 ± 3.76 mm at age 2; 257 ± 5.49 mm at age 3; 286 ± 13.11 mm at age 4; 290 ± 25.53 mm at age 5; and 261 ± 17.66 mm at age 6 (Table 3.3). The back-calculated lengths at age of Smallmouth Bass of the Ozark Highlands averaged (±SE) 101 ± 2.38 mm at age 1; 181 ± 2.93 mm at age 2; 232 ± 5.18 mm at age 3; 260 ± 10.79 mm at age 4; and 300 ± 23.36 at age 5 (Table 3.3). I removed all Smallmouth Bass age 5 or older from the statistical analyses due to low sample size (Figure 3.2). The von Bertalanffy growth equation parameters for Smallmouth Bass of the Boston Mountains were 330 mm for asymptotic length ($L_\infty$), 0.53 for the growth coefficient ($K$), and -0.70 for theoretical age at zero length ($t_0$). For Smallmouth Bass of the Ouachita Mountains, growth model parameters were 341 mm for $L_\infty$, 0.41 for $K$, and -0.94 for $t_0$. For Smallmouth Bass of the Ozark Highlands, growth model parameters were 429 mm for $L_\infty$, 0.20 for $K$, and -1.69 for $t_0$. Results from the One-Way ANOVA indicated relative weight (Figure 3.3) of Smallmouth Bass among ecoregions was statistically different among ecoregions ($F_{2,183} = 5.09$, df = 2, $P < 0.01$). Post hoc comparisons using Tukey test were carried out. Relative weight of Smallmouth Bass in the Boston Mountains ($W_r = 86$) was significantly higher ($P < 0.01$) than in the Ozark Highlands ($W_r = 82$).

### *Hydrology Measures in Relation to Smallmouth Bass Annual Growth*

Results from the linear mixed effects model indicated the coefficient of variation of Q ($F = 10.50$, df = 1, $P < 0.01$) and age ($F = 252.886$, df = 2, $P < 0.01$) significantly affected the annual growth of Smallmouth Bass. There was no significant interaction between coefficient of variation of Q and age of Smallmouth Bass. Annual growth of age-2 Smallmouth Bass had an inverse relationship with coefficient of variation of Q increased (Figure 3.4). The annual growth of age-3 Smallmouth Bass had visually no relationship with the coefficient of variation of Q (Figure 3.4). Annual growth of age-4 Smallmouth Bass had a direct relationship with the coefficient of variation of Q above 2.75 but an inverse relationship below (Figure 3.4)

# DISCUSSION

Length at age estimates for the ages 1-3 Smallmouth Bass I sampled were above average compared to similar populations from other locations (Beamesderfer and North 1995). However, the ages 4-6 Smallmouth Bass I captured had below average length-at-age estimates compared to other similar populations (Beamesderfer and North 1995). Age ranges for my sampled Smallmouth Bass from the three ecoregions was similar to findings from other studies at other locations in Ozark streams where maximum age ranged from 5 to 7 (Finnell et al. 1956; Orth et al. 1983; Stark and Zale 1991; Balkenbush and Fisher 1998). The von Bertalanffy growth coefficient (*K*) indicated above-average growth compared to similar Smallmouth Bass populations (Starks and Roger 2020) for the Boston Mountains, Ouachita Mountains, and Ozark Highlands. Additionally, the age where individuals had zero size ($t_0$) was higher in the Boston Mountains, Ouachita Mountains, and Ozark Highlands than the study done by Starks and Roger in 2020. Although, the asymptotic length where growth was zero ($L_\infty$) was lower for Smallmouth Bass in the Boston Mountains, Ouachita Mountains, and Ozark Highlands than reported by Starks and Roger (2020). The sampled populations sampled in this study seemed to be growing at an accelerated rate compared to other Smallmouth Bass populations but reaching a lower asymptotic length.

Smallmouth Bass annual growth declined significantly with increased age which was expected for younger individuals (Paragamian and Wiley 1987). In my study, growth was primarily associated with age and body size, similar to Paragamian and Wiley (1987). Whitledge and others (2006) concluded that increased fluctuations in available water could influence the growth potential of Smallmouth Bass. Documented effects of hydrologic regime on native Smallmouth Bass in the Boston Mountains, Ouachita Mountains, and Ozark Highlands of

Arkansas remain limited. Surges in flow may have increased available food supply (Sigler et al. 1984) which could have led to increased growth in Smallmouth Bass. Fluctuations in hydrologic regime may have influenced growth, as Elwood and Waters (1969) found severe floods to reduce prey selection and negatively affect brown trout populations. The endemic Smallmouth Bass in Arkansas may not be adapted or well suited to increased fluctuations in flow. Expanding the study duration to include Smallmouth Bass annual growth over more years and sites could improve understanding of how flow fluctuations affect growth of Smallmouth Bass in Arkansas streams.

This study encountered limitations for evaluation of environmental effects on Arkansas Smallmouth Bass age and growth. I only sampled alkalinity, calcium, dissolved oxygen, pH, and temperature in September 2019 (Table 3.4), so I was unable to incorporate the previous years with my historical hydrologic data and length at age back calculations. Capturing fish by hook and line provided samples most relevant to anglers of Arkansas, but this approach could have biased my estimates relative to the entire population of Smallmouth Bass. Also, I used the same baits over the sampling period whereas anglers may experience different catches with different colors in different environmental conditions.

Sharma and others (2009) expressed concern that the native subpopulations could be outcompeted by northern Smallmouth Bass as climate change progresses. A recent study (Middaugh et al. 2016) predicted that increased water temperatures during the spring and summer would lead to decreased growth potential in summer months due to exceeding optimal temperature for Smallmouth Bass growth. Thus, could lead to an increase in competition between native Smallmouth Bass and northern Smallmouth Bass and Largemouth Bass (Middaugh et al. 2016). Kaushel (2010) and others predict a general increase in air and water temperature in my study area. Increased stream temperatures and flow could increase the metabolic costs of endemic Smallmouth Bass and consequently affect their growth and condition. Understanding the current geographical range of the subspecies of Smallmouth Bass in Arkansas along with their life history differences (Homan 2005) from northern Smallmouth Bass should be a focus going forward.

TABLE 3.1. The GPS Coordinates (UTM Zone 15 North) and watershed area of each sampled stream in summer 2019.

| Ecoregion | Stream | UTM Easting | UTM Northing | Watershed Size (ha) |
|---|---|---|---|---|
| Boston Mountains | Big Creek | 493436 | 3977142 | 10,600 |
| | Big Piney Creek | 483550 | 3929155 | 79,300 |
| | Illinois Bayou | 496270 | 3924767 | 62,400 |
| | Mulberry River | 408008 | 3937501 | 96,600 |
| | Richland Creek | 506425 | 3961460 | 17,500 |
| Ouachita Mountains | Alum Fork Saline River | 506048 | 3850589 | 7,000 |
| | Caddo River | 444279 | 3804765 | 35,200 |
| | Cossatot River | 386330 | 3804984 | 23,200 |
| | Ouachita River | 436051 | 3830016 | 107,200 |
| | South Fourche LaFave River | 494874 | 3863280 | 54,400 |
| Ozark Highlands | Bear Creek | 525856 | 3977332 | 21,500 |
| | Illinois River | 378983 | 3996216 | 43,200 |
| | North Sylamore Creek | 570858 | 3983310 | 15,000 |
| | Osage Creek | 384209 | 4009335 | 33,700 |
| | War Eagle Creek | 423135 | 4006470 | 68,100 |

TABLE 3.2. Number of Smallmouth Bass caught for age and growth analysis in 15 Interior Highland streams (separated by ecoregion) throughout the duration of my study in the summer of 2019 in Arkansas.

| Ecoregion | Stream | Smallmouth Bass |
|---|---|---|
| Boston Mountains | Big Creek | 14 |
| | Big Piney Creek | 7 |
| | Illinois Bayou | 8 |
| | Mulberry River | 10 |
| | Richland Creek | 5 |
| Subtotal | | 44 |
| Ouachita Mountains | Alum Fork Saline River | 0 |
| | Caddo River | 10 |
| | Cossatot River | 12 |
| | Ouachita River | 19 |
| | South Fourche LaFave River | 13 |
| Subtotal | | 54 |
| Ozark Highlands | Bear Creek | 16 |
| | Illinois River | 9 |
| | North Sylamore Creek | 25 |
| | Osage Creek | 38 |
| | War Eagle Creek | 0 |
| Subtotal | | 88 |
| Total | | 186 |

TABLE 3.3. Mean, back-calculated, lengths-at-age (mm) for Smallmouth Bass (n=186) from 13 of my 15 sampled streams in Arkansas during the summer of 2019. Numbers in parentheses represent standard errors.

| | Ecoregion | | |
|---|---|---|---|
| Age | Boston Mountains | Ouachita Mountains | Ozark Highlands |
| 1 | 112(4) | 115(4) | 101(2) |
| 2 | 192(3) | 202(4) | 181(3) |
| 3 | 247(4) | 257(5) | 232(5) |
| 4 | 274(7) | 286(13) | 260(11) |
| 5 | 277(9) | 290(26) | 300(23) |
| 6 | 303 | 261(18) | |
| 7 | 316 | | |

TABLE 3.4. Environmental variables measured at each sampling location during 2019. Samples for determination of alkalinity (mg/L), calcium (mg/L), and pH were collected between 8 September and 12 September 2019. Conductivity (μs/cm), dissolved oxygen (mg/L), and turbidity (NTU) were collected with YSI meter on site from 8 September to 12 September, 2019.

| Ecoregion | Stream | Alkalinity | Calcium | pH | Conductivity | Dissolved Oxygen | Turbidity |
|---|---|---|---|---|---|---|---|
| Boston Mountains | Big Creek | 100 | 35 | 6.7 | 196.1 | 9.3 | 2.3 |
| | Big Piney Creek | 28 | 8.4 | 6.7 | 63.8 | 6.7 | 2.6 |
| | Illinois Bayou | 15 | 3.3 | 6.7 | 38.2 | 6.7 | 3.6 |
| | Mulberry River | 16 | 3.4 | 6.6 | 40.2 | 6.8 | 5.5 |
| | Richland Creek | 33 | 10 | 6.9 | 68.5 | 6.8 | 2.2 |
| Median | | 28 | 8.4 | 6.7 | 63.8 | 6.8 | 2.6 |
| Ouachita Mountains | Alum Fork Saline River | 10 | 1.5 | 6.9 | 26.4 | 6.0 | 2.5 |
| | Caddo River | 58 | 19 | 6.5 | 120.5 | 5.2 | 3.4 |
| | Cossatot River | 23 | 5.7 | 6.6 | 54.8 | 7.0 | 1.0 |
| | Ouachita River | 30 | 8.4 | 6.7 | 70.8 | 5.7 | 3.7 |
| | South Fourche Lafave River | 11 | 1.7 | 6.7 | 35.6 | 5.1 | 4.9 |
| Median | | 23 | 5.7 | 6.7 | 54.8 | 5.7 | 3.4 |
| Ozark Highlands | Bear Creek | 110 | 41 | 6.6 | 254.4 | 6.8 | 2.1 |
| | Illinois River | 130 | 48 | 6.1 | 308.4 | 7.9 | 8.0 |
| | North Sylamore Creek | 120 | 40 | 7.6 | 250.2 | 7.8 | 0.4 |
| | Osage Creek | 140 | 53 | 6.4 | 392.5 | 8.7 | 2.6 |
| | War Eagle Creek | 94 | 35 | 6.7 | 234.5 | 8.2 | 6.2 |
| Median | | 120 | 41 | 6.6 | 254.4 | 7.9 | 2.6 |

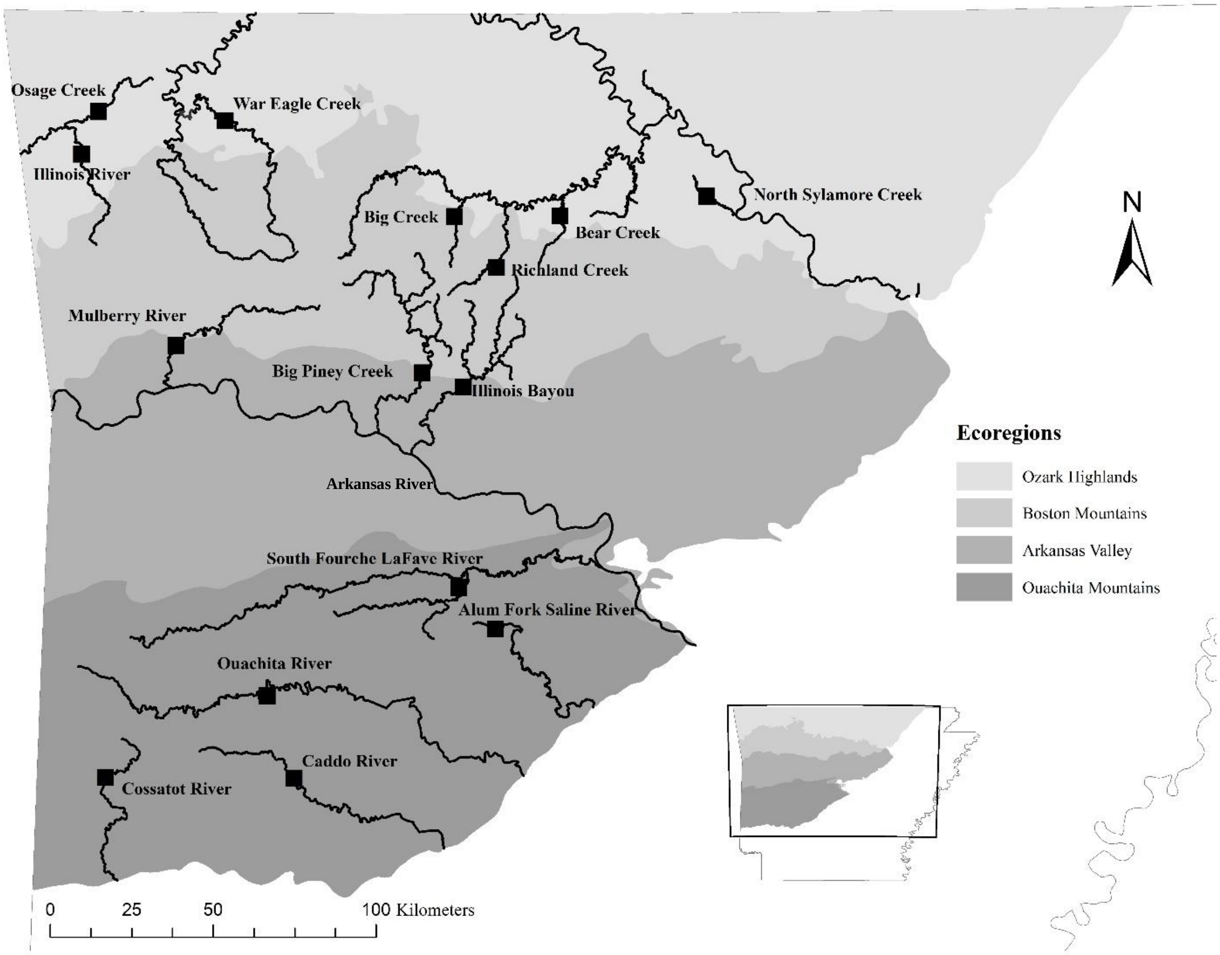

FIGURE 3.1. Map of the 15 study streams within the ecoregions sampled in Arkansas during the summer 2019. Black squares represent the location of USGS gauge stations.

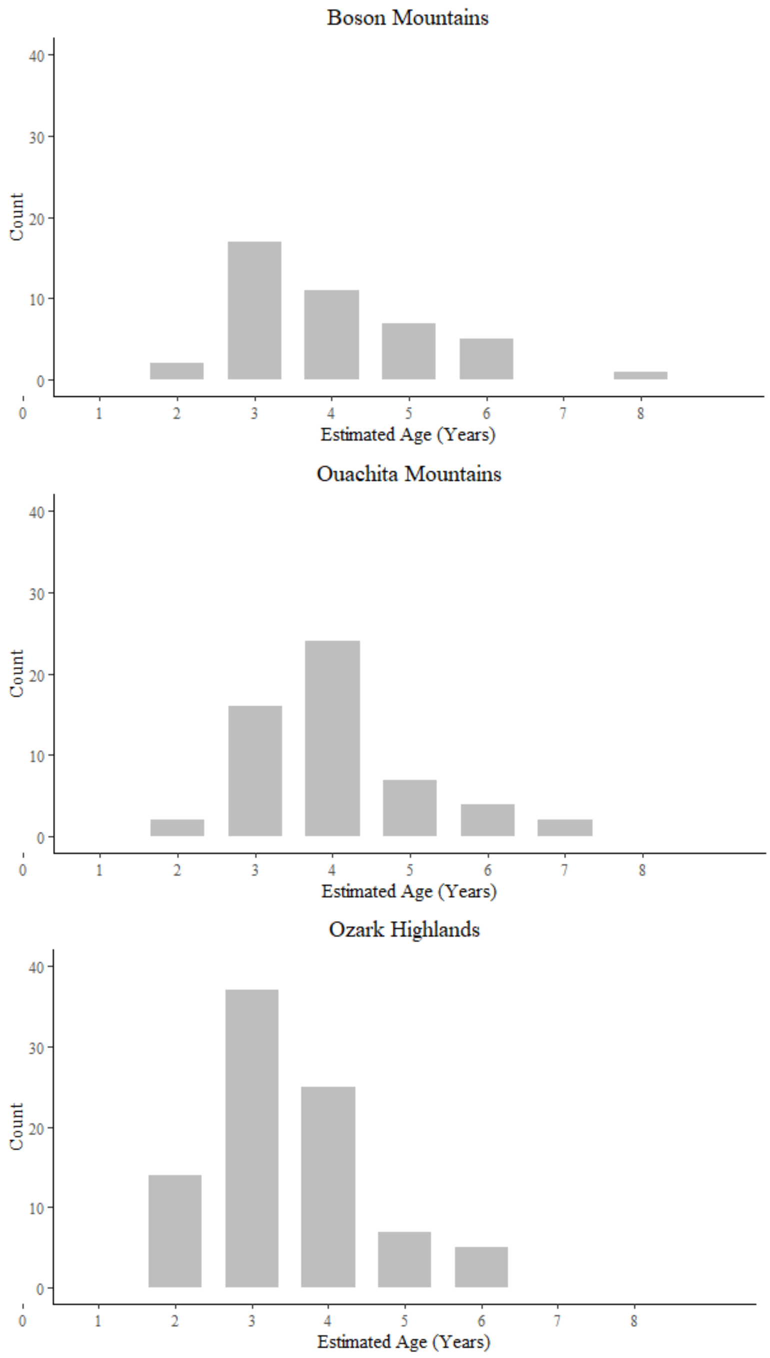

FIGURE 3.2. Number of all Smallmouth Bass in each represented age class sampled from the Boston Mountains, Ouachita Mountains, and Ozark Highlands during the summer of 2019.

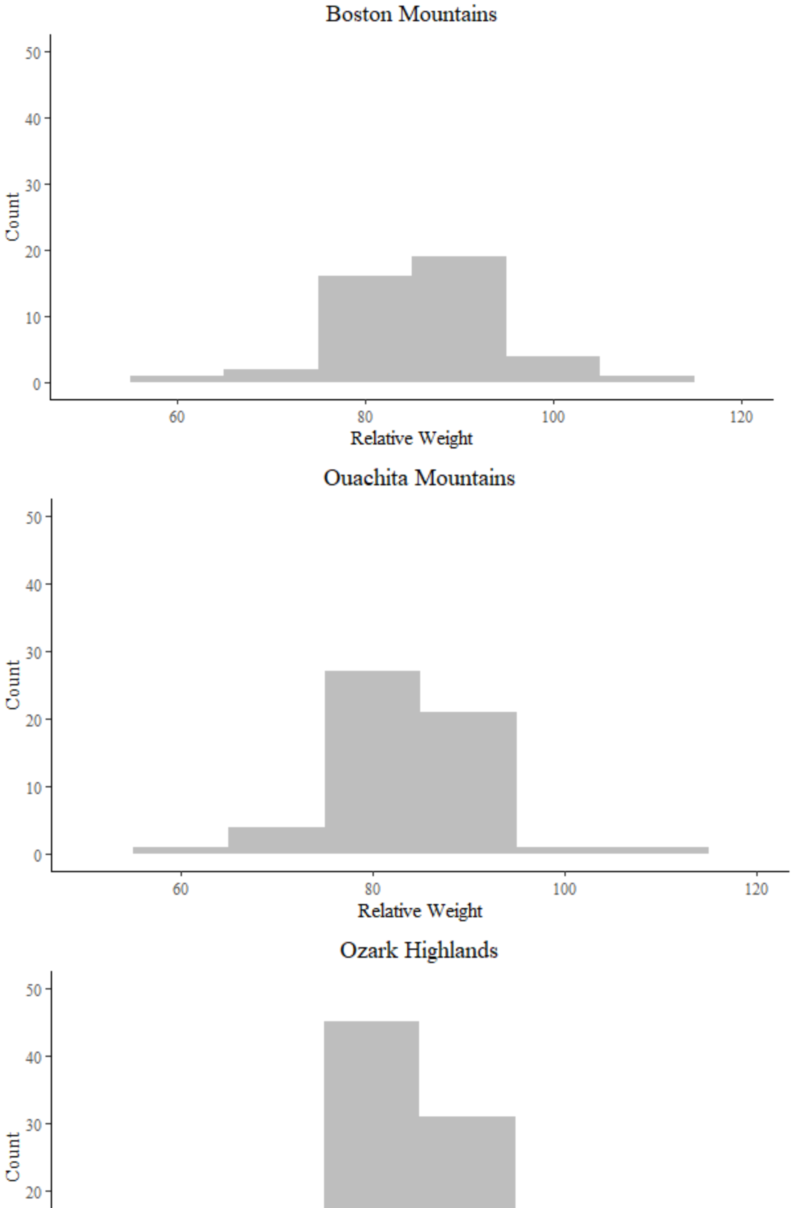

FIGURE 3.3. Relative weight in bins of five for all Smallmouth Bass (≥ 150mm) caught in the summer of 2019 by ecoregion.

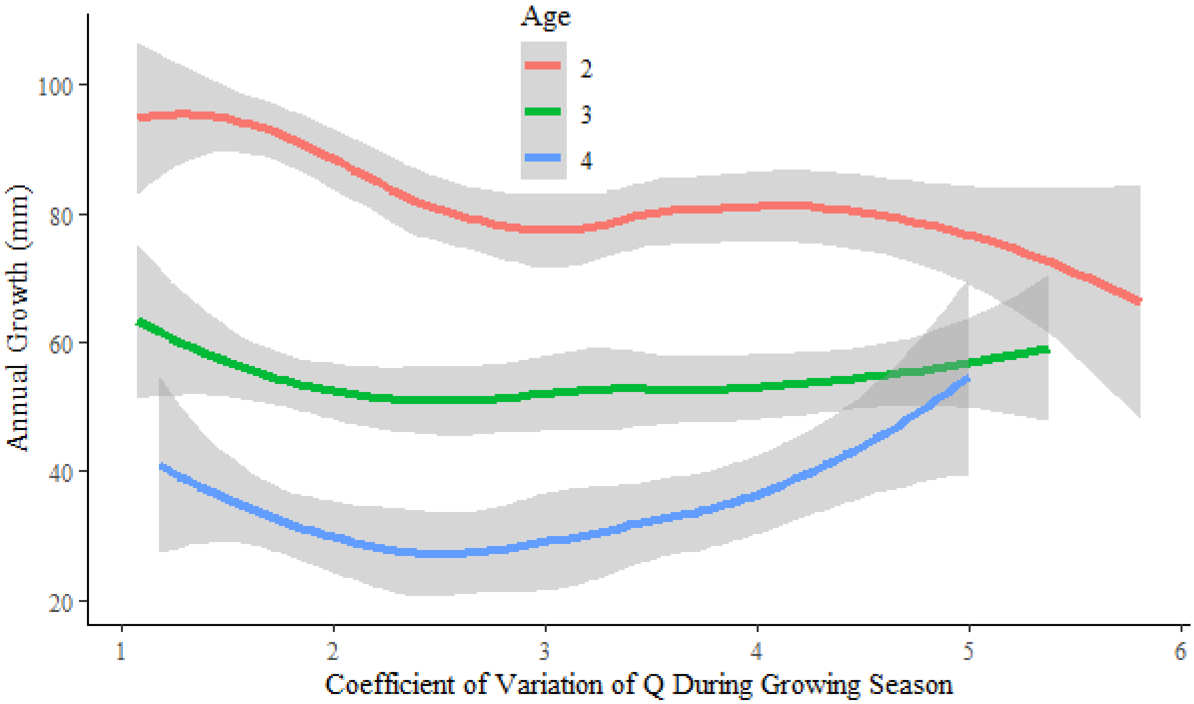

Figure 3.4. A general additive model showing the relationship of Smallmouth Bass annual growth to the coefficient of variation of flow during the growing season from 2014-2018 for 2-, 3-, and 4-year old fish caught during the summer of 2019.

# CHAPTER 4: CONCLUSION

The objectives of this study were to characterize the diets of Smallmouth Bass in areas prone to drying, monitor their potential diet changes in relation to presence of possible competitors, search for relationships between thermal regime and diet, compare age structure and growth rates of Smallmouth Bass among three ecoregions of Arkansas, and to characterize the relationship between hydrologic regime and annual growth rates of Smallmouth Bass. The major findings of this research are summarized below:

- There was a significant association between piscivores and their prey selection in Boston Mountain headwater streams prone to drying. Crayfish were the primary diet item of Smallmouth Bass throughout the summer of 2018.
- In the Interior Highlands of Arkansas, age-2 Smallmouth Bass annual growth was higher in streams with lower coefficient of variation of flow during the growing season.
- Smallmouth Bass in the Boston Mountains have a higher growth rate than the lineages in Ouachita Mountains and Ozark Highlands.

Lower Smallmouth Bass production in Boston Mountain streams is not likely driven by lack of prey species. However, competition could become more important if streams become warmer with less surface flow because of climate change. Additionally, climate change could lead to increased fluctuations in hydrologic regime and could reduce endemic Smallmouth Bass condition and growth in streams of the Interior Highlands of Arkansas.

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# APPENDIX

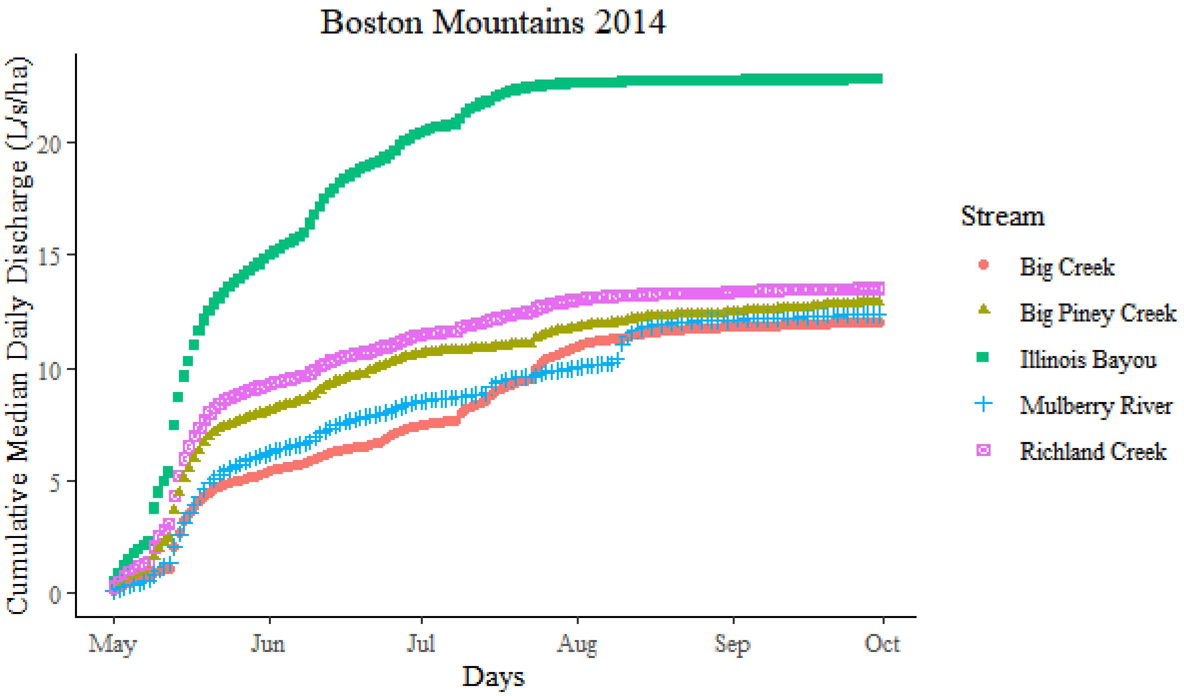

FIGURE A.1. Cumulative frequency distribution of median daily Q (L/s·ha$^{-1}$) from May 1 through September 30, 2014 in the Boston Mountains. Historical Q data was extracted from USGS gauging stations located in each stream.

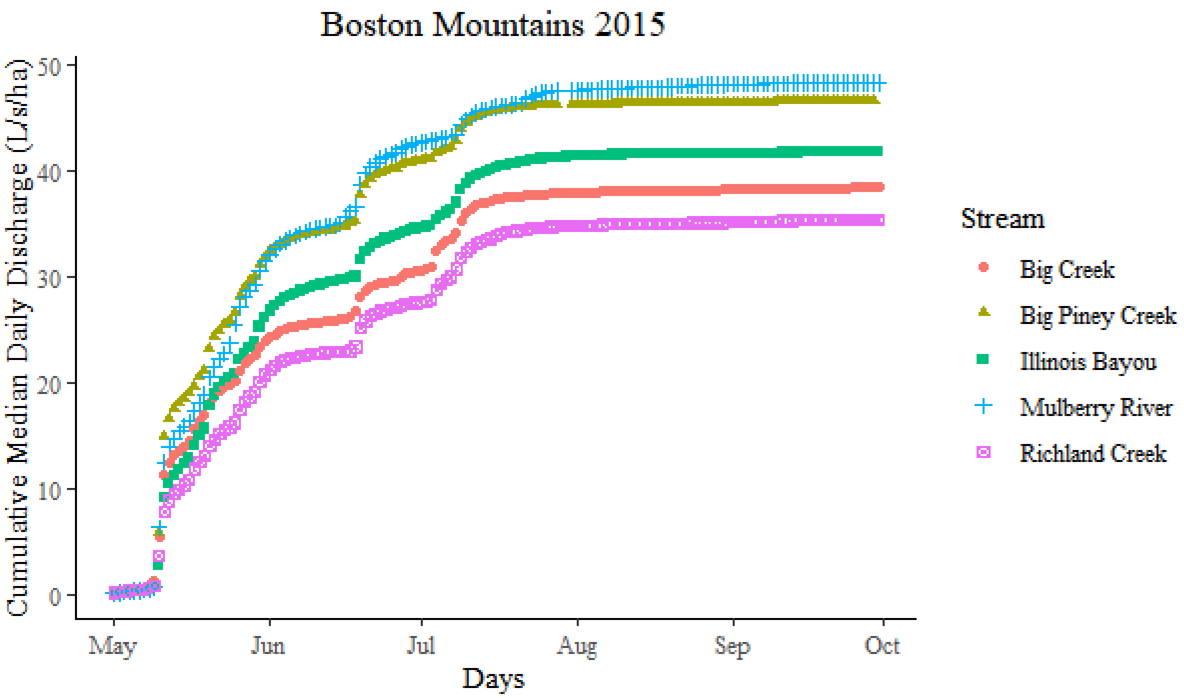

FIGURE A.2. Cumulative frequency distribution of median daily Q (L/s·ha$^{-1}$) from May 1 through September 30, 2015 in the Boston Mountains. Historical Q data was extracted from USGS gauging stations located in each stream.

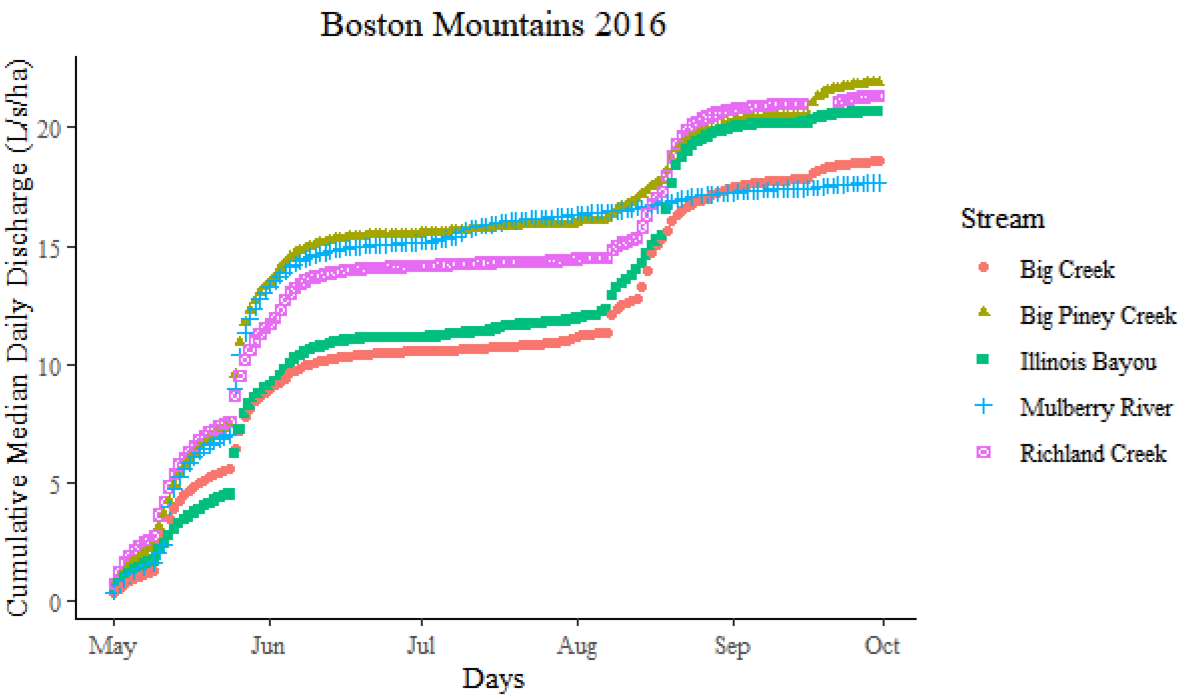

FIGURE A.3. Cumulative frequency distribution of median daily Q (L/s·ha$^{-1}$) from May 1 through September 30, 2016 in the Boston Mountains. Historical Q data was extracted from USGS gauging stations located in each stream.

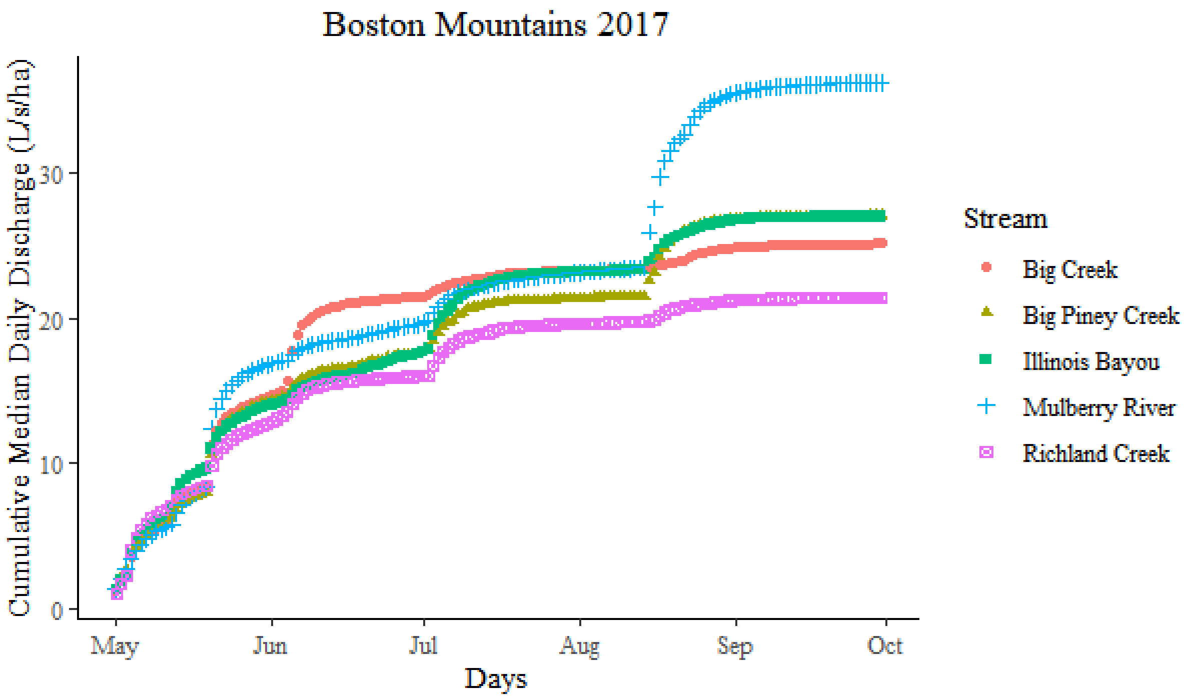

FIGURE A.4. Cumulative frequency distribution of median daily Q (L/s·ha$^{-1}$) from May 1 through September 30, 2017 in the Boston Mountains. Historical Q data was extracted from USGS gauging stations located in each stream.

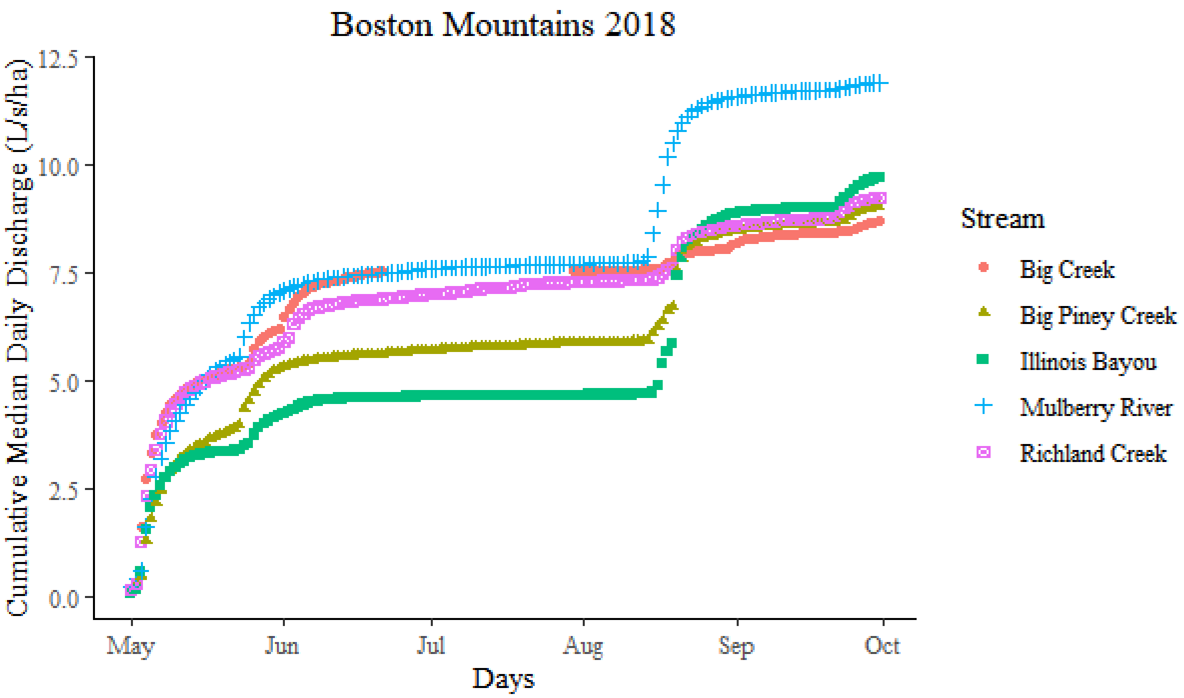

FIGURE A.5. Cumulative frequency distribution of median daily Q (L/s·ha$^{-1}$) from May 1 through September 30, 2018 in the Boston Mountains. Historical Q data was extracted from USGS gauging stations located in each stream.

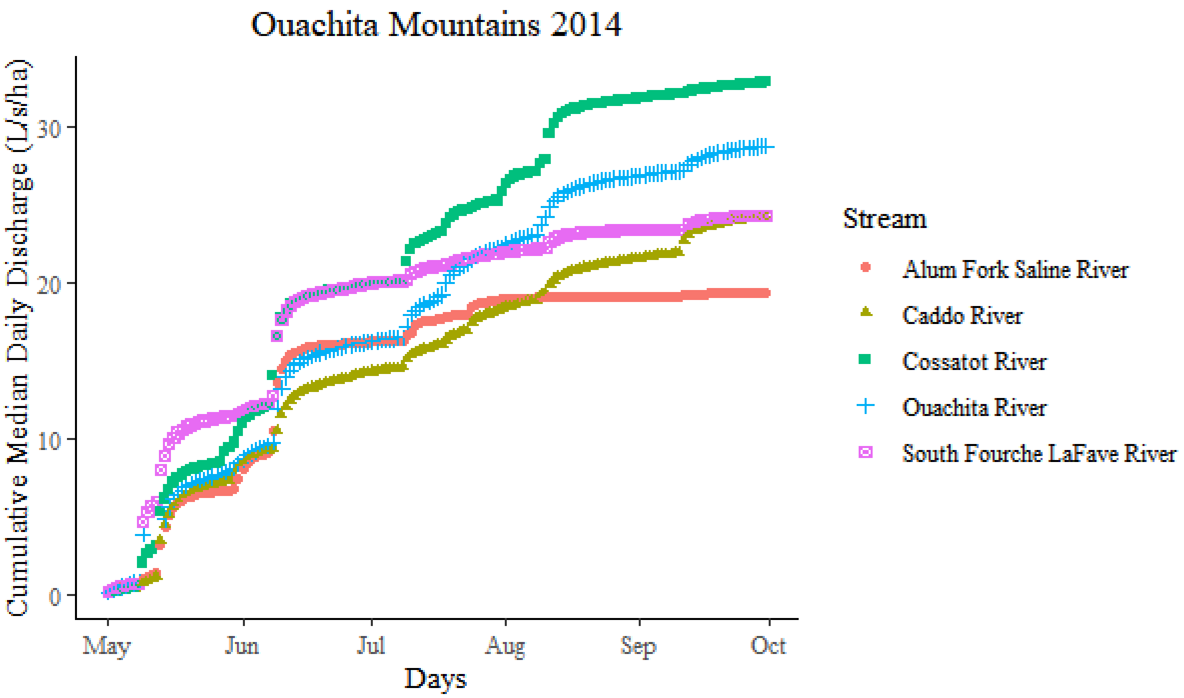

FIGURE A.6. Cumulative frequency distribution of median daily Q (L/s·ha$^{-1}$) from May 1 through September 30, 2014 in the Ouachita Mountains. Historical Q data was extracted from USGS gauging stations located in each stream.

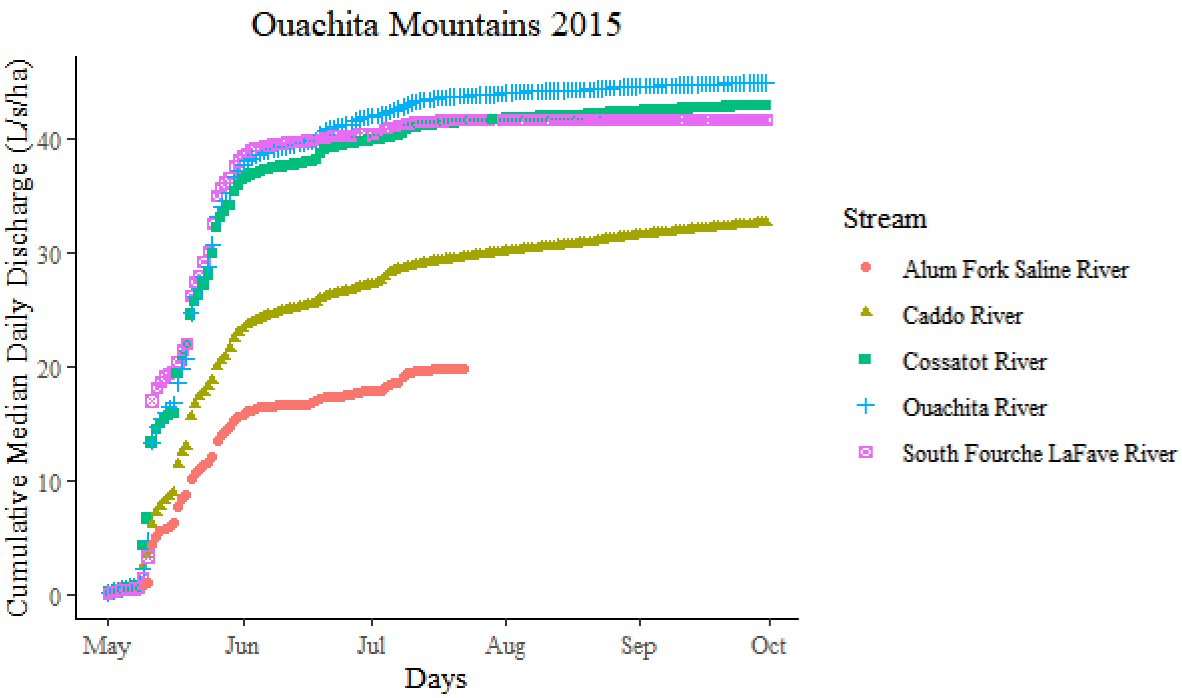

FIGURE A.7. Cumulative frequency distribution of median daily Q (L/s·ha$^{-1}$) from May 1 through September 30, 2015 in the Ouachita Mountains. Historical Q data was extracted from USGS gauging stations located in each stream.

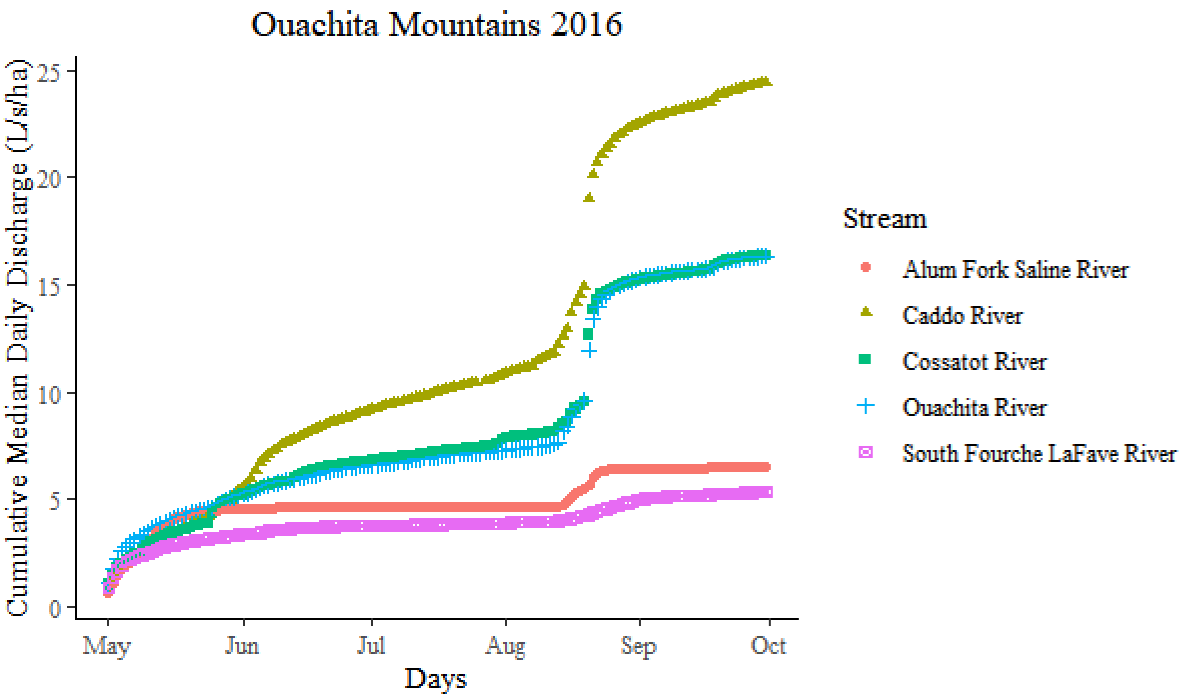

FIGURE A.8. Cumulative frequency distribution of median daily Q (L/s·ha$^{-1}$) from May 1 through September 30, 2016 in the Ouachita Mountains. Historical Q data was extracted from USGS gauging stations located in each stream.

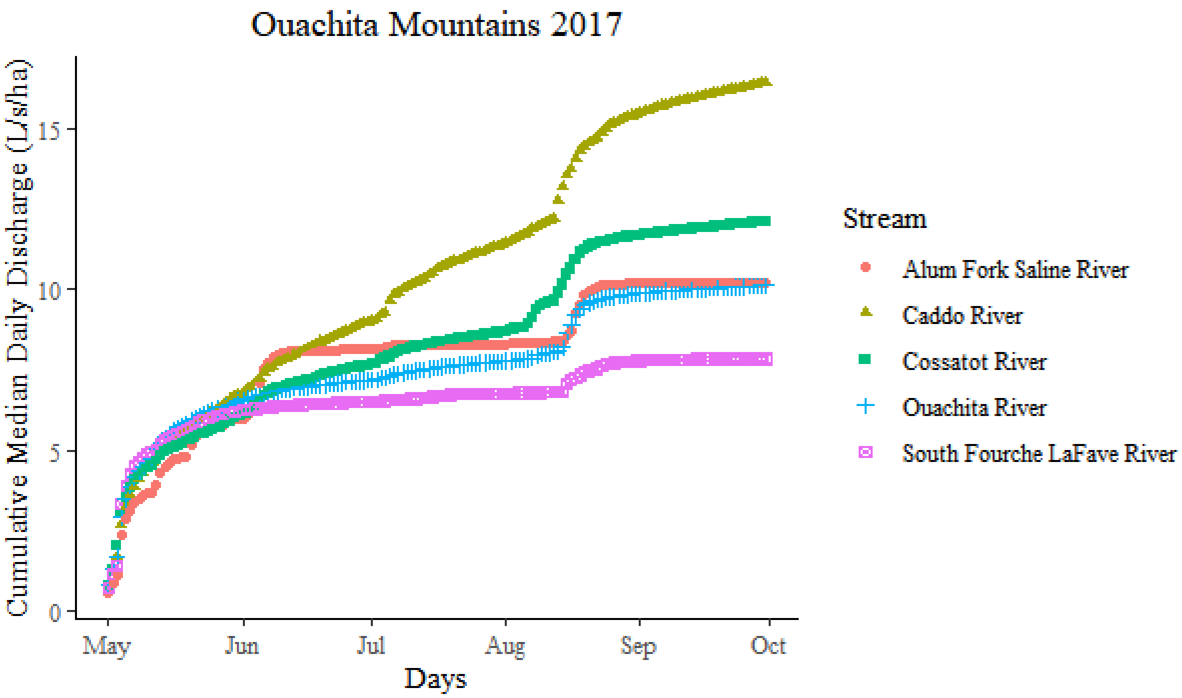

FIGURE A.9. Cumulative frequency distribution of median daily Q (L/s·ha$^{-1}$) from May 1 through September 30, 2017 in the Ouachita Mountains. Historical Q data was extracted from USGS gauging stations located in each stream.

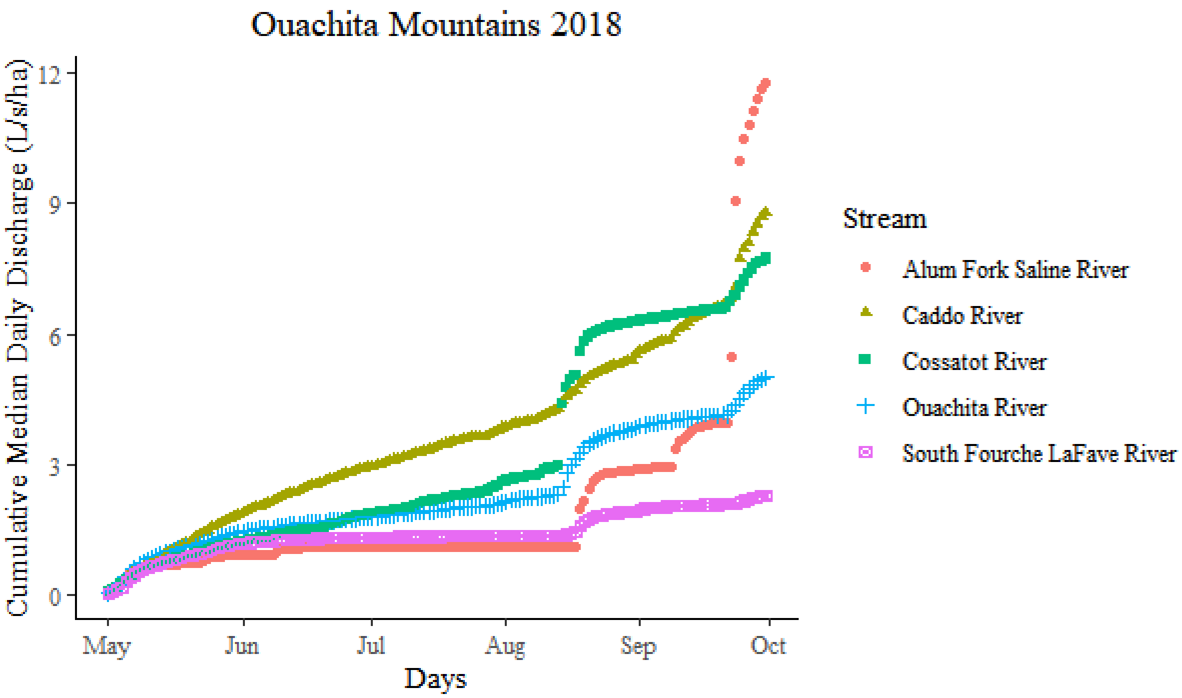

FIGURE A.10. Cumulative frequency distribution of median daily Q (L/s·ha$^{-1}$) from May 1 through September 30, 2018 in the Ouachita Mountains. Historical Q data was extracted from USGS gauging stations located in each stream.

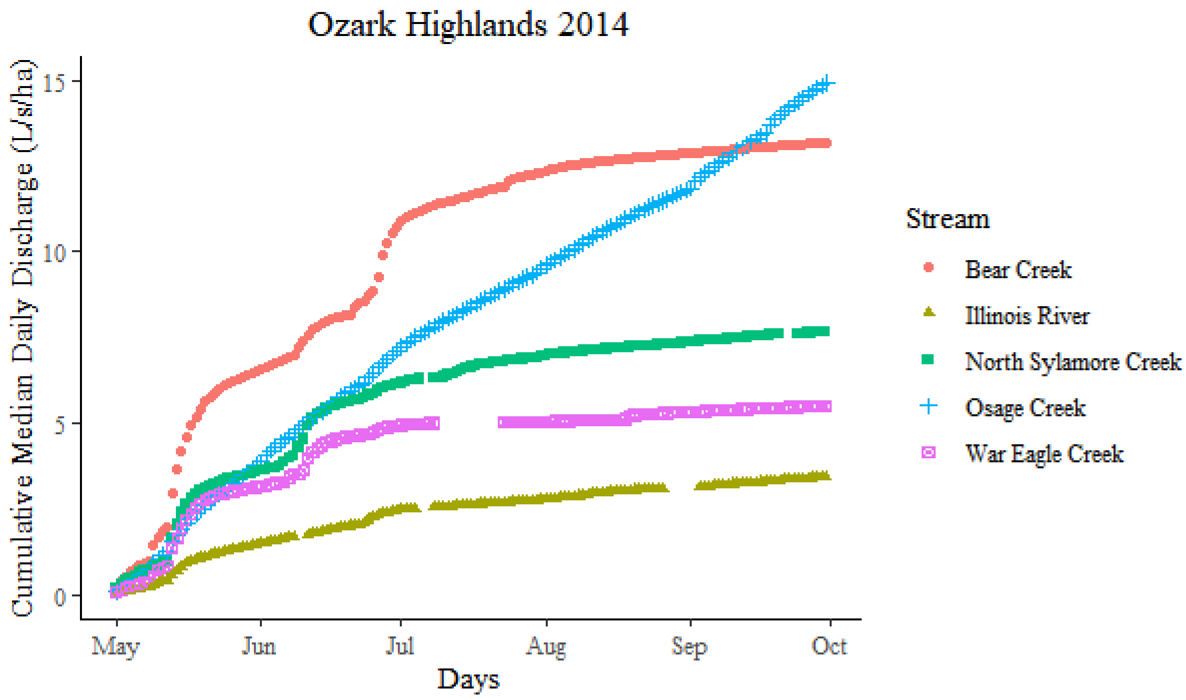

FIGURE A.11. Cumulative frequency distribution of median daily Q (L/s·ha$^{-1}$) from May 1 through September 30, 2014 in the Ozark Highlands. Historical Q data was extracted from USGS gauging stations located in each stream.

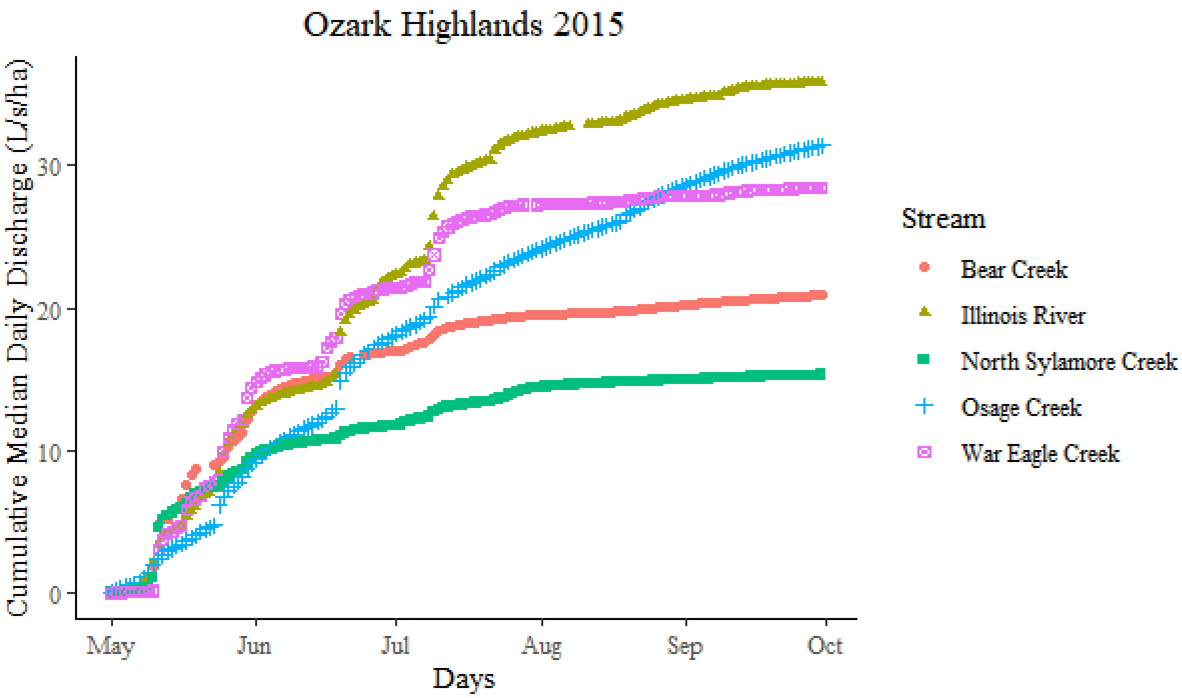

FIGURE A.12. Cumulative frequency distribution of median daily Q (L/s·ha$^{-1}$) from May 1 through September 30, 2015 in the Ozark Highlands. Historical Q data was extracted from USGS gauging stations located in each stream.

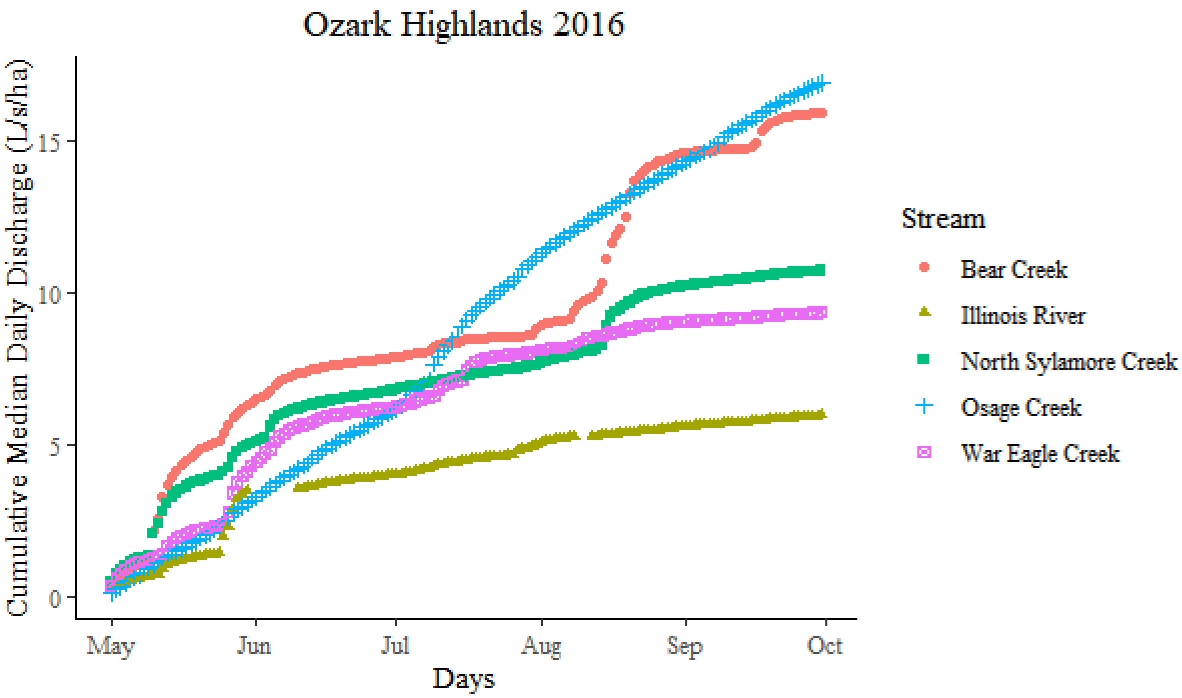

FIGURE A.13. Cumulative frequency distribution of median daily Q (L/s·ha$^{-1}$) from May 1 through September 30, 2016 in the Ozark Highlands. Historical Q data was extracted from USGS gauging stations located in each stream.

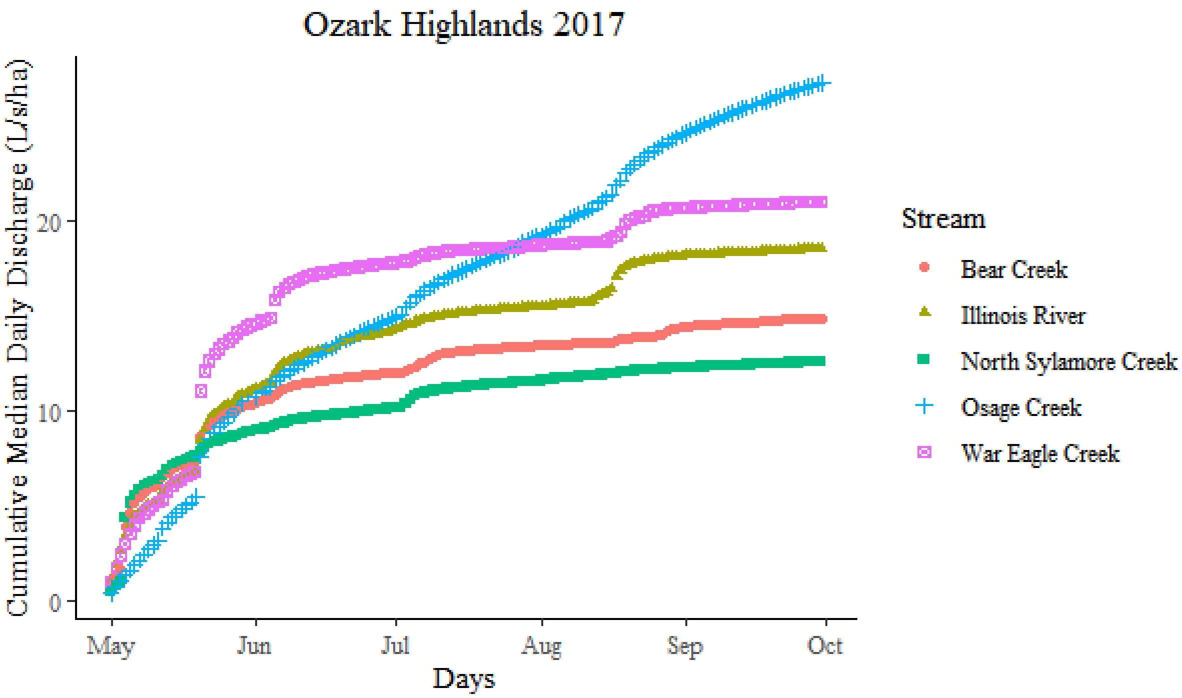

FIGURE A.14. Cumulative frequency distribution of median daily Q (L/s·ha$^{-1}$) from May 1 through September 30, 2017 in the Ozark Highlands. Historical Q data was extracted from USGS gauging stations located in each stream.

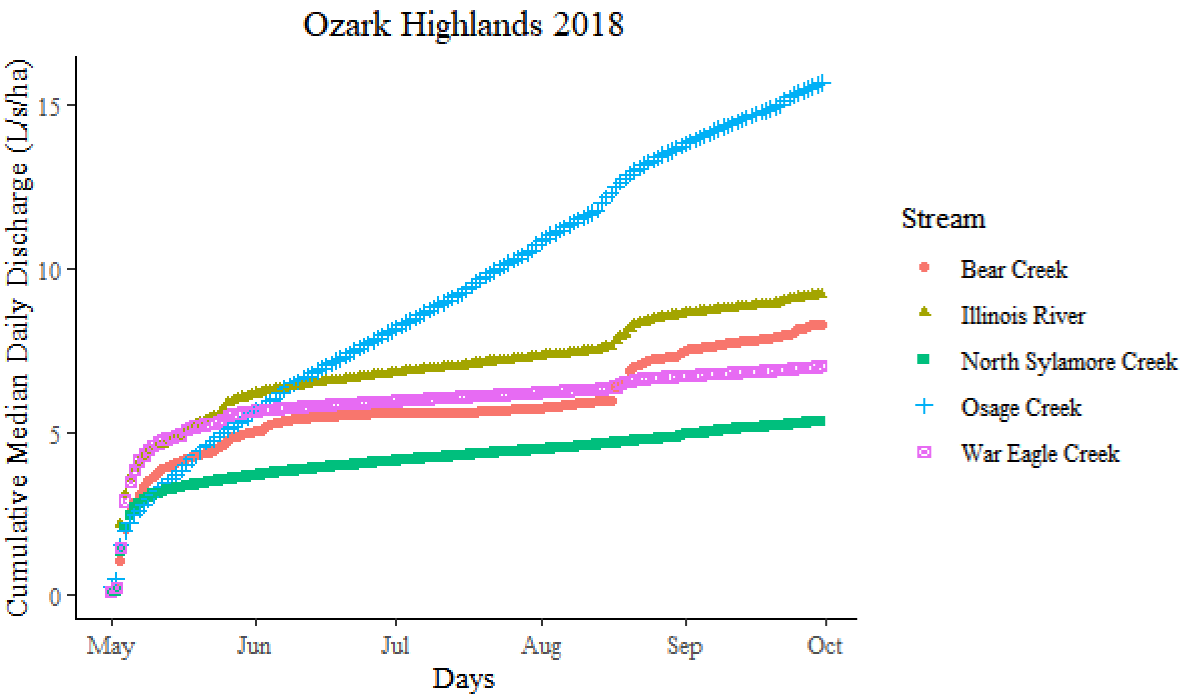

FIGURE A.15. Cumulative frequency distribution of median daily Q (L/s·ha$^{-1}$) from May 1 through September 30, 2018 in the Ozark Highlands. Historical Q data was extracted from USGS gauging stations located in each stream.

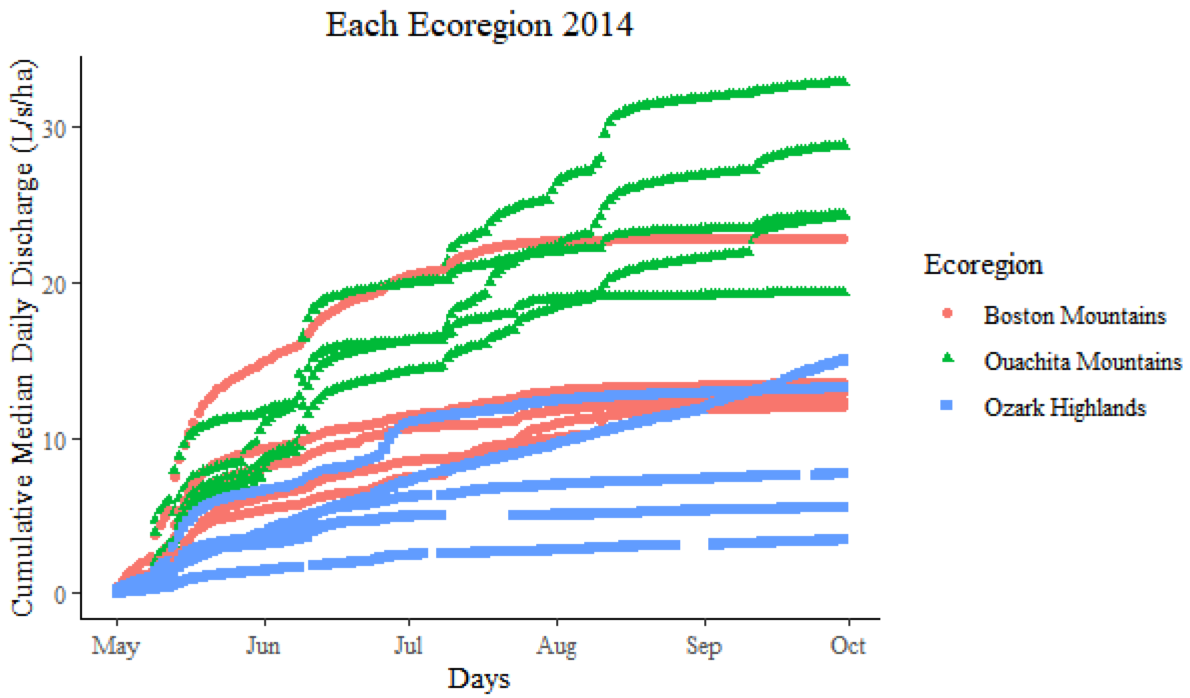

FIGURE A.16. Cumulative frequency distribution of median daily Q (L/s·ha$^{-1}$) from May 1 through September 30, 2014 in the Boston Mountains, Ouachita Mountains, and Ozark Highlands. Historical Q data was extracted from USGS gauging stations located in my sampled streams.

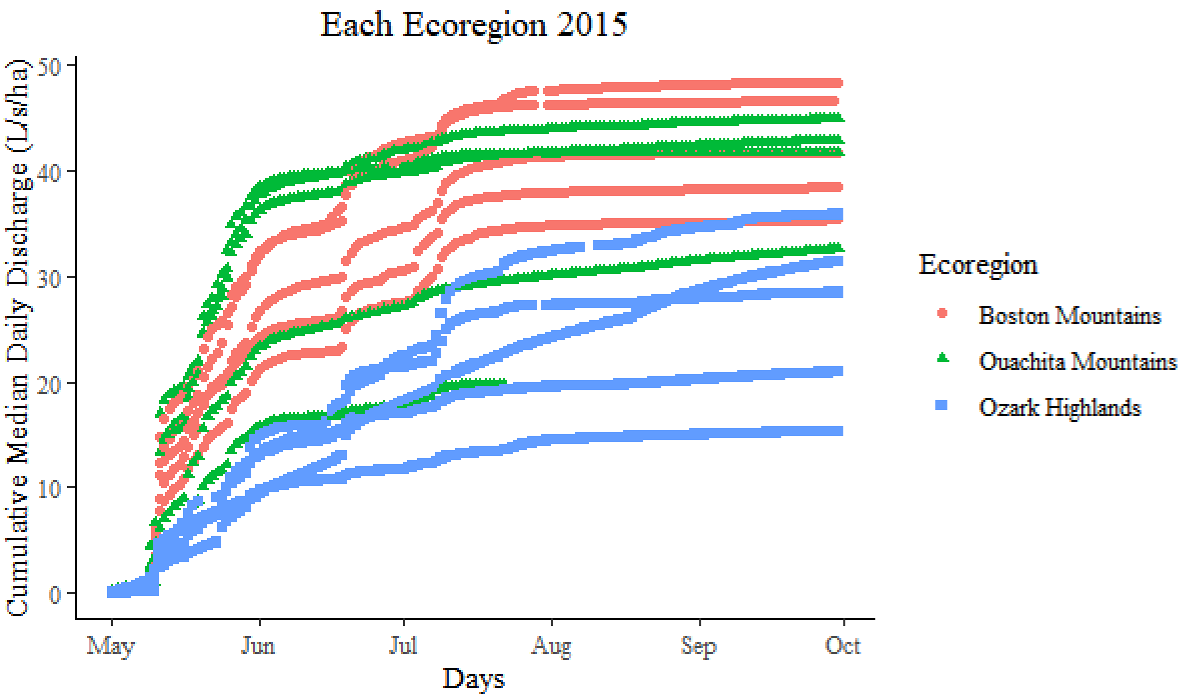

FIGURE A.17. Cumulative frequency distribution of median daily Q (L/s·ha$^{-1}$) from May 1 through September 30, 2015 in the Boston Mountains, Ouachita Mountains, and Ozark Highlands. Historical Q data was extracted from USGS gauging stations located in my sampled streams.

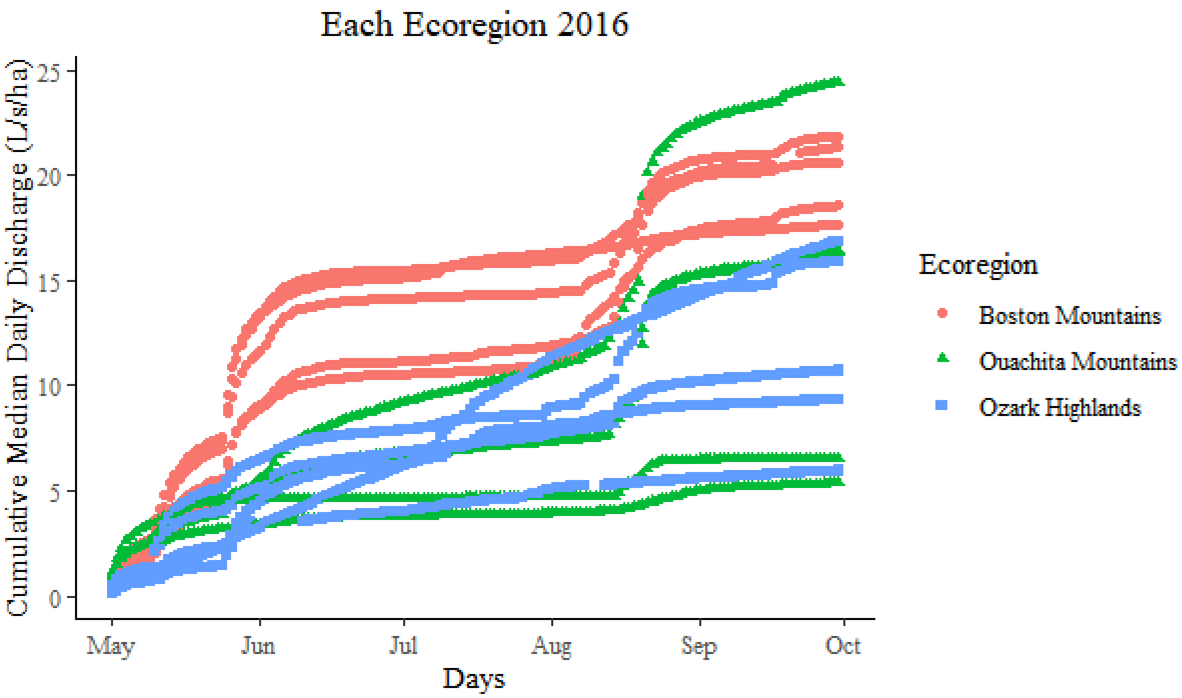

FIGURE A.18. Cumulative frequency distribution of median daily Q (L/s·ha$^{-1}$) from May 1 through September 30, 2016 in the Boston Mountains, Ouachita Mountains, and Ozark Highlands. Historical Q data was extracted from USGS gauging stations located in my sampled streams.

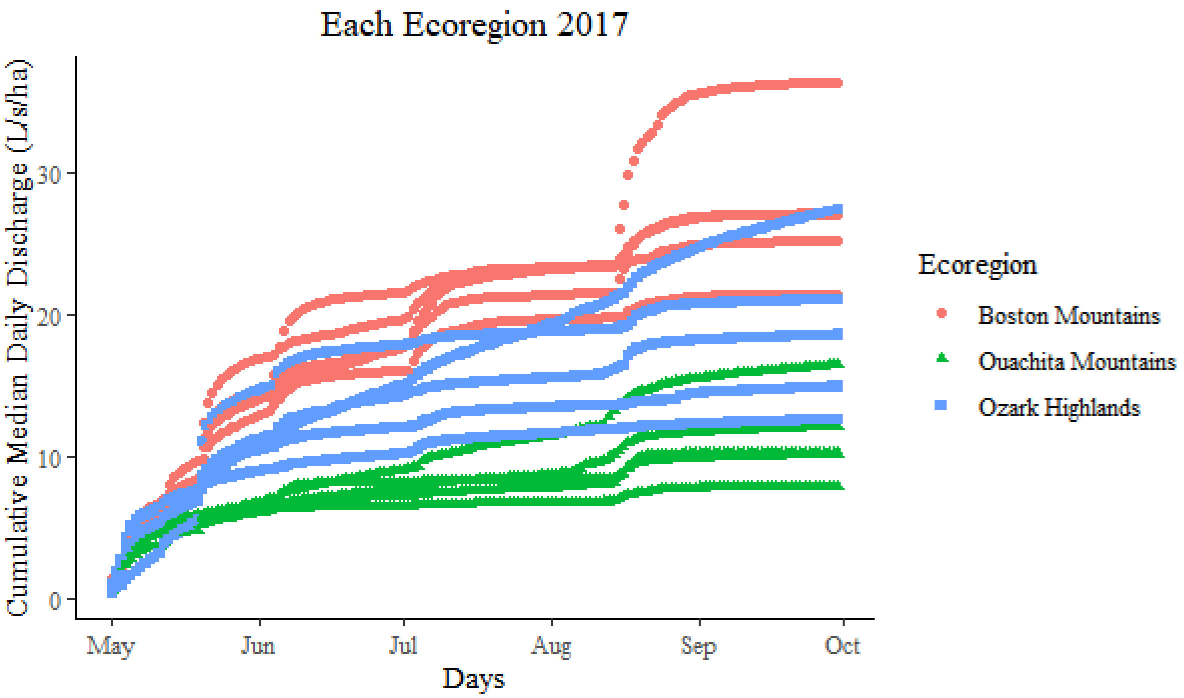

FIGURE A.19. Cumulative frequency distribution of median daily Q (L/s·ha$^{-1}$) from May 1 through September 30, 2017 in the Boston Mountains, Ouachita Mountains, and Ozark Highlands. Historical Q data was extracted from USGS gauging stations located in my sampled streams.

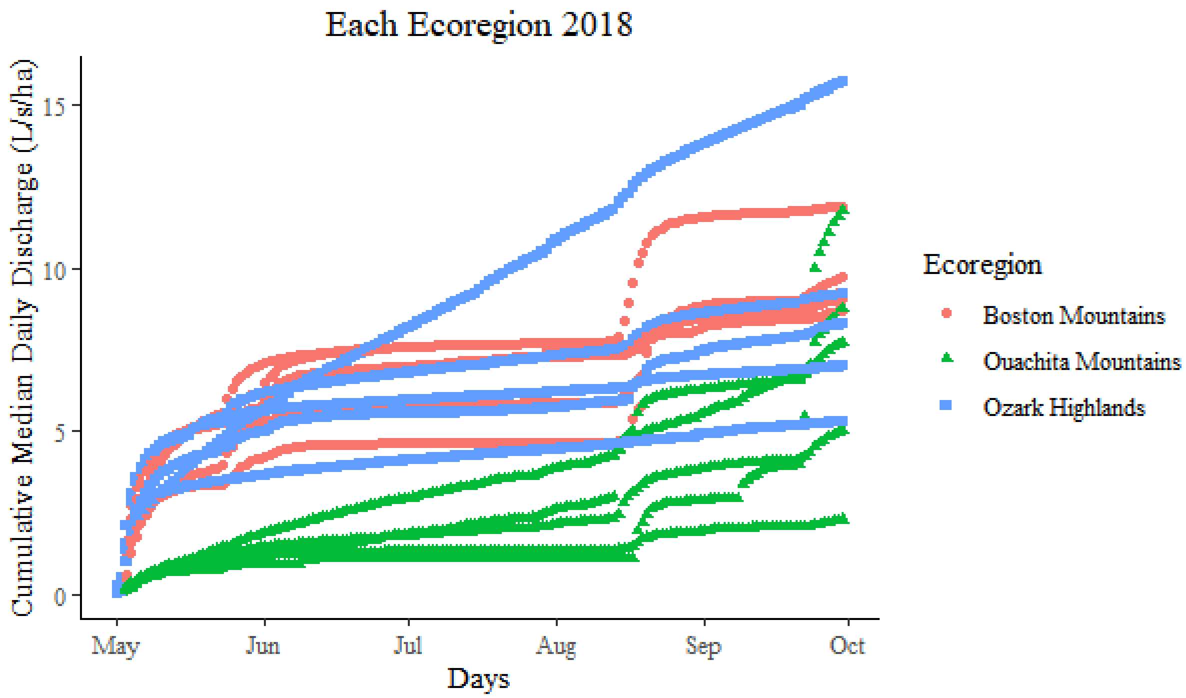

FIGURE A.20. Cumulative frequency distribution of median daily Q (L/s·ha$^{-1}$) from May 1 through September 30, 2018 in the Boston Mountains, Ouachita Mountains, and Ozark Highlands. Historical Q data was extracted from USGS gauging stations located in my sampled streams.

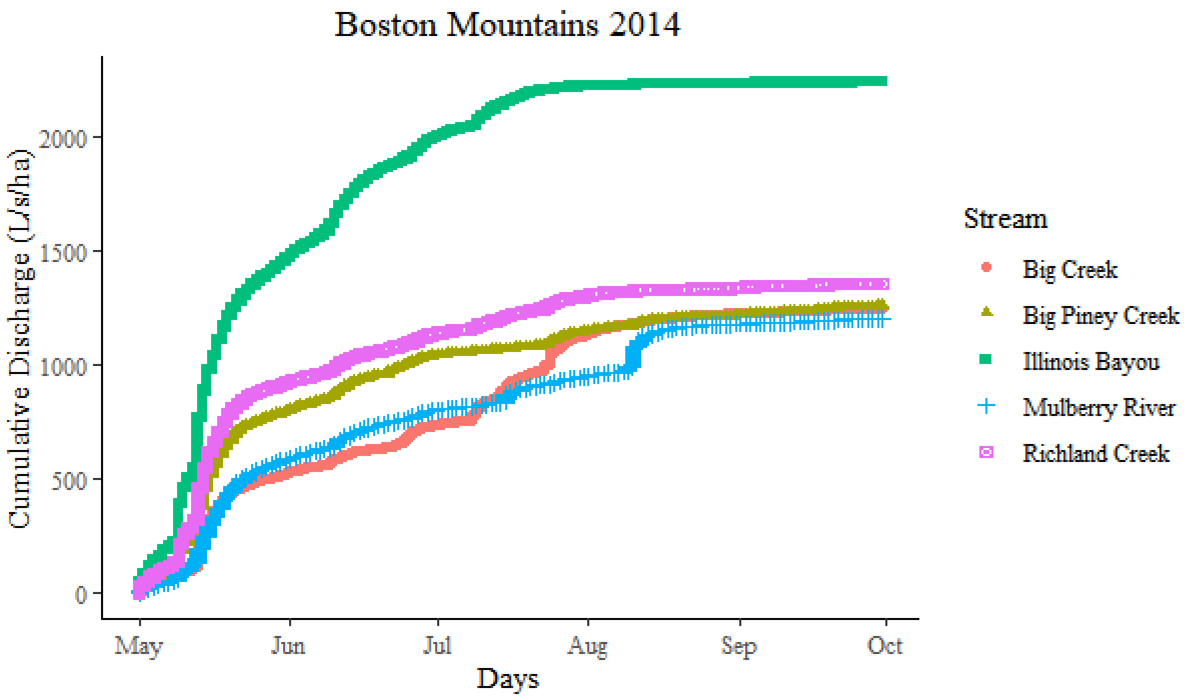

FIGURE A.21. Cumulative frequency distribution of all Q recordings each day (L/s·ha$^{-1}$) from May 1 through September 30, 2014 in the Boston Mountains. Historical Q data was extracted from USGS gauging stations located in each stream.

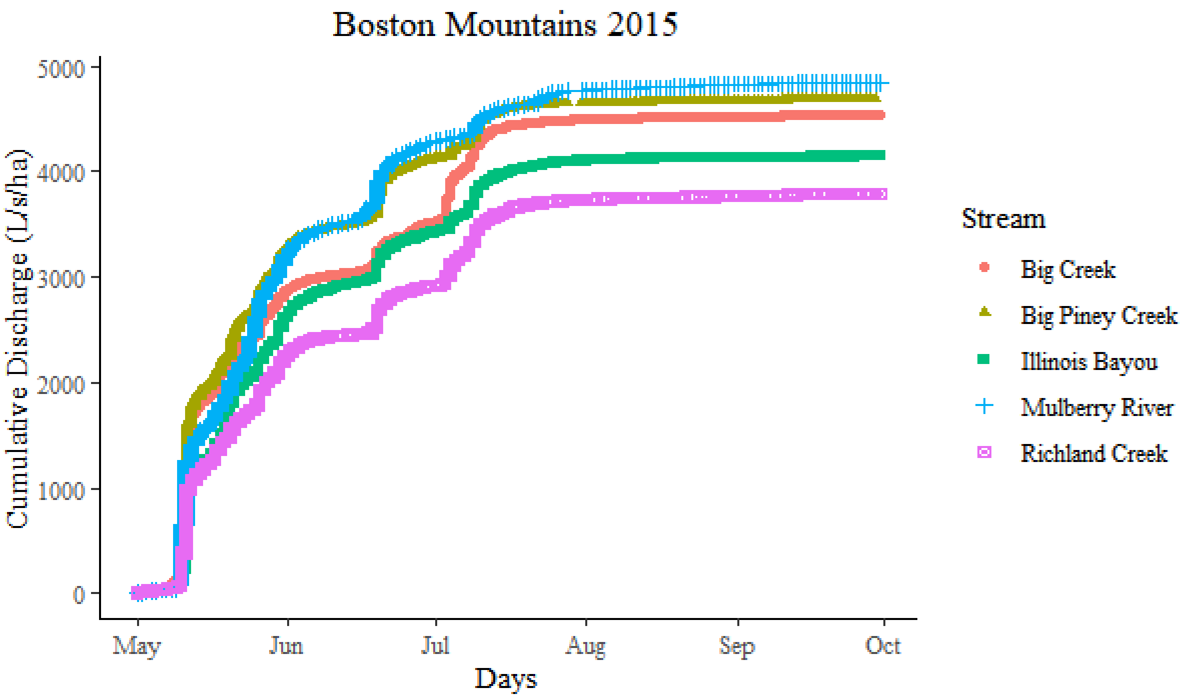

FIGURE A.22. Cumulative frequency distribution of all Q recordings each day (L/s·ha$^{-1}$) from May 1 through September 30, 2015 in the Boston Mountains. Historical Q data was extracted from USGS gauging stations located in each stream.

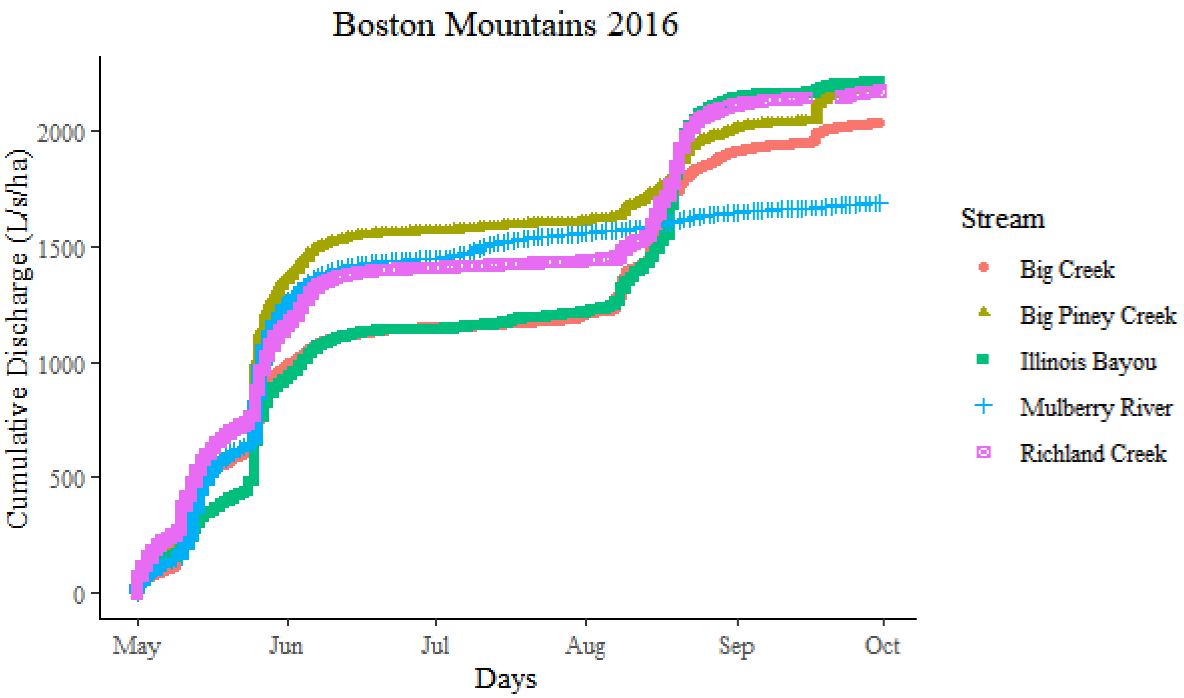

FIGURE A.23. Cumulative frequency distribution of all Q recordings each day (L/s·ha$^{-1}$) from May 1 through September 30, 2016 in the Boston Mountains. Historical Q data was extracted from USGS gauging stations located in each stream.

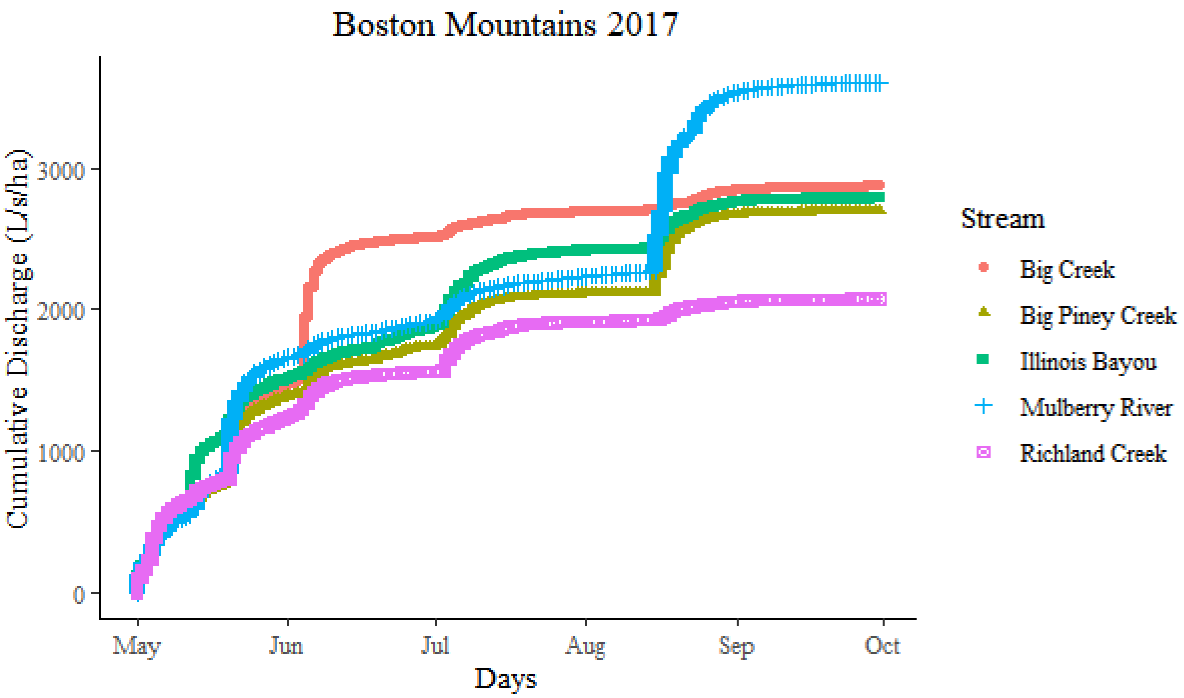

FIGURE A.24. Cumulative frequency distribution of all Q (L/s·ha$^{-1}$) recordings each day from May 1 through September 30, 2017 in the Boston Mountains. Historical Q data was extracted from USGS gauging stations located in each stream.

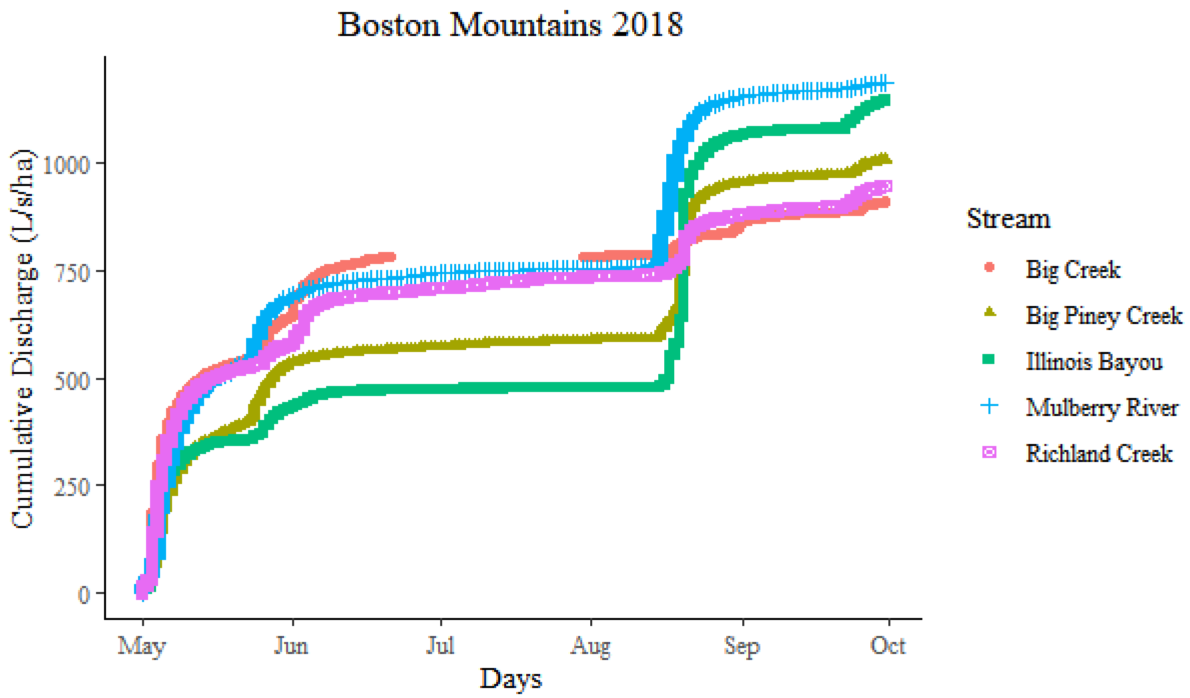

FIGURE A.25. Cumulative frequency distribution of all Q (L/s·ha$^{-1}$) recordings each day from May 1 through September 30, 2018 in the Boston Mountains. Historical Q data was extracted from USGS gauging stations located in each stream.

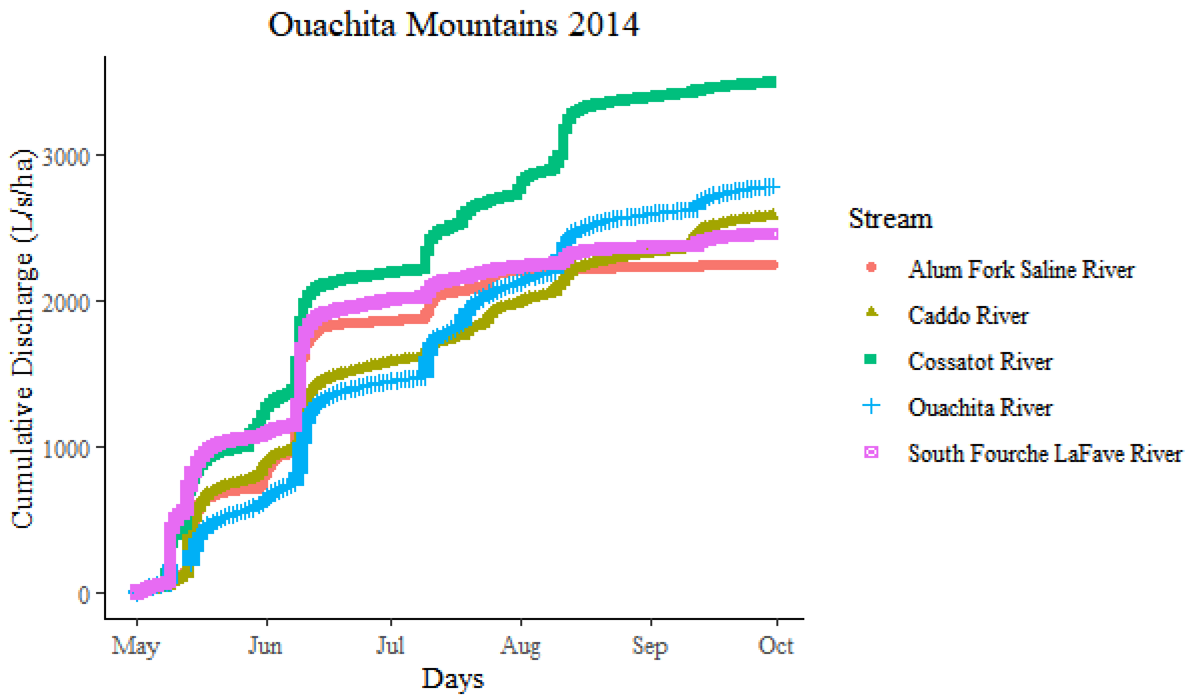

FIGURE A.26. Cumulative frequency distribution of all Q (L/s·ha$^{-1}$) recordings each day from May 1 through September 30, 2014 in the Ouachita Mountains. Historical Q data was extracted from USGS gauging stations located in each stream.

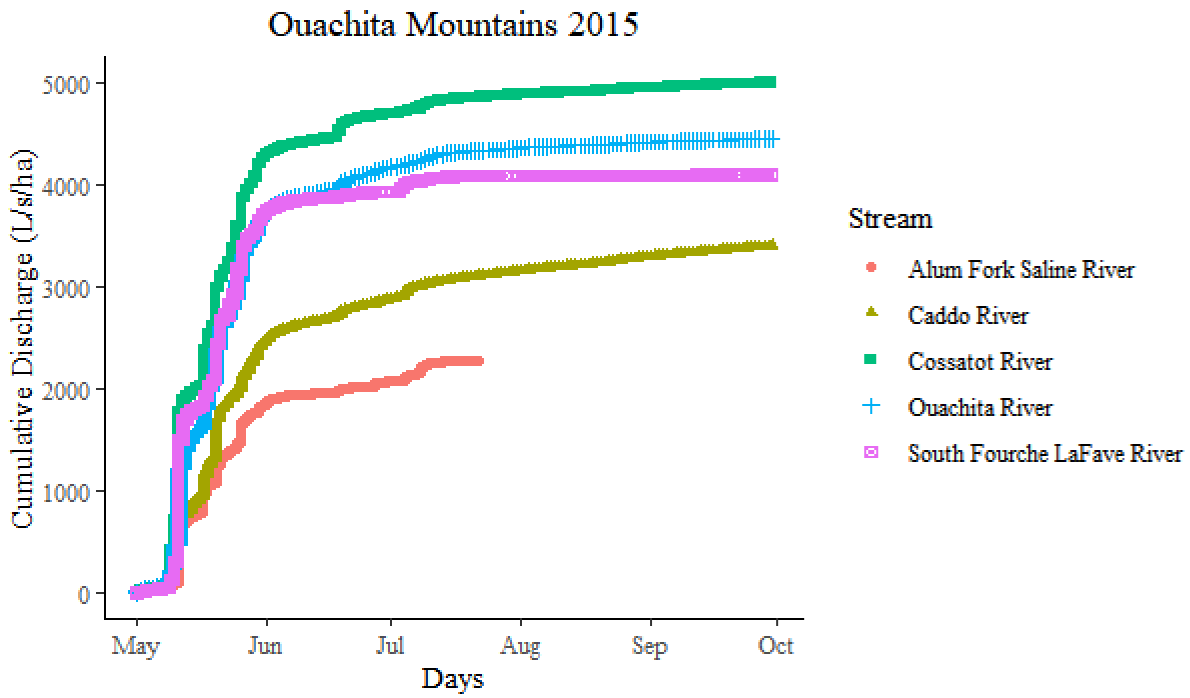

FIGURE A.27. Cumulative frequency distribution of all Q (L/s·ha$^{-1}$) recordings each day from May 1 through September 30, 2015 in the Ouachita Mountains. Historical Q data was extracted from USGS gauging stations located in each stream.

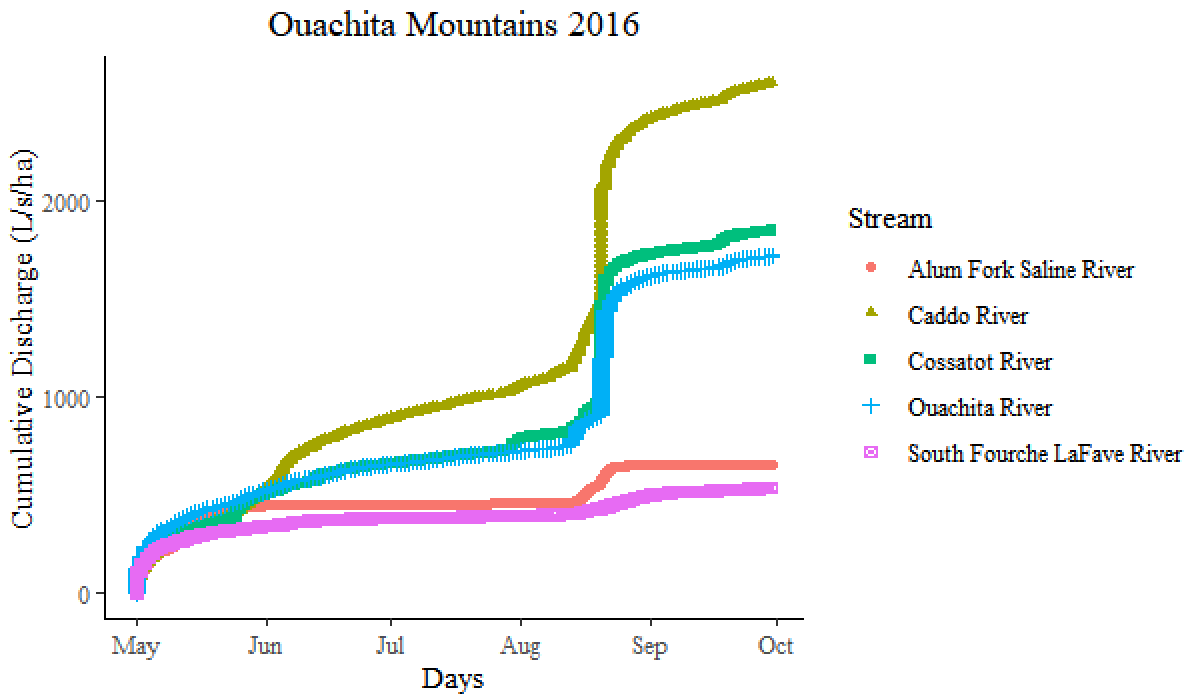

FIGURE A.28. Cumulative frequency distribution of all Q (L/s·ha$^{-1}$) recordings each day from May 1 through September 30, 2016 in the Ouachita Mountains. Historical Q data was extracted from USGS gauging stations located in each stream.

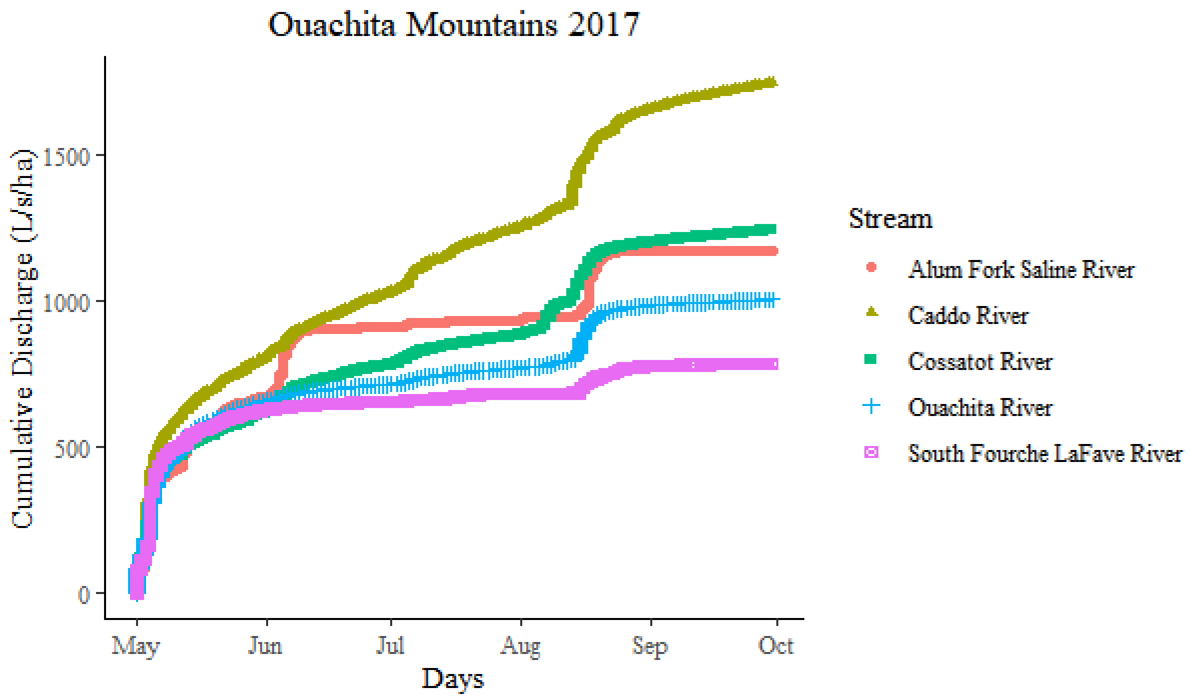

FIGURE A.29. Cumulative frequency distribution of all Q (L/s·ha$^{-1}$) recordings each day from May 1 through September 30, 2017 in the Ouachita Mountains. Historical Q data was extracted from USGS gauging stations located in each stream.

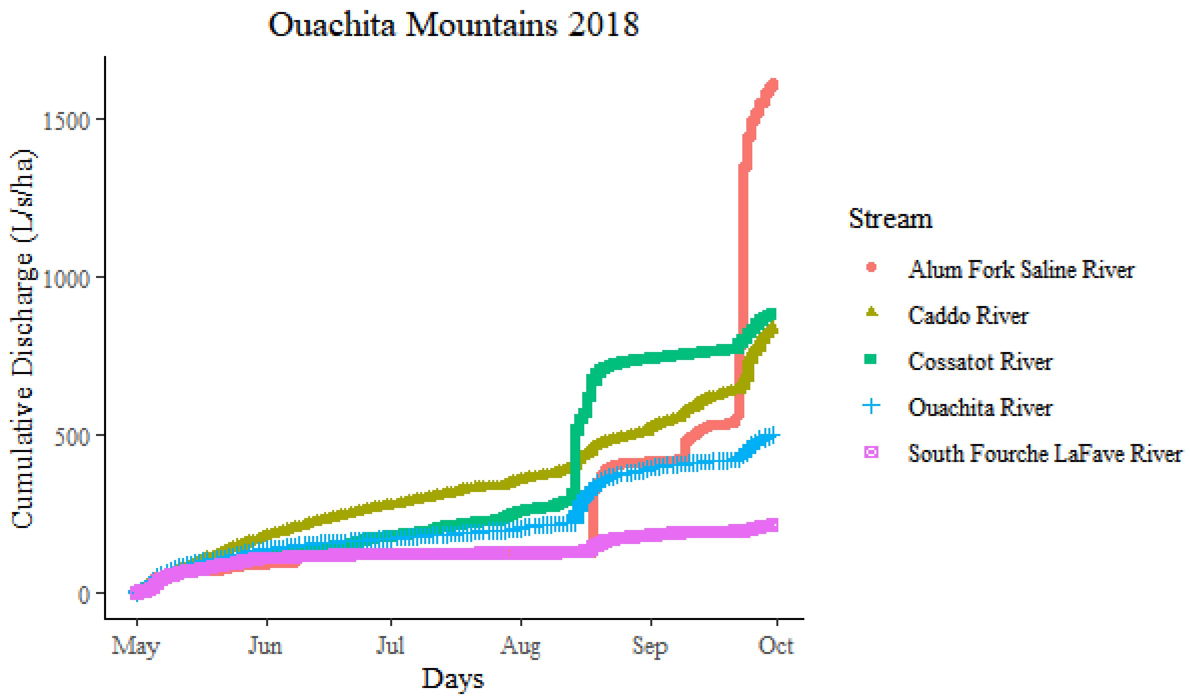

FIGURE A.30. Cumulative frequency distribution of all Q (L/s·ha$^{-1}$) recordings each day from May 1 through September 30, 2018 in the Ouachita Mountains. Historical Q data was extracted from USGS gauging stations located in each stream.

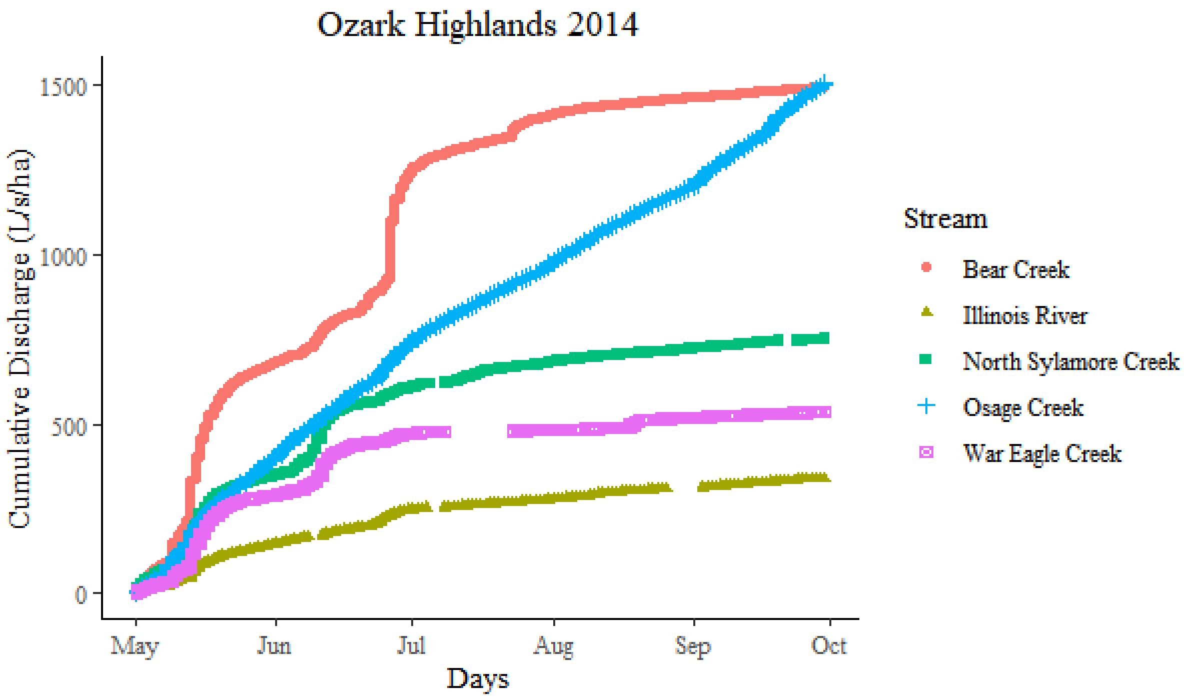

FIGURE A.31. Cumulative frequency distribution of all Q (L/s·ha$^{-1}$) recordings each day from May 1 through September 30, 2014 in the Ozark Highlands. Historical Q data was extracted from USGS gauging stations located in each stream.

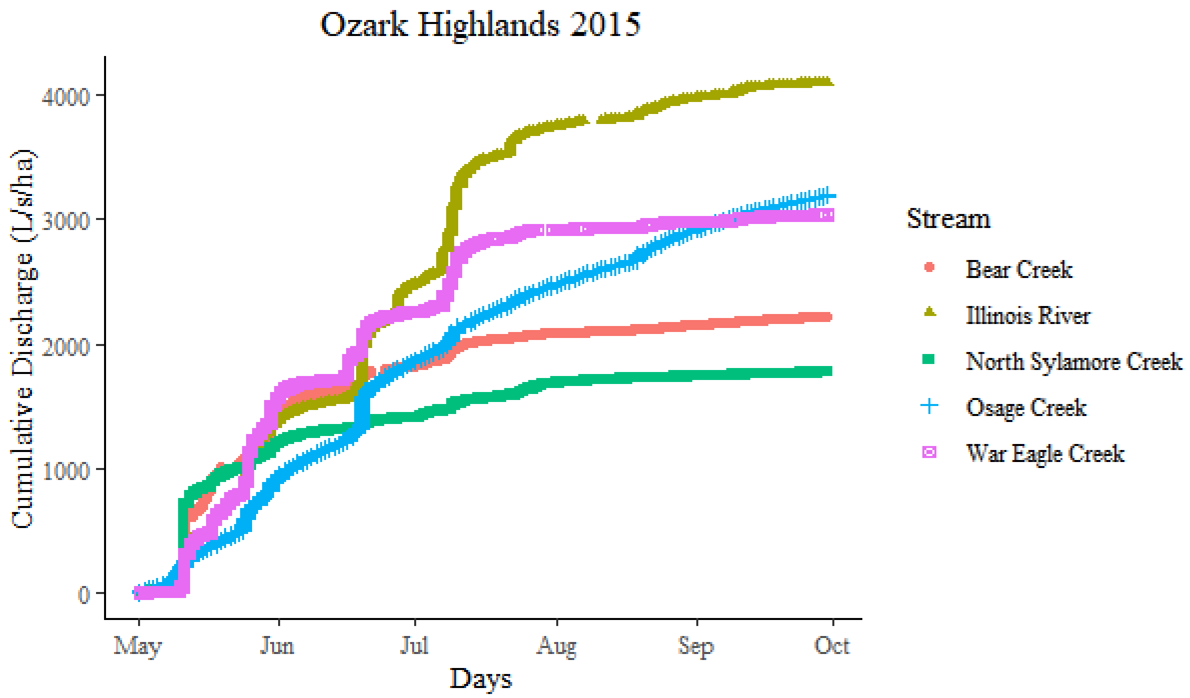

FIGURE A.32. Cumulative frequency distribution of all Q (L/s·ha$^{-1}$) recordings each day from May 1 through September 30, 2015 in the Ozark Highlands. Historical Q data was extracted from USGS gauging stations located in each stream.

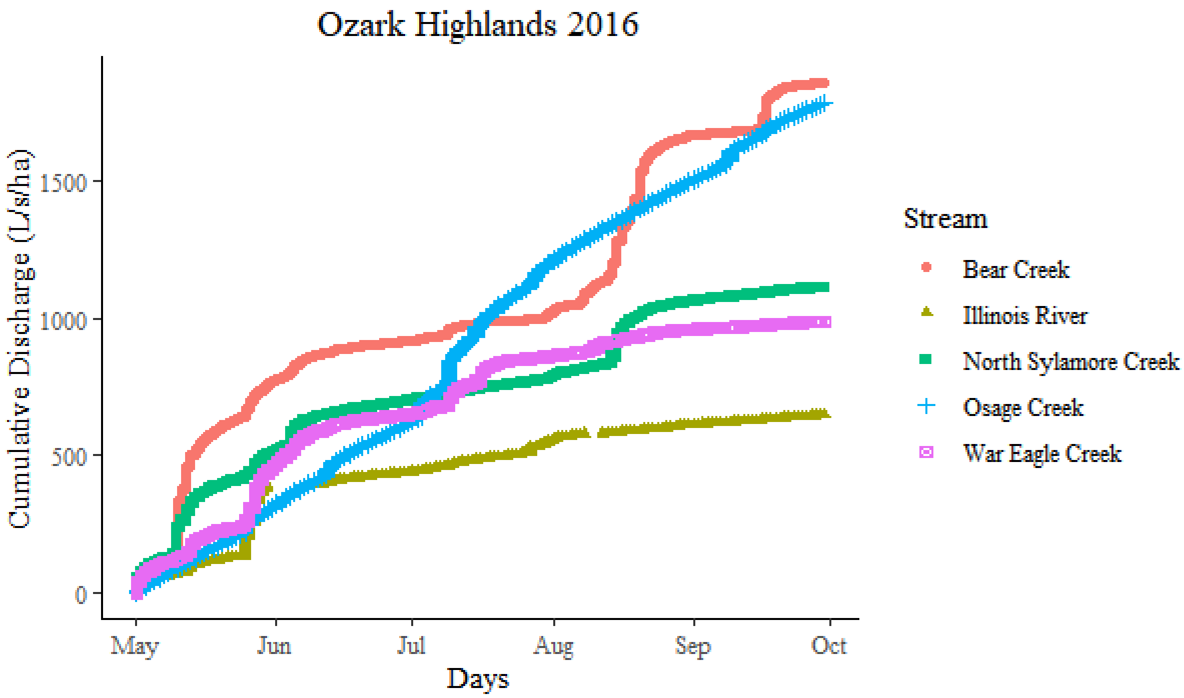

FIGURE A.33. Cumulative frequency distribution of all Q (L/s·ha$^{-1}$) recordings each day from May 1 through September 30, 2016 in the Ozark Highlands. Historical Q data was extracted from USGS gauging stations located in each stream.

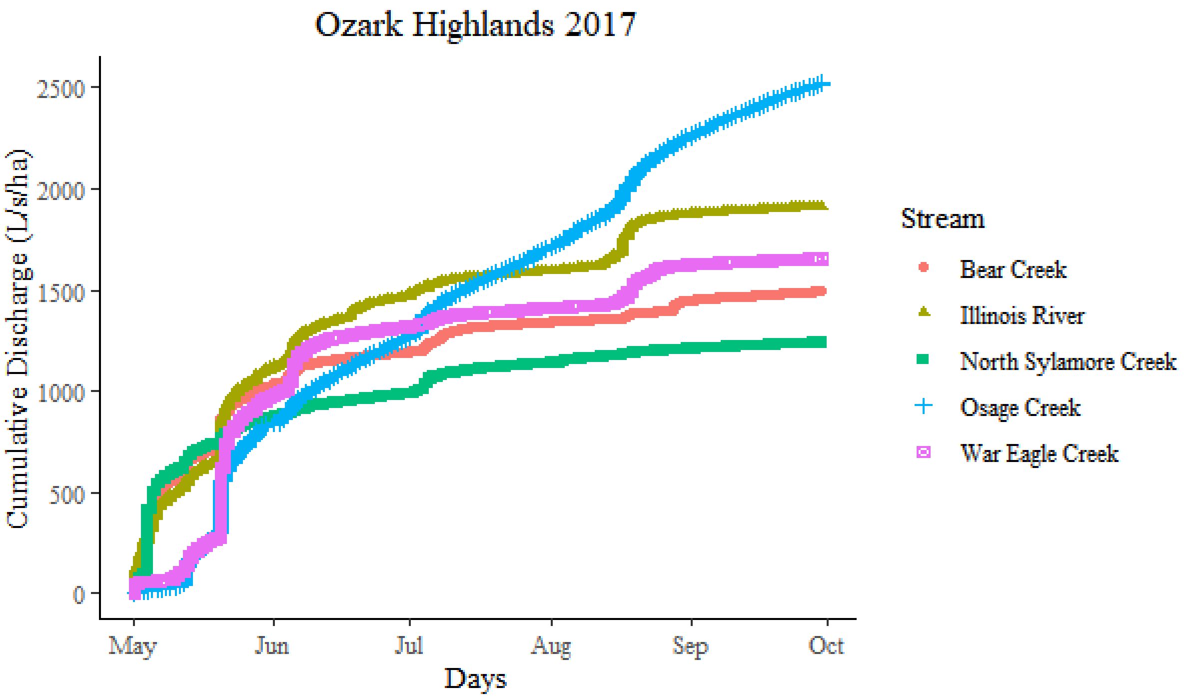

FIGURE A.34. Cumulative frequency distribution of all Q (L/s·ha$^{-1}$) recordings each day from May 1 through September 30, 2017 in the Ozark Highlands. Historical Q data was extracted from USGS gauging stations located in each stream.

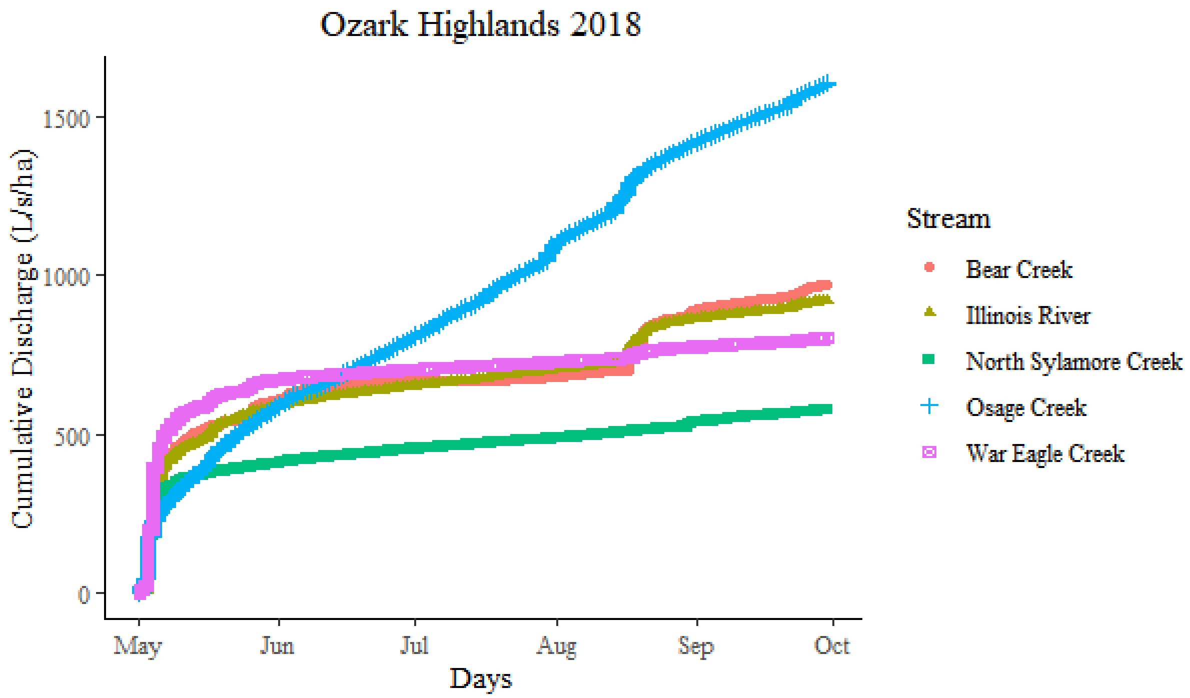

FIGURE A.35. Cumulative frequency distribution of all Q (L/s·ha$^{-1}$) recordings each day from May 1 through September 30, 2018 in the Ozark Highlands. Historical Q data was extracted from USGS gauging stations located in each stream.

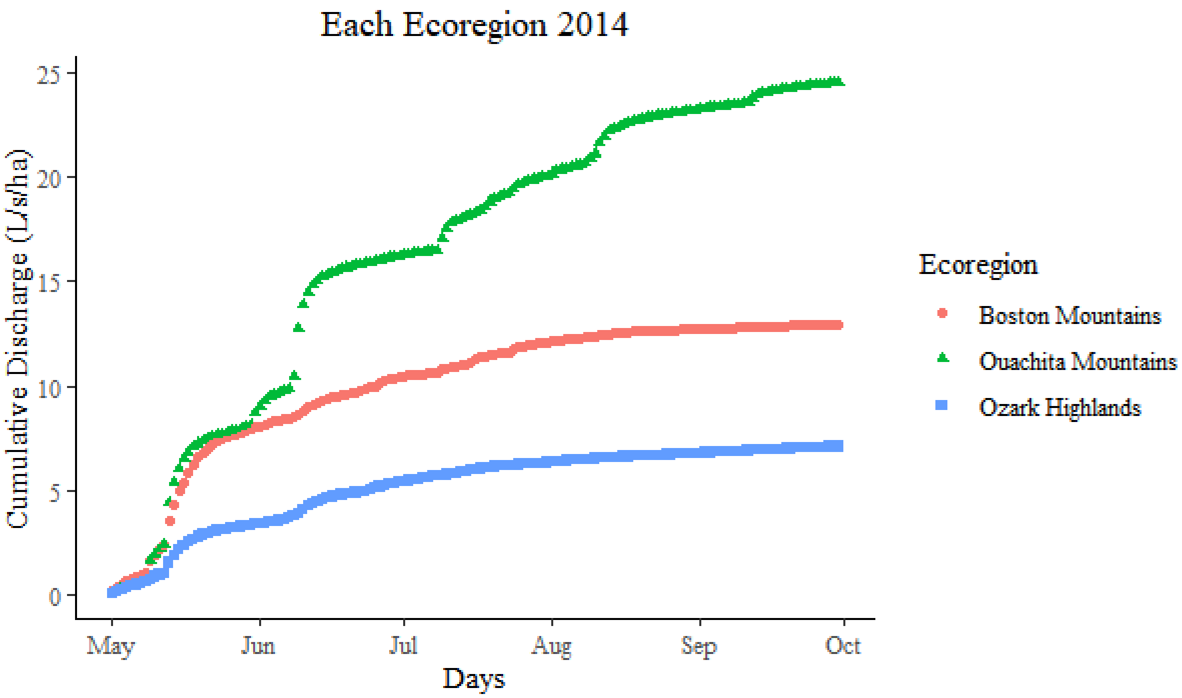

FIGURE A.36. Cumulative frequency distribution of median Q (L/s·ha$^{-1}$) recordings each day from May 1 through September 30, 2014 in the Boston Mountains, Ouachita Mountains, and Ozark Highlands. Historical Q data was extracted from USGS gauging stations located in my sampled streams.

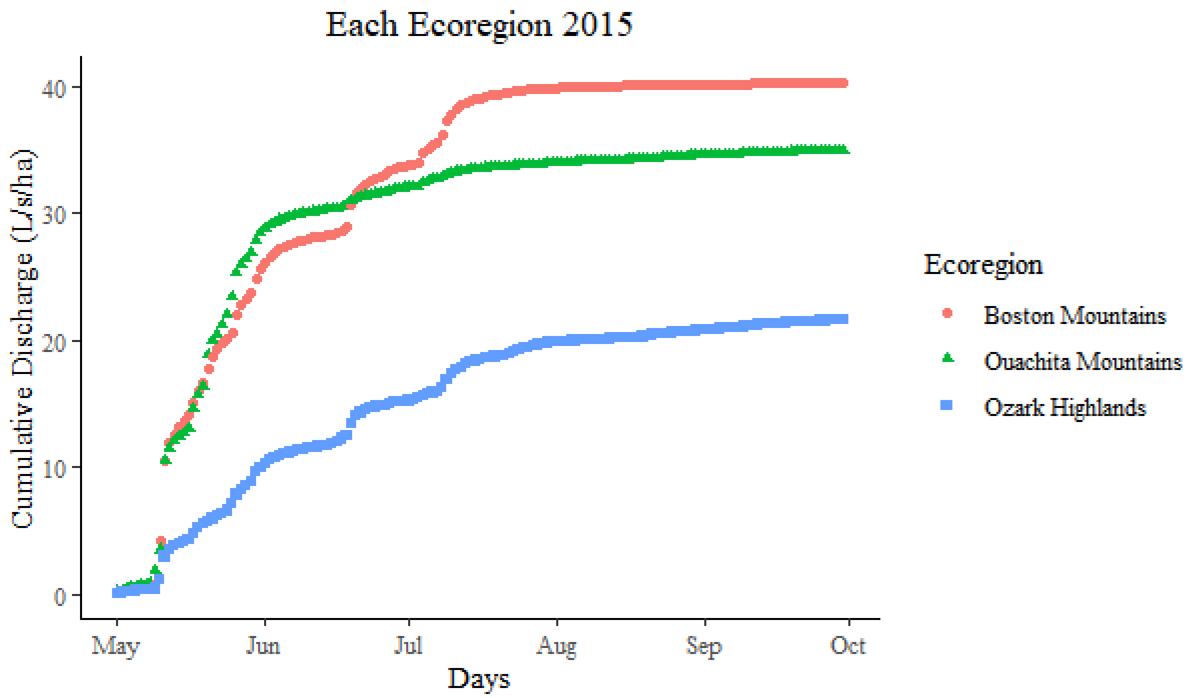

FIGURE A.37. Cumulative frequency distribution of median Q (L/s·ha$^{-1}$) recordings each day from May 1 through September 30, 2015 in the Boston Mountains, Ouachita Mountains, and Ozark Highlands. Historical Q data was extracted from USGS gauging stations located in my sampled streams.

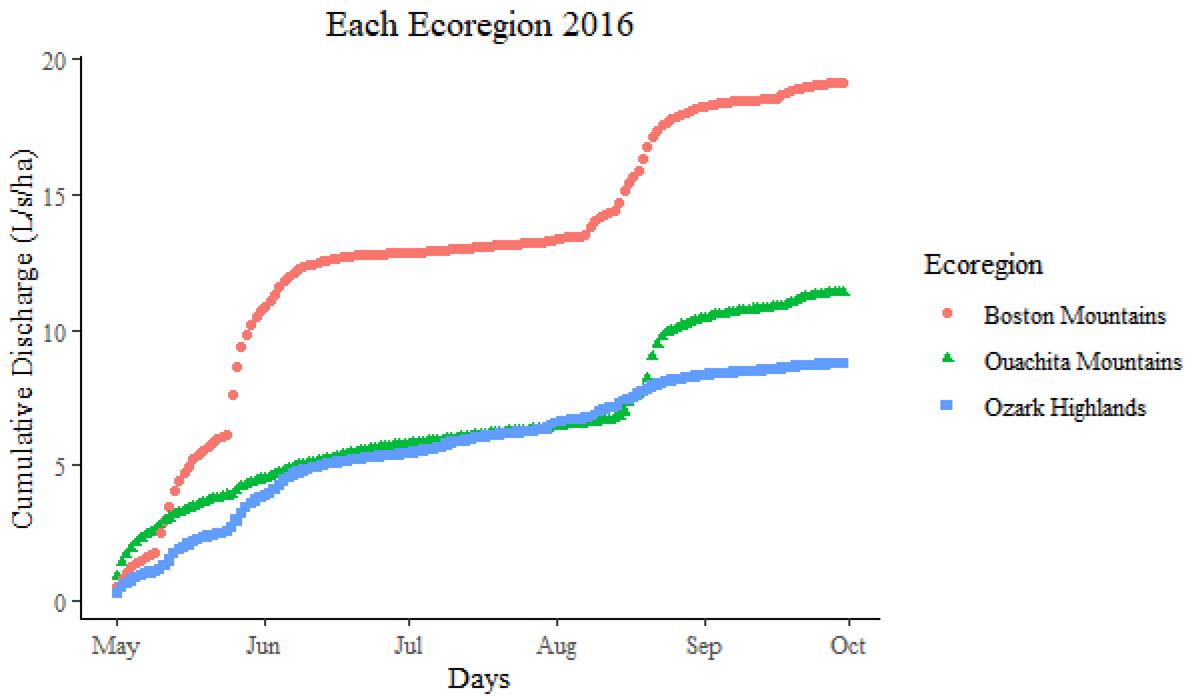

FIGURE A.38. Cumulative frequency distribution of median Q (L/s·ha$^{-1}$) recordings each day from May 1 through September 30, 2016 in the Boston Mountains, Ouachita Mountains, and Ozark Highlands. Historical Q data was extracted from USGS gauging stations located in my sampled streams.

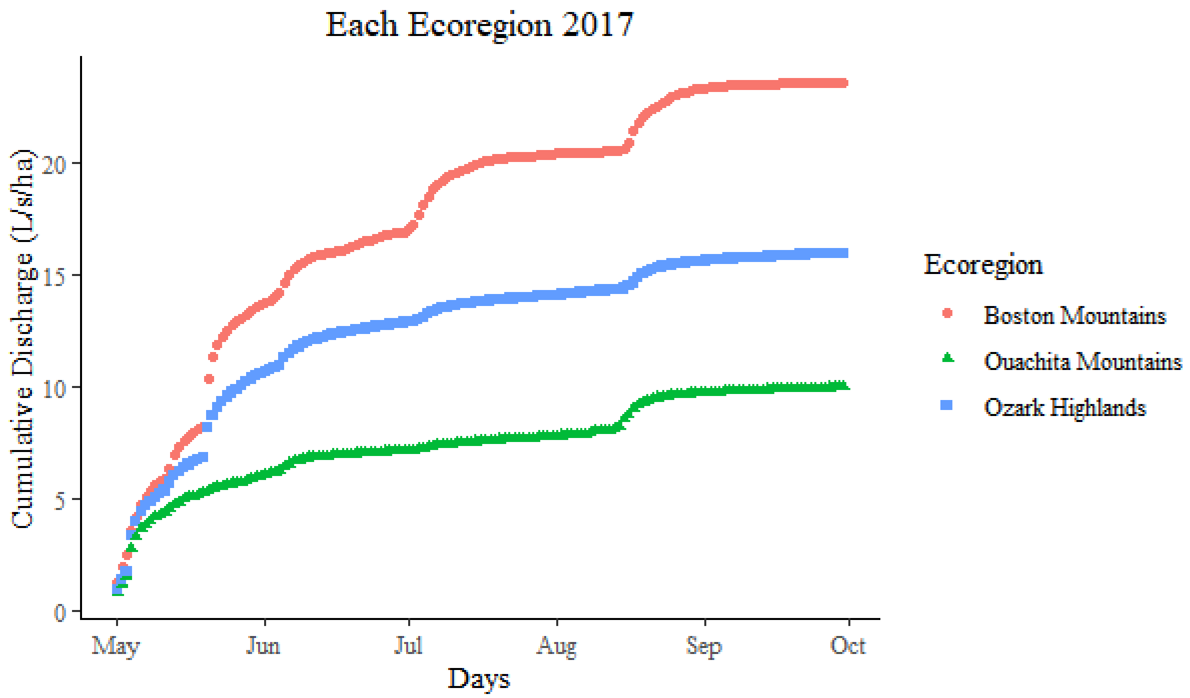

FIGURE A.39. Cumulative frequency distribution of median Q (L/s·ha$^{-1}$) recordings each day from May 1 through September 30, 2017 in the Boston Mountains, Ouachita Mountains, and Ozark Highlands. Historical Q data was extracted from USGS gauging stations located in my sampled streams.

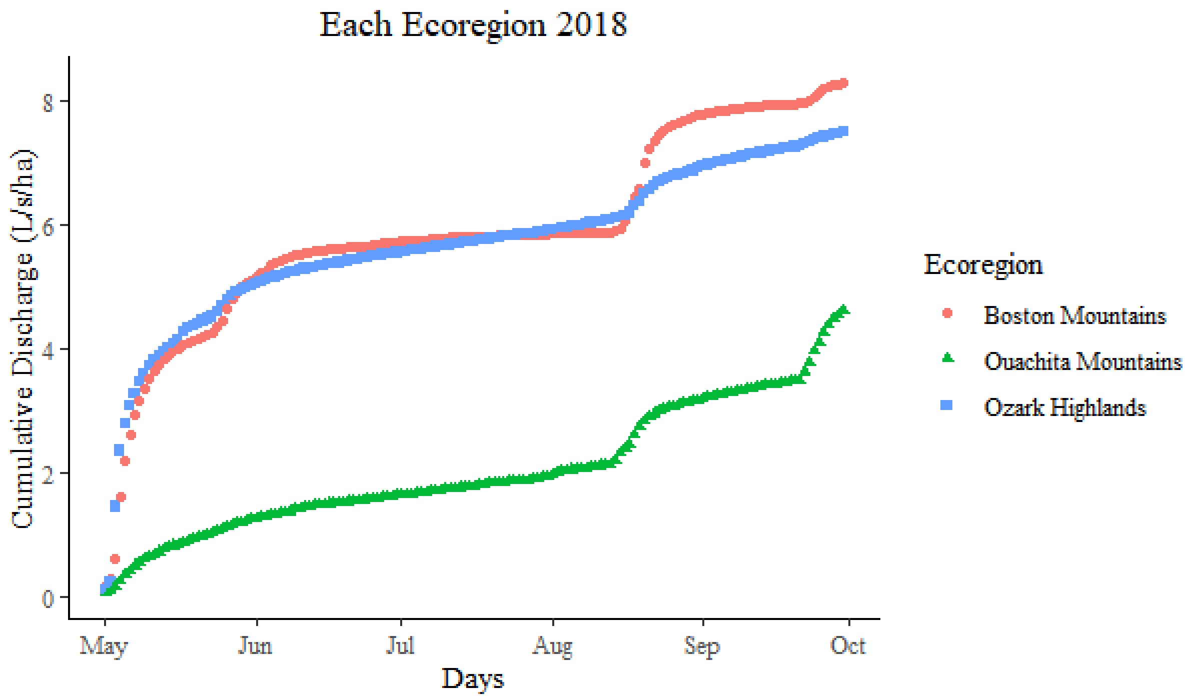

FIGURE A.40. Cumulative frequency distribution of median Q (L/s·ha$^{-1}$) recordings each day from May 1 through September 30, 2018 in the Boston Mountains, Ouachita Mountains, and Ozark Highlands. Historical Q data was extracted from USGS gauging stations located in my sampled streams.