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Effects of Hydrology on the Growth and Recruitment of Stream
Fish in the Eastern Broadleaf Province of Minnesota

By

Eric J. Krumm

A thesis submitted in partial fulfillment
of the requirements for the
Master of Science

Department of Biological Sciences
Minnesota State University, Mankato
2016

Effects of Hydrology on the Growth and Recruitment of Stream
Fish in the Eastern Broadleaf Province of Minnesota

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ABSTRACTEffects of Hydrology on the Growth and Recruitment of Stream
Fish in the Eastern Broadleaf Province of Minnesota

Eric J. Krumm

Master of Science Degree, Department of Biological Sciences
Minnesota State University, Mankato
2016

Agricultural practices and urban development have altered streamflows within the Eastern Broadleaf Province of Minnesota. Stream-flow alteration can produce significant changes in native freshwater communities. Therefore, knowledge of streamflow effects on representative freshwater populations and communities within the province are needed to maintain ecological integrity. Fish community and population dynamics often display predictable responses to flow regimes, which can make fishes model organisms for examining flow-ecology relationships.

In lotic systems, annual variation in streamflow can influence the annual growth and recruitment of fishes. Understanding the growth and recruitment of fish populations is essential for management and conservation efforts. Growth can affect population size structure and sexual maturation, while recruitment can affect the abundance, and genetic diversity of a population.

Recruitment was quantified using studentized residuals from weighted catch-curve regressions as a measure of year-class strength. Relationships between annual streamflow magnitude and variability and the recruitment of the three species of interest were identified according to species-specific traits. I quantified the growth of Smallmouth Bass *Micropterus dolomieu*, Rock Bass *Ambloplites rupestris*, and Northern Hogsucker *Hypentelium nigricans* populations with mixed-effects growth models. Data

from streams exhibiting growth-year effects were used to examine relationships between summer-high-flow duration and annual fish growth.

Little evidence was found for either long-term or short-term flow effects on recruitment during the adult spawning or juvenile rearing periods. The recruitment of nest-building and benthic-lithophilous fishes was not significantly related to long-term-spawning-period flow magnitude for the majority (*i.e.*, 10 of 14) of streams, and was not significantly related to short-term-spawning-period flow magnitude at any of the 14 streams. Recruitment of fishes exhibiting cruiser, maneuverer, and benthic-hugger locomotion morphologies was not significantly related to long-term-rearing-period flow variability for the majority (*i.e.*, 12 of 14) of streams, and was not related to short-term-rearing-period flow variability for any of the 14 streams. Growth was attributed to age and individual fish effects for 11 of the 28 fish populations among species. Most populations that exhibited growth-year effects among streams did not show a significant relationship between growth and the duration of summer-high flows (*i.e.*, 4 of 11 populations).

Temperature regimes, as well as the timing, magnitude, and frequency of flows may have contributed to differences in the annual recruitment and growth of fishes among some of the streams in this study. However, minimal growth-year effects observed at the majority of my streams suggest that biotic factors (*e.g.*, fish age, genetic differences) may play a large role in determining the growth rates of fishes within the streams studied.

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LIST OF ABBREVIATIONS

Δi	delta Akaike information criterion
AIC.....	Akaike information criterion
AICc.....	Akaike information criterion correction
DC.....	direct current
DF.....	degrees of freedom
dd.....	decimal degrees
ID.....	identification
K.....	model parameters
km.....	kilometers
km ²	square kilometers
m.....	meters
m ³ /s.....	cubic meters per second
mg/L.....	milligrams per liter
mm.....	millimeters
Miss.....	Mississippi
NA.....	not available
NB.....	North Branch
p.....	probability
r ²	coefficient of determination
RCD.....	recruitment coefficient of determination
SF.....	South Fork
spp.....	all species in a given genus
US.....	United States
USGS.....	United States Geological Survey
YOY.....	young-of-the-year

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BACKGROUND

A steady global population increase has led to freshwater resource conflicts and has impacted facets of society, as well as aquatic ecosystems (Arthington et al. 2006). Global climate change has further complicated matters by presenting new uncertainties about the variability of river flows that could potentially lead to increased water-engineering responses and escalating ecosystem stress (Arthington et al. 2006; Poff et al. 2010). Until relatively recently, anthropogenic uses of freshwater resources often took precedence over the water needs of aquatic ecosystems. However, there is now broad acceptance that it is in society's best interests to consider rivers (and other freshwater systems) as legitimate users of fresh water (Postel and Richter 2003; Arthington et al. 2006).

Methods designed to quantify minimum in-stream flows to sustain aquatic ecosystems first appeared in the U.S. in the late 1940s, and remains a prevalent technique for managing streamflow for riverine fisheries (O'Shea 1995; Arthington et al. 2006; Blann and Kendy 2012). However, owing to the advent of the "environmental flows" scientific field, scientists now recognize that arbitrary minimum flows are inadequate to maintain the structure and function of a riverine ecosystem.

Environmental flow prescriptions can be used to mimic natural flow variability and can be defined as the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems (Poff et al. 2010). Environmental flow methods that mimic the natural flow regime of a stream or river can be used to ensure that considerable socioeconomic benefits already provided by sustainable freshwater ecosystems are not lost and that degraded ecosystems are restored (Arthington et al. 2006; Poff et al. 2010).

Scientists can help water managers strike a balance between the water needs of river ecosystems and human water demands by providing environmental flow recommendations based on current, best available scientific information (Richter et al. 2006). To be effective, environmental flow recommendations must be explicit about

flow-ecology relationships that determine the amount and timing of water required (Davies et al. 2013).

Fish community and population dynamics often display predictable responses to flow regimes that can make fishes model organisms for examining flow-ecology relationships (McManamay and Frimpong 2015). For example, the growth and recruitment of many fish species has been shown to be positively related to high stream flows corresponding to increased habitat and food availability in floodplain environments (Gutreuter et al. 1999; King et al. 2003). By testing the transferability of fish-flow relationships to individual rivers and streams, managers can make informed decisions for the prescription of environmental flow targets (Richter et al. 2006).

After determining environmental flow targets based on fish responses; and/or other biological responses to stream flows, an adaptive management approach can be employed to monitor, evaluate, and make any necessary revisions to flow targets (Richter et al. 2006; Davies et al. 2013). In essence, each environmental flow prescription should be viewed as an experiment for which hypotheses can be developed and tested to enable scientific refinement of environmental flow recommendations. However, even in cases where an adaptive management process is not feasible due to monetary constraints or conflicting stakeholder goals, flow-ecology relationships should still be identified to make informed water management decisions (Richter et al. 2006).

In this study, I examined the effect of selected stream flow components on the recruitment and growth of fishes in streams in the Eastern Broadleaf Province of Minnesota. Many Minnesota waterways have been altered by anthropogenic factors, such as surface and subsurface drainage systems, land use and land cover changes (Lenhart et al. 2011). Alterations to natural streamflow patterns can put stress on certain native stream fish populations, and lead to declines in their growth and recruitment. Consequently, knowledge of the relationships between fish community and population dynamics and streamflow are critical to the management of fisheries in Minnesota's rivers and streams (Blann and Kendy 2012).

CHAPTER I - FISH RECRUITMENT RESPONSES TO FLOW MAGNITUDE AND VARIABILITY

Introduction

Recruitment is one of the most important factors affecting fish populations because it can influence abundance, size structure, and genetic composition (Cargnelli and Gross 1996). Recruitment can be variously defined as the number of fish hatched or born in any year that survive to various life stages, including reproductive size, harvestable size, a particular size or age, or a size captured by a particular sampling gear (Murphy and Willis 1996). Early life history stages corresponding to the first year of life are especially critical for fish recruitment, since substantial natural mortality is common during this interval (Ludsin and Devries 1997; Zanden et al. 1998; Garvey et al. 2002).

Two key time periods during a fishes' first year can dictate recruitment in any given year: the spawning and rearing periods (Craven et al. 2010). The spawning period has often been defined as the time from the start of pre-spawning activity (*e.g.*, adult movement to spawning habitat, nest building behaviors) until hatched larvae reach a free-swimming phase (DeAngelis et al. 1993). Adult fish body size, spawning habitat availability, and changes in the physical environment can strongly influence larval fish abundance at the end of the spawning time period (Chambers and Trippel 1997). The rearing period can be considered to encompass the time between the free-swimming larval phase until onset of winter (Nickelson 1992). Upon reaching the free-swimming phase, larval fishes must find habitat with adequate food, which can also serve as refuge from predators. The quality and quantity of available rearing habitat can be a limiting factor for young-of-the-year fish survival (Schlosser 1995).

In lotic systems, fish recruitment has been linked to abiotic factors during both the spawning and rearing time periods, particularly stream flows (Schlosser 1991; 1995). Stream-flow conditions can provide negative or positive effects to fish recruitment.

For example, the timing of high flows during the spawning time period may serve as an important environmental cue initiating adult fish spawning behaviors, whereas lack of high flows may prohibit successful spawning (Schlosser 1991; Poff and Allan 1995). The simple volume of water associated with differing streamflows, also defines the physical habitat space available for rearing larval and over-wintering juvenile fishes in lotic systems. Furthermore, temporal patterns in streamflow volume dictate longitudinal and latitudinal access to spawning, nursery, and feeding habitats fundamental to successful recruitment of stream fishes (Schlosser 1991; Poff and Allan 1995; Poff et al. 1997; Bunn and Arthington 2002; Mims and Olden 2012; 2013).

Different spawning strategies of adult fishes may interact with streamflows during the spawning period affecting recruitment (Craven et al. 2010). Common spawning strategies of stream fishes include nest-spawning, benthic-lithophil broadcast spawning, and open-water-pelagophil broadcast spawning (Simon 1999). Prolonged high stream flows during and immediately after spawning of nest-building and benthic-lithophil fishes has been shown to negatively affect recruitment, due in part to nest scouring, and egg and fry displacement (Jennings and Phillip 1994; Lukas and Orth 1995; Weyers et al. 2003). Conversely, pelagophil-riverine fishes require prolonged high flows during and immediately after spawning to keep eggs and larvae adrift until reaching the free-swimming phase. The absence of high flows during and immediately after spawning can cause drifting eggs and larval fishes to settle out of the water column onto the substrate where they may be fatally buried by sediments (Durham and Wilde 2006; Dudley and Platania 2007).

Another species trait that can mediate stream flow effects on fish recruitment is locomotion morphology. Locomotion morphology is defined as the differential body shapes and sizes observed among fishes as they relate to movement within their environment. Goldstein and Meador (2004) identified six dominant locomotion morphology types termed cruisers, accelerators, maneuverers, benthic-high-velocity huggers, benthic-low-velocity creepers, and specialists. Fish species were classified into

these six dominant morphology types based on a descriptive body shape pattern and a taxonomic identity representative of each locomotion morphology type. Body shape descriptors and taxonomic archetypes for the six morphology types were cruisers (torpedo; Salmonidae), accelerators (arrow; Esocidae), maneuverers (disk; *Lepomis* spp.), benthic-high-velocity huggers (arched; Cottidae), benthic-low-velocity creepers (teardrop; Ictaluridae), and specialists (elongate; Anguillidae). Locomotion morphology can especially influence the response of age-0 stream fishes to high and variable flows during the rearing period (Goldstein and Meador 2004; Craven et al. 2010). For example, Craven et al. (2010) found that young-of-the-year (YOY; *i.e.*, fishes born in a particular reproductive year) fishes that exhibited cruiser locomotion morphology (torpedo-shaped fishes) were more negatively influenced by discharge variability relative to species with other swimming morphologies. Many species that display cruiser-locomotion morphology inhabit the water column, which can make them more vulnerable to high-magnitude spates and flashy flows (Craven et al. 2010). Similarly, Bernardo et al. (2003) found that recruitment of Pumpkinseed Sunfish *Lepomis gibbosus*, a species that displays maneuverer-locomotion morphology, was negatively impacted by high-magnitude spates and flashy streamflows. Fish species that exhibit maneuverer-locomotion morphologies are not adapted to maintain position in turbulent currents and may be displaced to unfavorable areas (Bernardo et al. 2003).

Craven et al. (2010) examined hydrology effects on fish recruitment, as measured through YOY fish density in the fall, for two flow time periods: short-term (10 day) and long-term (60 or 90 days). They found that short-term flow magnitude and variability during spawning and rearing periods had stronger effects on fish recruitment than long-term flow magnitude and variability. Specifically, Craven et al. (2010) found strong fish recruitment in years when short-term flows were high during the spawning period and less variable during the rearing period. Modeling results in Craven et al. (2010) also found little support for long-term flow effects on stream fish recruitment. However, Craven et al. (2010) noted that specific relationships between recruitment and

short term flow magnitude and variability were dependent on spawning strategies and locomotion morphologies. For example, recruitment of broadcast spawning fishes (including benthic lithophils) was negatively related to short-term high flows during the spawning period whereas recruitment of cruiser morphology species was more negatively related to short-term flow variation during the rearing period compared to fishes with other locomotion morphologies.

In Minnesota, increases in land devoted to agricultural production and urban development have altered stream hydrology (Lenhart et al. 2011; Blann and Kendy 2012). Due to agricultural practices such as subsurface tiling, large areas of southern and central Minnesota have seen significant increases in mean annual flows, and most median monthly flows, and a decrease in annual variability of flows (Lenhart et al. 2011; Blann and Kendy 2012). The effects of these altered flows on stream fishes in Minnesota are almost completely unknown. To assess effects of these altered flow regimes on stream fish populations in Minnesota, water resource managers need tools to predict how changes in flow regimes affect fishes (Lenhart et al. 2011; Blann and Kendy 2012). Life history traits such as spawning strategies and locomotion morphology types can exhibit predictable responses to stream flows that can aid development of water management plans (Mims and Olden 2012; Peterson and Shea 2014).

Streams and rivers in central and southeastern Minnesota in the Eastern Broadleaf Province support relatively high fish diversity in the state and include important recreational fisheries, especially for Smallmouth Bass *Micropterus dolomieu* (Thorn and Anderson 1999). Smallmouth Bass, Rock Bass *Ambloplites rupestris* and Northern Hogsucker *Hypentelium nigricans* are three common stream fishes endemic to this ecoregion that also represent contrasting spawning strategies and locomotion morphologies. Smallmouth Bass are a nest-spawning species with cruiser-body morphology. Rock Bass are another nest-spawning fish but exhibit maneuverer body morphology. Northern Hogsuckers use a lithophilic spawning strategy where adults deposit eggs over rock and gravel substrates and hatched larvae continue to hide

beneath coarse substrates with no parental care. Northern Hogsuckers represent benthic-high-velocity-hugger body morphologies. Based on current literature, especially findings in Craven et al. (2010) and Peterson and Shea (2014), several predictions can be made regarding the likely effects of altered hydrology on fish recruitment in streams and rivers in the Eastern Broadleaf Province of Minnesota (Table 1.1). To verify the geographic transferability of these predictions, I tested associations between fish recruitment and the magnitude, and variability of stream flows during spawning and rearing time periods for fishes representing nest-building and lithophilic spawning strategies and cruiser, maneuverer and benthic-hugger body morphologies. I predicted that:

- recruitment of nest-building fishes would show positive relationships with short-term spawning flow magnitude;
- recruitment of benthic lithophils would show a negative relationship with short-term- spawning flow magnitude;
- long-term magnitude of streamflow would show no relationship with recruitment of fishes regardless of spawning strategy during the spawning period;
- recruitment of fishes exhibiting cruiser and maneuverer morphologies would show a negative relationship with short-term-rearing flow variability;
- recruitment of fishes exhibiting cruiser morphology would show a negative relationship with long term flow variability during the rearing period;
- maneuverer recruitment would show no relationship with long-term-rearing flows;
- and recruitment of fish with benthic-hugger morphology would show no relationship with long- or short-term-flow variability during the rearing period.

Table 1.1. Predicted relationships between recruitment and hydrological variables for Smallmouth Bass, Rock Bass, and Northern Hogsuckers in the Eastern Broadleaf Province of Minnesota based on spawning strategy and locomotion morphology. (0 = no relationship; - = negative relationship; + = positive relationship)

Fishes	Predicted recruitment relationships with increases in:	Spawning		Rearing
		Spawning Strategy	Juvenile Body Morphology	
Smallmouth Bass		Nest-builder	Cruiser	
	Short-term flow magnitude	+		
	Long-term flow magnitude	0		
	Short-term flow variability		-	
Rock Bass	Long-term flow variability		-	
		Nest-builder	Manueverer	
	Short-term flow magnitude	+		
	Long-term flow magnitude	0		
Northern Hogsucker	Short-term flow variability		-	
	Long-term flow variability		0	
		Benthic Lithophil	Benthic hugger	
	Short-term flow magnitude	-		
	Long-term flow magnitude	0		
	Short-term flow variability		0	
	Long-term flow variability		0	

Study Area

The Eastern Broadleaf Province in Minnesota extends in a northwest direction from the extreme southeast through the central portion of the state, and serves as a transitional zone between the prairie to the west and the mixed coniferous-deciduous forest to the northeast (Figure 1.1). Topography varies from level to rolling plains in the northwest and central portions to steep blufflands bordering the Mississippi River in the southeast. Row crop agriculture is one of the major land uses in the province (Minnesota Department of Natural Resources 2006). It is also home to a majority of Minnesotans, as it includes the urban and suburban areas of Minneapolis and St. Paul, and other regional centers like St. Cloud and Rochester.

To test associations between fish recruitment and selected hydrologic variables, I randomly selected study sites representative of streams and rivers within the Eastern Broadleaf Province that were publicly accessible. To ensure representative hydrologic data, I only selected sites within 50 river km of an adequate hydrologic gage. A gage was considered adequate if it had discharge data for the years 2000-2012 and a major dam was not located between the gage and study site. Discharge records from 2000-2012 were required so that all age classes of fishes captured in this study (see below) were encompassed within the hydrologic period of interest. Gages that had a dam between them and the site of interest were discounted, because dams often alter hydrology (Braatne et al. 2008). In certain cases when more than one site was randomly selected on a particular river or stream within 50 river km, and not separated by a dam, fish recruitment data from those sites were combined to better represent the fish population. A total of 17 sites on eight rivers fit the established criteria. Six sites were combined with a nearby site, resulting in 11 individual study rivers or streams (Table 1.2).

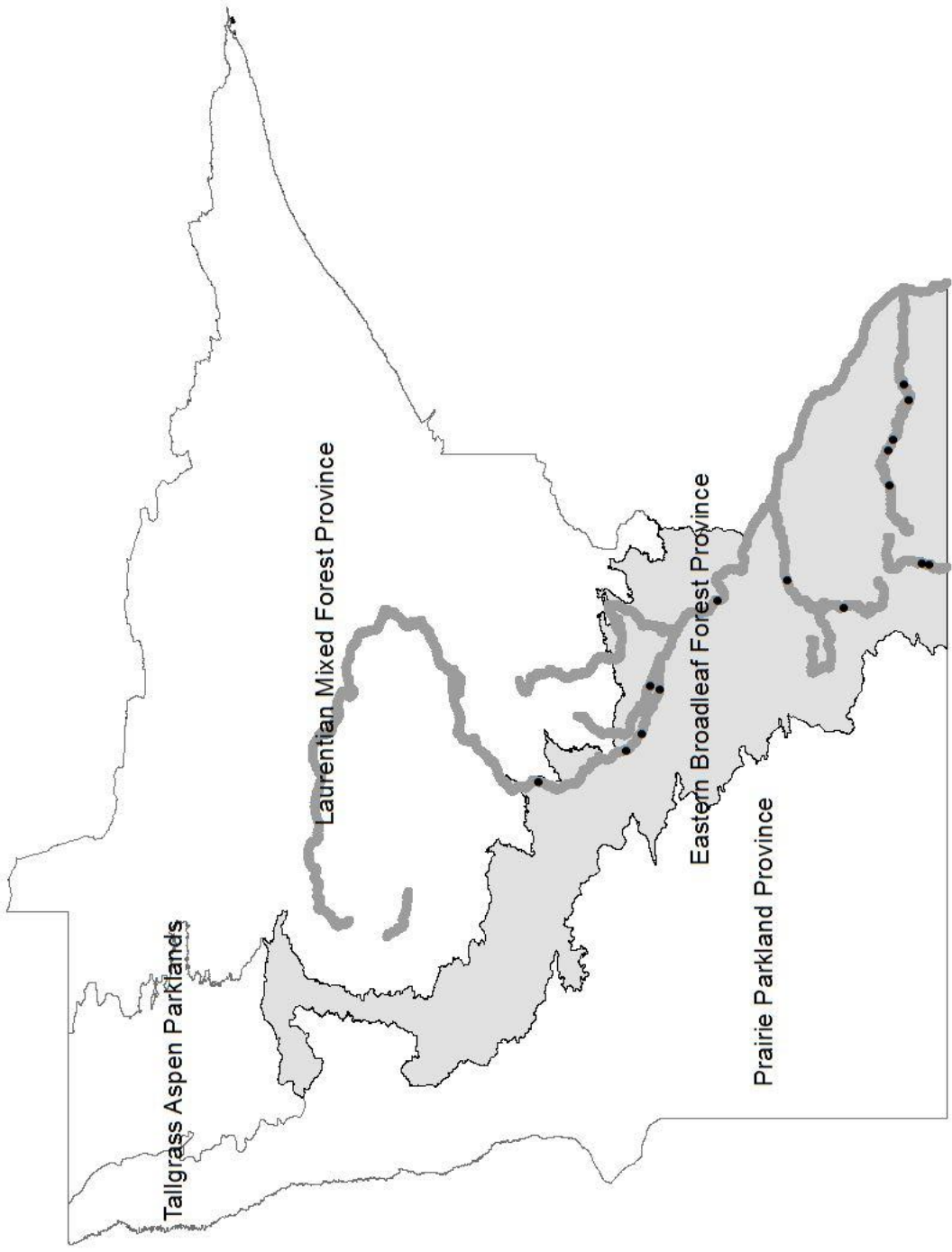


Figure 1.1. Map of the Ecological Provinces of Minnesota and the streams and stream sites (represented by black dots) sampled to assess stream fish recruitment in this study.

Table 1.2. Stream site locations in the Eastern Broadleaf Province of Minnesota sampled in June-September of 2012 and 2013, including associated latitude and longitude coordinates (decimal degrees), gear type used at sites, upstream drainage area, and gage identification numbers. (For gear types, MBEF = Mini Boom Electrofisher, and TBEF = Tow Barge Electrofisher. All sites are USGS gage sites, unless noted as a dam).

Stream Site	Location Description	Latitude and Longitude (dd)	Gear Type Used	Upstream Drainage Area (km ²)	Stream Width (m)	Gage I.D.
Cannon River	Upstream of Lake Bylesby	44.5042 -93.0776	MBEF	2,478	30	Northfield Dam
Cedar River	Near Austin, MN	43.6372 -92.9744	TBEF	1,031	26	05457000
Elk River	Near Big Lake, MN	45.3588 -93.7382	TBEF	1,435	19	05275000
Mississippi River	At Camp Ripley, MN	46.0599 -94.3397	MBEF	28,852	175	05242300 + Sylvan Dam
Mississippi River	Near Saint Cloud, MN	45.5147 -94.1396	MBEF	36,075	159	05270700
Mississippi River	At Monticello, MN	45.2965 -93.7592	MBEF	36,493	148	05270700
Mississippi River	At Pool 1	44.9356 -93.1991	MBEF	51,291	237	Lower Saint Anthony Dam
North Branch Root River	Near Cummingsville, MN	43.8710 -92.2598	TBEF	600	22	05383950
Root River	Near Peterson, MN	43.7742 -91.8474	MBEF	2,489	36	05385000
Rum River	Near Saint Francis, MN	45.3277 -93.3722	MBEF	3,619	40	05286000
Straight River	Near Owatonna, MN	44.1483 -93.2448	TBEF	649	20	05353800

Methods

Fishes were sampled from June to September in 2012 and 2013 when streams were near baseflow conditions to expedite representative sampling of all lotic habitats present. Sampling distance for wadeable and non-wadeable stream sites were based on recommendations in Lyons (1992), and Lyons et al. (2001) to ensure sampling of most microhabitats. Wadeable streams were sampled for a distance of 35 times the mean stream width using a three-anode-tow-barge electrofisher. A single pass upstream was completed at each site. On non-wadeable rivers, fishes were sampled with a two-anode-4.3 m mini boom electrofisher, using a standardized sampling distance of 1,600 m. Boat electrofishing was conducted in a downstream manner with the current. All sampling was done in a zig-zag pattern using pulsed DC current, with net mesh sizes of 17 mm. To increase sample size at some sites, supplemental sampling was conducted to acquire more target fishes. Captured fishes were counted, measured (nearest 1.0-mm TL), and had species-specific structures taken to facilitate aging. Sagittal otoliths were used to age Smallmouth Bass and Rock Bass, while pectoral fin rays were used to age Northern Hogsucker (Maceina and Sammons 2006; Reid 2007).

Procurement of pectoral fin rays from Northern Hogsucker was possible without the need to sacrifice fish, but euthanasia was necessary to obtain sagittal otoliths from most Smallmouth Bass and Rock Bass. Fishes were euthanized by immersion in an overdose of MS-222 (tricaine-methanesulfonate; 250-500 mg/L; Topic-Popovic et al. 2012). Some fishes were spared at sites where it was determined that sacrificing all bass might decimate the local population, or where I collected more than 100 individuals. For sites where otoliths were not collected for all bass, an age-length key was developed and used to determine ages for spared fishes (Devries and Frie 1996). Aged fishes from each stream site were considered representative of the age structure of the population.

An Olympus (Unitron z850) dissecting and Leica (DM750) compound microscope were used to age fishes. Sagittal otoliths were aged in whole-view, and annuli were

identified and counted, starting at the focus (center of otolith) to the anterior edge (Sipe and Chittenden 2001). Pectoral fin rays were sectioned with a low speed diamond saw (Buehler Isomet, Buehler Inc., Lake Bluff, IL) prior to being aged. To prevent fracturing during cutting, fin rays were embedded in epoxy resin. As with sagittal otoliths, annuli of pectoral fin rays were identified and counted, starting at the focus and proceeding to the outer edge (Mills and Chalanchuk 2004). Two independent readers were used to age fishes. If the two readers did not agree on the age of a particular fish, the fish was not used in the study.

To quantify recruitment I used a catch-curve method (Maceina 1997; Maceina and Pereira 2007). Maceina and Pereira (2007) used studentized residuals from weighted linear catch-curve regressions as a measure of recruitment variability in fish populations, where negative and positive residuals represent weak and strong year-classes, respectively. An advantage of using the weighted catch-curve method as described by Maceina and Pereira (2007) is that inferences about past recruitment can be secured from a single sample year, rather than requiring multiple years of relative abundance data. The method assumes that fishes were aged accurately, that mortality was constant among age groups, and requires identification of the first age group that was fully recruited to the sampling gear as well as the oldest age group adequately captured by the sampling gear. Recruitment estimates only apply to age groups fully recruited and adequately captured by the sampling gear. The age at which fishes were fully recruited to a population was based on a catch-curve histogram assessment across all stream sites for each species of interest (Allen and Hightower 2010).

Based on age-frequency histograms, Smallmouth Bass and Rock Bass were considered to be recruited to the electro-fishing gear at age 1 (Figures 1.2 and 1.3), and Northern Hogsuckers were considered to be recruited to the electro-fishing gear at age 4 (Figure 1.4). To determine the oldest age group adequately captured by the sampling gear I used criteria from Isermann et al. (2002).

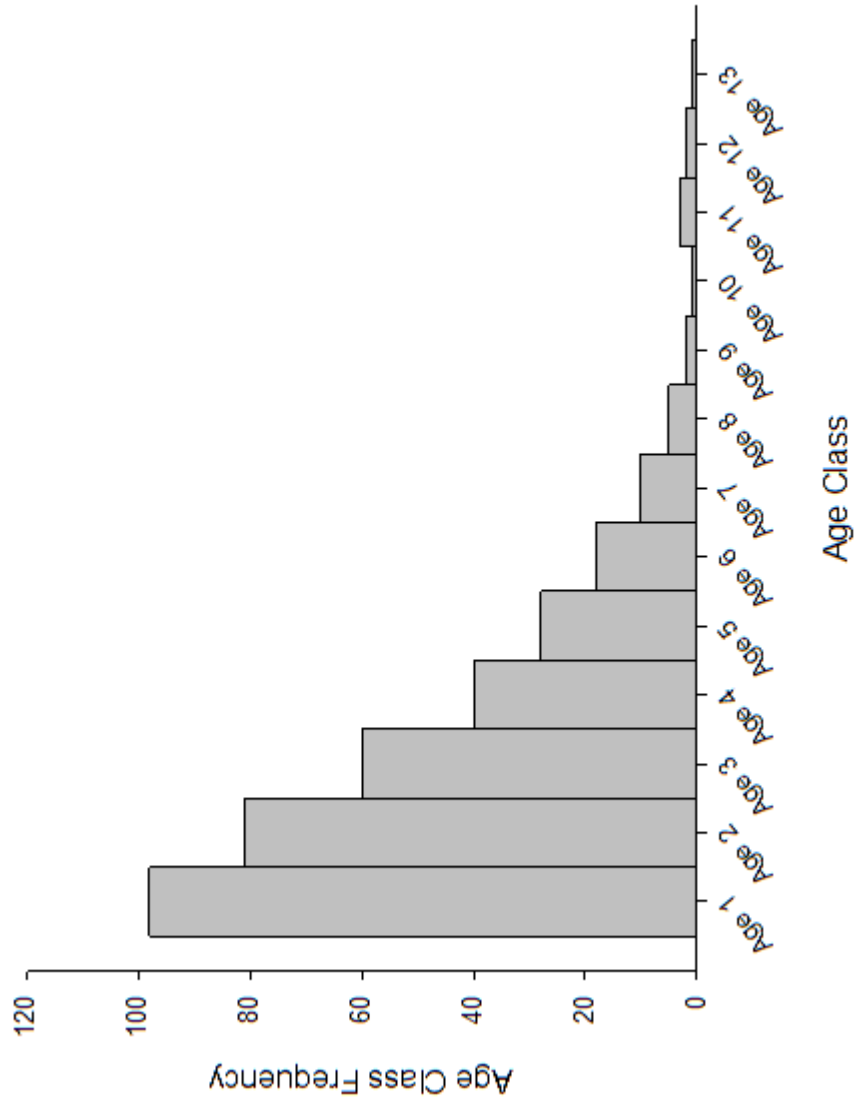


Figure 1.2. Smallmouth Bass age frequency histogram across 8 stream sites in the Eastern Broadleaf Province of Minnesota sampled from June-September of 2012 and 2013.

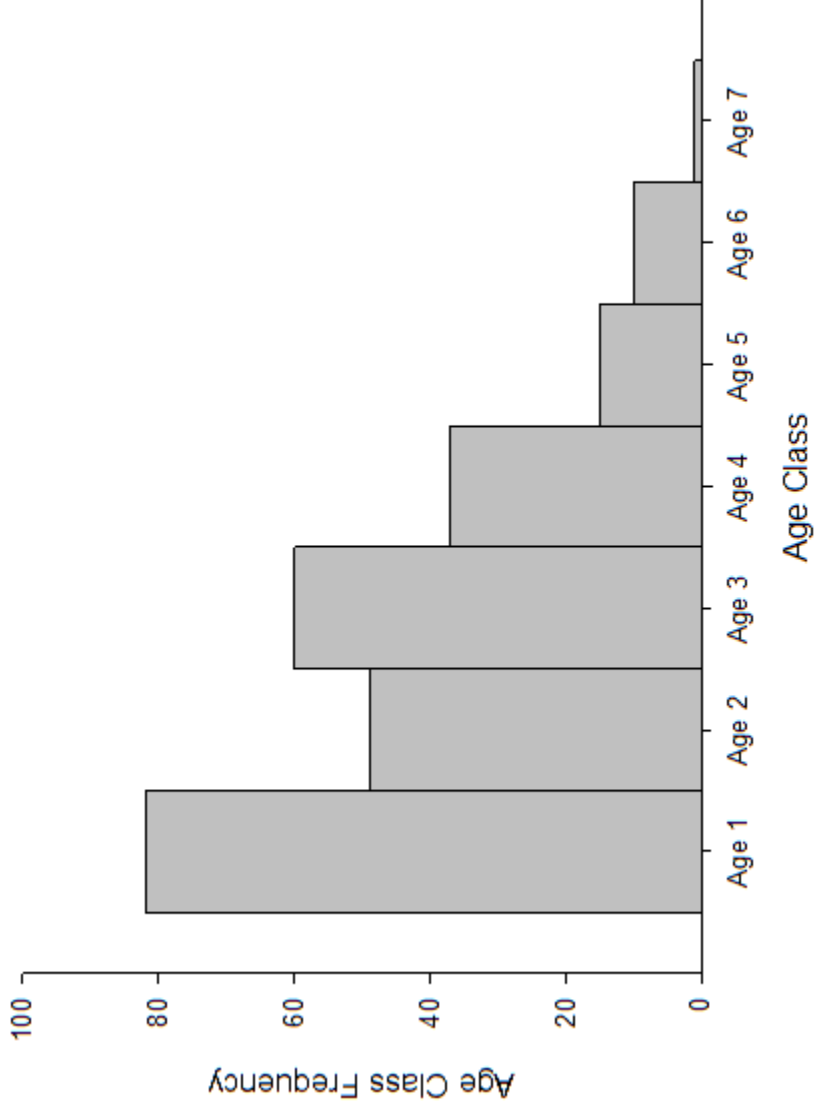


Figure 1.3. Rock Bass age frequency histogram across 5 stream sites in the Eastern Broadleaf Province of Minnesota sampled from June-September of 2012 and 2013.

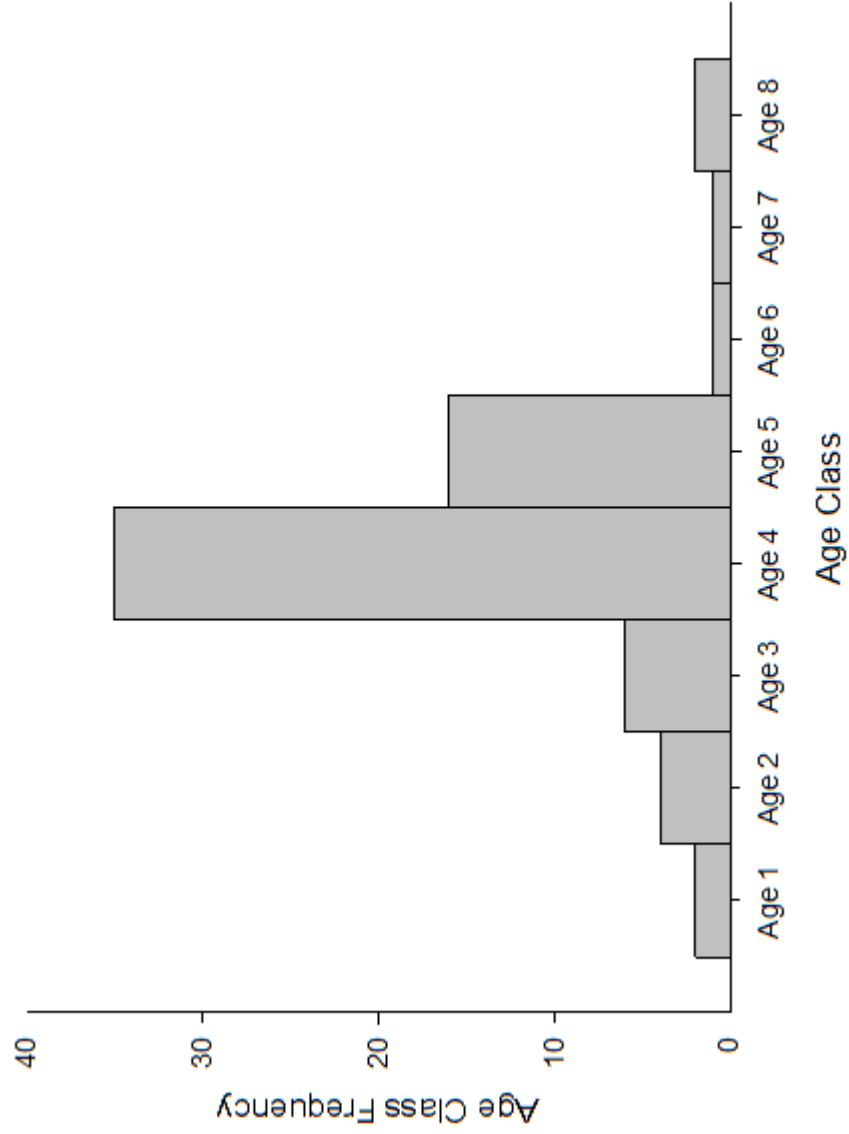


Figure 1.4. Northern Hogsucker age frequency histogram for the Root River in the Eastern Broadleaf Province of Minnesota sampled from June-September of 2012 and 2013.

Isermann et al. (2002) recommended only including age groups in a recruitment index calculation if a minimum of two fish per age-class were collected. Age classes with less than two individuals could be included only if subsequent year classes included more than two fish, or subsequent age classes were not represented in the sample.

Total recruitment variation among streams was measured using the recruitment coefficient of determination (RCD) method developed by (Isermann et al. 2002). The RCD is based on r^2 values from a weighted catch curve and ranges from 0-1, with values closer to one indicative of more stable recruitment. The RCD assumes that total mortality acts as a negative exponential and is equal among age classes (Isermann et al. 2002). A minimum sample size of 20 fully recruited fish was used to make recruitment estimates among stream sites to allow for the inclusion of low density populations. A minimum of four year-classes per population was also required, as the studentized residuals from catch-curves heavily skewed values (values were either 1 or -1) when calculated with less than four year classes.

To identify the specific spawning and rearing periods to facilitate calculation of hydrologic indices for the three fish species in this study, I consulted regional taxonomy references (Becker 1983; Pflieger 1997). Based on these sources, the spawning time period was defined as the interval from April-May for Northern Hogsucker and May-June for Smallmouth Bass and Rock Bass. Rearing periods for Smallmouth Bass and Rock Bass were defined as the interval from July-November, while the Northern Hogsucker rearing period was set as June-November.

To quantify inter-annual differences in magnitude and variability of stream flows, daily discharge data near sampling sites was obtained from the U.S. Geological Survey's National Water Information System Website (<http://waterdata.usgs.gov/mn/nwis/rt>), and hydroelectric dam data from county databases. Hydrologic variables representing short-term and long-term variation in magnitude and variability of streamflow were calculated for spawning, and rearing periods with the aid of Indicators of Hydrologic Alteration Software (The Nature Conservancy 2009; Table 1.3).

Table 1.3. Hydrologic Variables used for measures of long-term and short-term variation and magnitude of stream flow for sites in the Eastern Broadleaf Province of Minnesota.

Hydrologic Variable	Calculation Explanation (reason for inclusion)	Example Calculation
Long-term Spawning Period Flow Magnitude	The median of flows for an entire phase (Long term measure of flow magnitude)	Median of Spawning period = median of days between May 1 st and June 30 th for Smallmouth Bass and Rock Bass.
Short-term Spawning Period Flow Magnitude	The mean of the consecutive 7-day interval with the maximum mean amount of flow (Short term measure flow magnitude)	May 1-May 7 flows = 15,18,19,13,12,16,11 May 8-May 15 flows = 2,3,5,3,2,4,11 May 1-May 7 flows has the higher mean, and is the 7 day maximum for the spawning period
Long-term flow Rearing Period Flow Variation	The Coefficient of Dispersion for an entire phase (Long term measure of flow variability)	Coefficient of Dispersion of Rearing period = (75 th percentile minus the 25 th percentile) divided by the median of days between July 1-November 30 for Smallmouth Bass and Rock Bass
Short-term flow Rearing Period Flow Variation	The coefficient of dispersion of the consecutive 7-day interval with the minimum mean amount of flow. (Short term measure of flow variability)	July 1-July 7 flows = 15,18,19,13,12,16, 11 July 8-July 15 flows = 2,3,5,3,2,4,11 July 8-July 15 flows has lowest mean, so the coefficient of dispersion of July 8-July 15 flows is calculated. Coefficient of dispersion = (75 th percentile minus the 25 th percentile) divided by the median for July 8-July 15 flows

Short-term hydrologic variables were defined as intervals of seven days because the Indicators of Hydrologic Alteration software recommends seven-day intervals to define ecologically relevant short-term time periods.

The short-term flow magnitude was determined by first calculating the mean daily flow for each seven-day interval in each spawning, and rearing period. For example, for a spawning-time period from May 1-June 30 a mean flow was calculated for each consecutive seven-day interval (e.g. May 1 – May 7; May 8 – May 15; etc.,). The seven-day interval with the highest mean value was the seven-day flow magnitude value used. To calculate short-term-flow variability, the seven-day interval with the lowest mean value was selected and the coefficient of dispersion was calculated for those seven days.

The rationale for using the seven-day period with the lowest mean flow was that the time period when flows were at their lowest would be expected to have the greatest impact (*i.e.*, the least amount of habitat volume available) to fishes if flows fluctuated substantially. Long-term hydrology variables encompassed an entire period of interest (*i.e.*, all days within each spawning, and rearing period). The median daily flow over all days within each spawning time period constituted the long-term magnitude flow values. The coefficient of dispersion was then calculated across all the days within each rearing time period and used to characterize the long-term flow variability.

To test associations between fish recruitment and hydrology variables, I used univariate-least-squares regression. For each fish species, regressions were developed and tested independently for each of the 12 streams to further assess spatial repeatability of predictions. Years were replicates in all regressions. Dependent variables were the inter-annual recruitment estimates (*i.e.*, inter-annual studentized residual values from catch-curve regressions). Independent variables were the inter-annual values for short-term-flow magnitude, long-term-flow magnitude, short-term-flow variability, and long-term-flow variability. A Shapiro-Wilk test was used to

determine data normality, and a Breusch-Pagan test was used to examine the constant variance assumptions for each regression analysis. An alpha value of 0.10 was chosen to determine statistical significance. I deviated from a typical alpha value of 0.05 to identify additional biologically significant relationships that may be present at alpha values between 0.05 and 0.10. A Bonferroni correction was implemented to maintain the experiment-wide alpha value of 0.10. All regressions were performed using R 3.1.3 statistical software (R Core Team 2015).

Results

A total of 466 Smallmouth Bass, 295 Rock Bass, and 196 Northern Hogsuckers were captured across the 11 stream sites. Smallmouth Bass were captured at all 11 sites, but the minimum of 20 fish fully recruited to the gear was only obtained at eight sites. The highest numbers of Smallmouth Bass were captured at the Mississippi River site at Monticello, and the lowest at the Cannon River site (Appendix 1). Rock Bass were captured at all sites except for the Mississippi River at Pool 1, and the Cannon River. However, the minimum of 20 fully recruited fish were only captured at five sites. The greatest numbers of Rock Bass were captured in the Cedar River, while lowest numbers were captured in the Straight River (Appendix 2). Northern Hogsuckers were captured at six of the 11 sites. The streams where Northern Hogsuckers were captured were the Root River, Cannon River, Straight River, Cedar River, Mississippi River near Saint Cloud, and the North Branch Root River. Out of the six streams where Northern Hogsuckers were captured, only the Root River met the minimum criteria of 20 fully recruited fish. The Cannon River, Straight River, Cedar River, and Mississippi River near Saint Cloud sites did not have the minimum of 20 fully recruited fish, and the North Branch at Root River did not have at least four fully recruited year classes (Appendix 3).

Recruitment

Mississippi River sites at Monticello and near Saint Cloud had the most Smallmouth Bass year classes present, 13 and 11 respectively, whereas, the Cannon and North Branch Root rivers had the fewest (Table 1.4). Smallmouth Bass year classes between 2006 and 2011 were present in most river and stream sites. Although Smallmouth Bass recruitment varied among most streams and years, a few years seemed to show ecoregion-wide similarities in Smallmouth Bass recruitment. For example, Smallmouth Bass recruitment was strong in almost all streams in 2010 and strong in half of streams in 2009, whereas, bass recruitment was weak at most sites in 2007 and 2011 (Table 1.4).

For Rock Bass, the Cedar River had the most, and the North Branch Root River the fewest year classes recruited to the gear. Few Rock Bass captured were older than age four at most sites (Table 1.4). Similar to Smallmouth Bass, Rock Bass recruitment varied among most streams and years but had one similarity. Rock Bass recruitment was similarly weak in almost all streams in 2011. Contrary to strong Smallmouth Bass recruitment in 2010, Rock Bass recruitment was neither strong nor weak in any streams in that year. However, Rock Bass recruitment was strong in all three streams sampled in 2012.

Year classes of Northern Hogsuckers were present for the years 2004-2008 in the Root River. The strongest and weakest year classes were in 2006 and 2008, respectively. Furthermore, the 2007 year class was particularly strong, and the 2005 year class particularly weak (Table 1.4). With a RCD value of 0.89, Northern Hogsucker recruitment appeared to be relatively stable (Table 1.5).

RCD values for Smallmouth Bass varied among streams and ranged from 0.84 at the North Branch Root River to 0.02 at the Mississippi River at Pool 1. The North Branch Root River, Mississippi River near Saint Cloud, and the Root River all had RCD values > 0.65 suggesting relatively stable recruitment.

Table 1.4. Year class strength of Smallmouth Bass, Rock Bass, and Northern Hogsuckers populations in streams of the Eastern Broadleaf Province of Minnesota represented by studentized residuals from a weighted catch curve (bold values > 0.8, and underlined values < -0.8 indicate particularly strong and weak year classes, respectively).

Stream site	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
<u>Smallmouth Bass</u>													
Mississippi River at Camp Ripley							1.10	<u>-1.17</u>	-0.22	-0.37	1.64	<u>-0.92</u>	
Mississippi River near St. Cloud			0.88	<u>-0.90</u>	<u>-1.46</u>	-0.61	1.37	-0.02	0.02	0.39	1.44	0.29	<u>-1.89</u>
Mississippi River at Monticello	0.35	0.75	-0.04	-0.30	0.12	-0.15	0.10	-0.77	1.57	<u>-1.54</u>	<u>-2.00</u>	0.74	1.62
Mississippi River at Pool 1								<u>-0.88</u>	-0.63	1.07	1.13	0.33	<u>-1.64</u>
Rum River							-0.29	0.08	<u>-1.05</u>	1.45	0.82	<u>-1.42</u>	
Cannon River								<u>-1.34</u>	1.16	-0.24	1.01	<u>-1.19</u>	
North Branch Root River										1.35	<u>-0.86</u>	-0.78	1.20
Root River					0.48	0.02	0.01	-0.13	<u>-1.87</u>	1.36	1.07	<u>-0.93</u>	
<u>Rock Bass</u>													
Mississippi River at Camp Ripley							1.81	-0.27	<u>-1.15</u>	-0.44	-0.38	0.96	
Elk River									1.64	<u>-0.96</u>	-0.30	-0.67	1.12
Straight River									-0.71	0.98	0.38	<u>-1.53</u>	0.96
North Branch Root River										0.37	0.35	<u>-1.41</u>	1.26
Cedar River						<u>-1.60</u>	0.45	-0.01	0.37	1.44	0.28	<u>-1.68</u>	
<u>Northern Hogsuckers</u>													
Root River					-0.45	<u>-0.88</u>	1.26	0.81	<u>-1.40</u>				

Table 1.5. Recruitment Coefficient of Dispersion estimates for Smallmouth Bass, Rock Bass, and Northern Hogsuckers populations in streams of the Eastern Broadleaf Province of Minnesota.

Stream Site	RCD
<u>Smallmouth Bass</u>	
Mississippi River at Camp Ripley	0.07
Mississippi River near St. Cloud	0.67
Mississippi River at Monticello	0.52
Mississippi River at Pool 1	0.02
Rum River	0.35
Cannon River	0.19
North Branch Root River	0.84
Root River	0.66
<u>Rock Bass</u>	
Mississippi River at Camp Ripley	0.96
Elk River	0.73
Straight River	0.01
North Branch Root River	0.02
Cedar River	0.70
<u>Northern Hogsuckers</u>	
Root River	0.89

Conversely, the Cannon River, Mississippi River sites at Camp Ripley and Pool 1 each had values < 0.19 indicating relatively unstable recruitment (Table 1.5).

Rock Bass recruitment stability varied among streams. RCD values ranged from 0.96 at the Mississippi River at Camp Ripley to 0.01 at the Straight River. The Mississippi River at Camp Ripley, Elk River, and Cedar River had values > 0.69 indicating relatively stable recruitment, whereas the North Branch Root River and Straight River had values < 0.03 , suggesting relatively unstable recruitment (Table 1.5).

Hydrology

Hydrology during the Smallmouth Bass-spawning period exhibited considerable variation among streams and years (Tables 1.6, 1.7). Long-term spawning flow magnitudes were much higher in the four Mississippi River sites than in the Cannon River, North Branch Root River, Root River, and Rum River. In many years, long-term spawning flow magnitudes at the Mississippi River sites were at least five times greater than that of the other four streams. For the Mississippi River sites, the lowest long-term spawning flows ($96 \text{ m}^3/\text{s}$) were observed in the Mississippi River at Camp Ripley in 2010, whereas the highest flows ($801 \text{ m}^3/\text{s}$) occurred in the Mississippi River at Pool 1 in 2011. Among the other four streams, long-term spawning flows ranged from a low of $6 \text{ m}^3/\text{s}$ in the Cannon and North Branch Root Rivers in 2009 and 2012, respectively, to a high of $66 \text{ m}^3/\text{s}$ in the Rum River in 2011. The Root River had the most stable long-term spawning flows, with coefficient of dispersion values < 0.50 for most years. Conversely, long-term spawning flows were the least stable at the Cannon and Root Rivers, with coefficient of dispersion values > 0.60 in a majority of years.

The highest stability of long-term spawning flows (coefficient of dispersion = 0.20) were found in the Root River in 2011, whereas extremely variable long term spawning flows (coefficient of dispersion > 1.0) were present in 2006 at Mississippi River sites at Monticello and near St. Cloud and in the Rum River.

Table 1.6. Long-term flow magnitude and (variation) of the spawning period for eight stream sites in the Eastern Broadleaf Province Minnesota corresponding to year classes of Smallmouth Bass. Maximum values are in bold, and minimum values are underlined. Flow magnitude is in m³/s. Flow variation is a coefficient of dispersion.

Stream Site	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Mississippi River at Camp Ripley							184 (0.84)	149 (0.47)	287 (0.47)	163 (0.72)	96 (0.54)	332 <u>(0.33)</u>	
Mississippi River at Saint Cloud			214 (0.72)	194 (0.64)	157 (0.51)	371 (0.64)	206 (1.07)	186 (0.46)	348 (0.52)	186 (0.64)	135 (0.42)	436 <u>(0.33)</u>	391 (0.90)
Mississippi River at Monticello	173 (0.36)	575 (0.40)	214 (0.72)	194 (0.64)	157 (0.51)	371 (0.64)	206 (1.07)	186 (0.46)	348 (0.52)	186 (0.64)	135 (0.42)	436 <u>(0.33)</u>	391 (0.90)
Mississippi River at Pool 1								236 (0.52)	549 (0.59)	258 (0.62)	245 (0.42)	801 <u>(0.30)</u>	618 (0.71)
Rum River						20 (1.50)	<u>11</u> (0.54)	42 (1.14)	42 (1.14)	<u>11</u> (0.78)	20 (0.66)	66 <u>(0.32)</u>	
Cannon River							8 (0.84)	28 (0.95)	28 (0.95)	<u>6</u> <u>(0.69)</u>	9 (1.08)	37 (0.73)	
North Branch Root River										9 (0.71)	10 (1.04)	26 (0.38)	6 <u>(0.37)</u>
Root River				32 (1.09)	26 (0.23)		32 (0.43)	24 (0.31)	56 (0.43)	<u>13</u> (0.27)	<u>13</u> (0.39)	21 <u>(0.20)</u>	

Table 1.7. Short-term magnitude and (variation) of the spawning period for 8 stream sites in the Eastern Broadleaf Province of Minnesota corresponding to year classes of Smallmouth Bass. Maximum values are in bold, and minimum values are underlined. Flow magnitude is in m³/s. Flow variation is a coefficient of dispersion.

Stream Site	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Mississippi River at Camp Ripley						375 (0.12)	237 (0.19)	394 <u>(0.05)</u>	302 (0.09)	<u>192</u> (0.07)	382 <u>(0.05)</u>		
Mississippi River at Saint Cloud		349 (0.17)	470 (0.10)	<u>247</u> (0.26)	573 (0.07)	430 (0.13)	275 (0.25)	480 (0.11)	343 (0.10)	278 (0.08)	522 <u>(0.02)</u>	757 (0.07)	
Mississippi River at Monticello	297 (0.33)	824 (0.13)	349 (0.17)	470 (0.10)	<u>247</u> (0.26)	573 (0.07)	430 (0.13)	275 (0.25)	480 (0.11)	343 (0.10)	278 (0.08)	522 <u>(0.02)</u>	757 (0.07)
Mississippi River at Pool 1							424 (0.33)	778 (0.18)	463 <u>(0.08)</u>	433 (0.18)	948 (0.11)	1109 (0.43)	
Rum River						<u>13</u> (0.11)	35 (0.20)	14 (0.26)	21 <u>(0.05)</u>	84 (0.08)	91 (0.10)		
Cannon River							22 (0.60)	74 (0.08)	<u>15</u> (0.06)	49 <u>(0.05)</u>	90 (0.47)		
North Branch Root River									36 (0.20)	29 (0.04)	36 (0.11)	<u>12</u> <u>(0.03)</u>	
Root River			156 (0.07)	37 (0.10)		61 (0.17)	38 (0.07)	272 (0.06)	<u>23</u> (0.06)	25 <u>(0.01)</u>	26 (0.13)		

Extremely variable long-term spawning flows were also present in 2010 in the Cannon and North Branch Root rivers and the Root River in 2004. Short-term spawning flow magnitudes at the Mississippi River sites were also greater (at least five times greater) than flows in the Cannon, North Branch Root, Root, and Rum rivers in many years. The magnitude of short-term spawning flows for Mississippi River sites ranged from 192 m³/s in the Mississippi River at Camp Ripley in 2010 to 1109 m³/s in the Mississippi River at Pool 1 in 2012. Short-term spawning flows in the other four streams ranged from a low of 12 m³/s in the North Branch Root River in 2012 to a high of 272 m³/s in the Root River in 2008. Spawning flows over short-term intervals were relatively stable (coefficient of dispersion < 0.40) among years and streams in the spawning period. However, short term flows were slightly more variable for the Mississippi River site at Pool 1 in 2012, and for the Cannon River in 2007, with coefficients of dispersion of 0.43, and 0.60, respectively.

Similar to Smallmouth Bass-spawning-period flows, Smallmouth Bass-rearing-period flows showed variation among streams and years, but trends in flow magnitude and variability were somewhat similar between the two periods (Tables 1.8, 1.9). Long-term-rearing-flow magnitudes at the Mississippi River sites were at least three times higher than for the Cannon, North Branch Root, Root, and Rum Rivers in most years. For the Mississippi River sites, long-term-rearing-flow magnitude ranged from a low of 36 m³/s in the Mississippi River at Camp Ripley in 2006 to a high of 280 m³/s in the Mississippi River at Pool 1 in 2010.

In the remaining four streams, long-term-rearing-flow magnitude ranged from 3 m³/s in the Cannon and North Branch Root Rivers in 2008 and 2012, respectively, to 37 m³/s in the Rum River in 2011. The Root River had the most stable long-term-rearing flows with coefficients of dispersion < 0.35 for most years, whereas the Mississippi River sites at Camp Ripley and Pool 1, and the Cannon River had the least stable long-term-rearing flows with coefficients of dispersion of > 0.80 for most years.

Table 1.8. Long-term magnitude and (variation) of the rearing period for 8 stream sites in the Eastern Broadleaf Province of Minnesota corresponding to year classes of Smallmouth Bass. Maximum values are in bold, and minimum values are underlined. Flow magnitude is in m³/s. Flow variation is a coefficient of dispersion.

Stream Site	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Mississippi River at Camp Ripley						36 (0.61)	55 (1.42)	82 (0.82)	61 (0.94)	138 <u>(0.26)</u>	82 (1.14)		
Mississippi River at Saint Cloud	199 (0.49)	115	88 (0.80)	86 (1.68)	38 (0.39)	39 (0.58)	58 (1.16)	77 (0.44)	161 <u>(0.25)</u>	135 (1.72)			
Mississippi River at Monticello	95 (0.53)	124 (0.37)	199 (0.49)	86 (1.68)	88 (0.80)	38 (0.39)	39 (0.58)	58 (1.16)	77 (0.44)	161 <u>(0.25)</u>	135 (1.72)		
Mississippi River at Pool 1						93 (1.28)	135 (0.72)	129 (0.81)	280 <u>(0.67)</u>	170 (2.45)	83 (2.06)		
Rum River						7 (0.40)	4 <u>(0.37)</u>	9 (0.40)	8 (0.60)	23 (1.02)	37 (0.82)		
Cannon River						8 (3.09)	3 <u>(0.40)</u>	4 (0.85)	18 (1.20)	4 (5.40)			
North Branch Root River						6 (0.84)	11 (0.62)	6 <u>(0.17)</u>					
Root River						24 (0.65)	19 (0.25)	18 <u>(0.15)</u>	24 (1.05)	25 (0.34)	13 (0.28)	13 (0.25)	

Table 1.9. Short-term magnitude and (variation) for the rearing period for eight stream sites in the Eastern Broadleaf Province of Minnesota corresponding to year classes of Smallmouth Bass. Maximum values are in bold, and minimum values are underlined. Flow magnitude is in m³/s. Flow Variation is a coefficient of dispersion.

Stream Site	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Mississippi River at Camp Ripley							<u>68</u> (0.10)	270 (0.08)	151 <u>(0.06)</u>	170 (0.09)	351 <u>(0.06)</u>	246 (0.07)	
Mississippi River at Saint Cloud			539 (0.09)	438 (0.14)	228 (0.34)	318 (0.21)	<u>78</u> (0.07)	312 (0.23)	176 (0.25)	229 (0.08)	459 (0.12)	354 <u>(0.05)</u>	629 (0.30)
Mississippi River at Monticello	331 (0.13)	291 (0.08)	539 (0.09)	438 (0.14)	228 (0.34)	318 (0.21)	<u>78</u> (0.07)	312 (0.23)	176 (0.25)	229 (0.08)	459 (0.12)	354 <u>(0.05)</u>	629 (0.30)
Mississippi River at Pool 1								422 (0.48)	246 <u>(0.18)</u>	324 <u>(0.08)</u>	712 (0.14)	667 (0.12)	818 (0.52)
Rum River							84 (0.13)	<u>25</u> (0.07)	94 (0.20)	25 <u>(0.03)</u>	50 (0.16)	92 (0.08)	
Cannon River								99 (0.18)	<u>7</u> (0.20)	28 <u>(0.07)</u>	283 (0.30)	79 (0.51)	
North Branch Root River										47 <u>(0.01)</u>	115 (0.10)	19 <u>(0.01)</u>	<u>4</u> <u>(0.01)</u>
Root River					174 (0.02)	75 (0.07)	22 (0.02)	355 (0.03)	47 (0.02)	24 <u>(0.01)</u>	26 (0.09)	<u>17</u> <u>(0.01)</u>	

The highest stability of long-term-rearing flows (coefficient of dispersion = 0.15) were found in the Root River in 2006.

Extremely variable long-term flows occurred in 2012 for the Mississippi sites at Monticello, near Saint Cloud, and at Pool 1, as well as for the Mississippi River sites at Camp Ripley and Pool 1, and the Cannon River in 2007 and 2011. Similar to long-term-rearing-flow magnitudes, short-term-rearing-flow magnitudes at the Mississippi River sites were at least three times higher than that of the four smaller streams for most years. Short-term-rearing flows among the Mississippi River sites ranged from 68 m³/s in the Mississippi River at Camp Ripley in 2006 to 818 m³/s in the Mississippi River at Pool 1 in 2012.

Magnitudes of the short-term-rearing period for the remaining streams ranged from a low of 4 m³/s in the North Branch Root River in 2012 to a high of 355 m³/s in the Root River in 2007. Like short-term-spawning flows for Smallmouth Bass, short-term-rearing flows for Smallmouth Bass were relatively stable among streams and years. The least stable flows occurred in the Cannon River in 2011 (coefficient of dispersion = 0.51), and the Mississippi River at Pool 1 in 2012 (coefficient of dispersion = 0.52).

For the five streams where Rock Bass were captured, hydrology during the Rock Bass-spawning period varied among streams and years (Table 1.10). The Mississippi River at Camp Ripley displayed long-term-spawning-period flow magnitudes much higher than the Cedar, Elk, North Branch Root, and Straight River. In many years long-term-spawning flows in the Mississippi River at Camp Ripley were at least 12 times greater than flows in the other four streams. Long-term-spawning-period flow magnitudes in the Mississippi River at Camp Ripley were the lowest (96 m³/s) in 2010 and the highest (332 m³/s) in 2011. In the four remaining streams long-term-spawning flow magnitude ranged from 5 m³/s in the Elk River in 2009 to 26 m³/s in the North Branch Root River in 2011.

Table 1.10. Long-term and short-term magnitude and (variation) of flows during Rock Bass spawning time period for five streams in the Eastern Broadleaf Province of Minnesota. Maximum values in bold, and minimum values are underlined. Flow magnitude is in m³/s. Flow variation is a coefficient of dispersion.

Long-Term								
Stream Site	2005	2006	2007	2008	2009	2010	2011	2012
Mississippi River at Camp Ripley		184 (0.84)	149 (0.47)	287 (0.47)	163 (0.72)	<u>96</u> (0.54)	332 <u>(0.33)</u>	
Elk River				16 (0.83)	<u>5</u> (0.57)	7 (0.46)	20 <u>(0.39)</u>	19 (0.76)
Straight River				16 (0.87)	7 <u>(0.80)</u>	<u>6</u> (1.63)	18 (1.14)	9 (1.66)
North Branch Root River					9 (0.71)	10 (1.04)	26 (0.38)	<u>6</u> <u>(0.37)</u>
Cedar River	8 (0.58)	9 (0.93)	<u>7</u> (0.66)	13 (0.97)	8 (1.06)	8 (1.11)	17 <u>(0.43)</u>	
Short-Term								
Stream Site	2005	2006	2007	2008	2009	2010	2011	2012
Mississippi River at Camp Ripley		375 (0.12)	237 (0.19)	394 <u>(0.05)</u>	302 (0.09)	<u>192</u> (0.07)	382 <u>(0.05)</u>	
Elk River				31 (0.07)	<u>10</u> (0.14)	14 <u>(0.05)</u>	32 (0.17)	39 (0.32)
Straight River				60 (0.25)	<u>17</u> (0.17)	48 <u>(0.11)</u>	57 (0.27)	42 (0.40)
North Branch Root River					36 (0.20)	29 (0.04)	36 (0.11)	<u>12</u> <u>(0.03)</u>
Cedar River	<u>19</u> (0.14)	23 (0.23)	21 (0.11)	136 (0.25)	39 (0.30)	36 <u>(0.09)</u>	35 (0.12)	

The Mississippi River at Camp Ripley and the Elk River showed the most stable long-term-spawning flows with coefficient of dispersion values < 0.60 for most years, whereas the Straight and Cedar Rivers had the least stable long-term-spawning flows with coefficient of dispersion values > 0.80 in many years.

The highest stability of long-term-spawning flows (coefficient of dispersion = 0.38) were found at the North Branch Root River in 2011 whereas extremely variable flows were found at the Straight, Cedar, and North Branch Root Rivers in 2010.

Extremely variable long-term-spawning flows were also observed in the Straight River in 2011 and 2012, and in the Cedar River in 2009. Similar to long-term-spawning flow magnitudes among streams, short-term-spawning flow magnitudes at the Mississippi River at Camp Ripley were much greater than that of the other four streams. However, unlike with long-term-spawning flow magnitudes, short-term-spawning flow magnitudes at the Mississippi River at Camp Ripley were only 3 times greater than other streams in most years. For the Mississippi River at Camp Ripley short-term spawning flows ranged from $394 \text{ m}^3/\text{s}$ in 2008 to $192 \text{ m}^3/\text{s}$ in 2010. In the other four streams short-term-spawning flows ranged from $10 \text{ m}^3/\text{s}$ in the Elk River in 2009 to $136 \text{ m}^3/\text{s}$ in the Cedar River in 2008. Flows were relatively stable (coefficient of dispersion ≤ 0.40) among streams and years for short-term intervals during the Rock Bass spawning period.

As with flows during the Rock Bass spawning period, flows during the Rock Bass-rearing period varied among streams and years (Table 1.11). Also, as with long-term spawning flows, long-term-rearing flow magnitudes were much greater (at least 11 times greater) at the Mississippi River at Camp Ripley than for the other four streams in most years. Long-term variability of rearing flows was fairly high (coefficient of dispersion > 0.70) among streams and years. The most stable flows (coefficient of dispersion = 0.17) were found in the North Branch Root River in 2012. Extreme flow variability was observed at all streams except for the North Branch Root River in 2011, and was also found in the Mississippi River at Camp Ripley in 2007, and the Cedar River in 2007 and 2011.

Table 1.11. Long-term and short-term magnitude and (variation) of flows during Rock Bass rearing time period for five streams in the Eastern Broadleaf Province of Minnesota. Maximum values in bold, and minimum values are underlined. Flow magnitude is in m³/s. Flow variation is a coefficient of dispersion.

Long-Term								
Stream Site	2005	2006	2007	2008	2009	2010	2011	2012
Mississippi River at Camp Ripley		<u>36</u> (0.61)	55 (1.42)	82 (0.82)	61 (0.94)	138 <u>(0.26)</u>	82 (1.14)	
Elk River				4 <u>(0.26)</u>	<u>3</u> (0.75)	13 (0.71)	6 (1.95)	<u>3</u> (0.69)
Straight River				<u>1</u> (0.75)	2 (0.89)	9 (0.98)	2 (3.53)	2 <u>(0.51)</u>
North Branch Root River					6 (0.84)	11 (0.62)	6 (0.55)	<u>3</u> <u>(0.17)</u>
Cedar River	4 (0.68)	4 <u>(0.54)</u>	8 (1.96)	<u>2</u> (0.55)	3 (0.96)	7 (1.16)	<u>2</u> (1.34)	
Short-Term								
Stream Site	2005	2006	2007	2008	2009	2010	2011	2012
Mississippi River at Camp Ripley		<u>68</u> (0.10)	270 (0.08)	151 <u>(0.06)</u>	170 (0.09)	351 <u>(0.06)</u>	246 (0.07)	
Elk River				<u>6</u> (0.18)	7 (0.11)	26 (0.11)	23 (0.04)	10 <u>(0.01)</u>
Straight River				5 <u>(0.03)</u>	10 <u>(0.03)</u>	205 (0.16)	51 (0.05)	<u>4</u> (0.07)
North Branch Root River					47 <u>(0.01)</u>	115 (0.10)	19 <u>(0.01)</u>	<u>4</u> <u>(0.01)</u>
Cedar River	39 <u>(0.04)</u>	14 (0.10)	63 (0.19)	<u>6</u> (0.13)	25 (0.07)	120 (0.16)	48 (0.05)	

Short-term rearing flow magnitude at the Mississippi River at Camp Ripley was approximately three to four times greater than that of the other four streams among most years. Short-term-rearing flow magnitude ranged from 68 m³/s in 2006 to 138 m³/s in 2010. The short-term-rearing flows at the remaining streams ranged from 4 m³/s in the North Branch Root and Straight Rivers in 2012 to 205 m³/s in the Straight River in 2010. Flows were very stable (coefficient of dispersion < 0.20) in the short-term among streams and years during the Rock Bass rearing period.

Northern Hogsucker spawning flows in the Root River varied among years. Long-term spawning flows ranged from 13 m³/s in 2004 to 59 m³/s in 2008. Flows were most stable in 2005, and least stable in 2004 and 2006 (Table 1.12). Short-term spawning flows ranged from 44 m³/s in 2005 to 111 cm in 2006. Flows for short term intervals in the spawning period were all very stable (coefficient of dispersion < 0.20) among years (Table 1.12).

Similar to flows in the Northern Hogsucker spawning period, flows during the rearing period varied among years in the Root River. Long-term rearing flows ranged from 17 m³/s in 2006 to 30 m³/s in 2007. Long-term flows were most stable in 2005 and 2006, and least stable in 2007 (Table 1.12). Short-term rearing flows ranged from 31 m³/s in 2006 to 355 m³/s in 2007. Short term rearing flows were always very stable in the Root River among years with coefficients of dispersion ≤ 0.20 (Table 1.12).

Associations between Recruitment and Hydrology

Recruitment of nest-building fishes (Smallmouth Bass and Rock Bass) was not significantly related to short-term flow spawning flow magnitude for any of the streams in this study (Table 1.13). Consequently, the data did not support the prediction that recruitment of nest building fishes would be positively related to short-term flow magnitude during the spawning period.

Table 1.12 Long-term and short-term magnitude and (variation) of flows during Northern Hogsucker spawning, and rearing time periods in the Root River, Minnesota. Maximum values in bold, and minimum values are underlined. Flow magnitude is in m³/s. Flow variation is a coefficient of dispersion.

2004	2005	2006	2007	2008
Spawning Period (Long Term)				
<u>13</u> (0.64)	31 <u>(0.25)</u>	46 (0.65)	27 (0.46)	59 (0.59)
Spawning Period (Short Term)				
46 (0.15)	<u>44</u> <u>(0.02)</u>	111 (0.11)	70 (0.09)	96 (0.09)
Rearing Period (Long Term)				
23 (0.63)	19 (0.34)	17 (0.27)	30 (0.79)	22 (0.69)
Rearing Period (Short Term)				
174 (0.20)	75 (0.06)	31 (0.02)	355 (0.13)	272 <u>(0.02)</u>

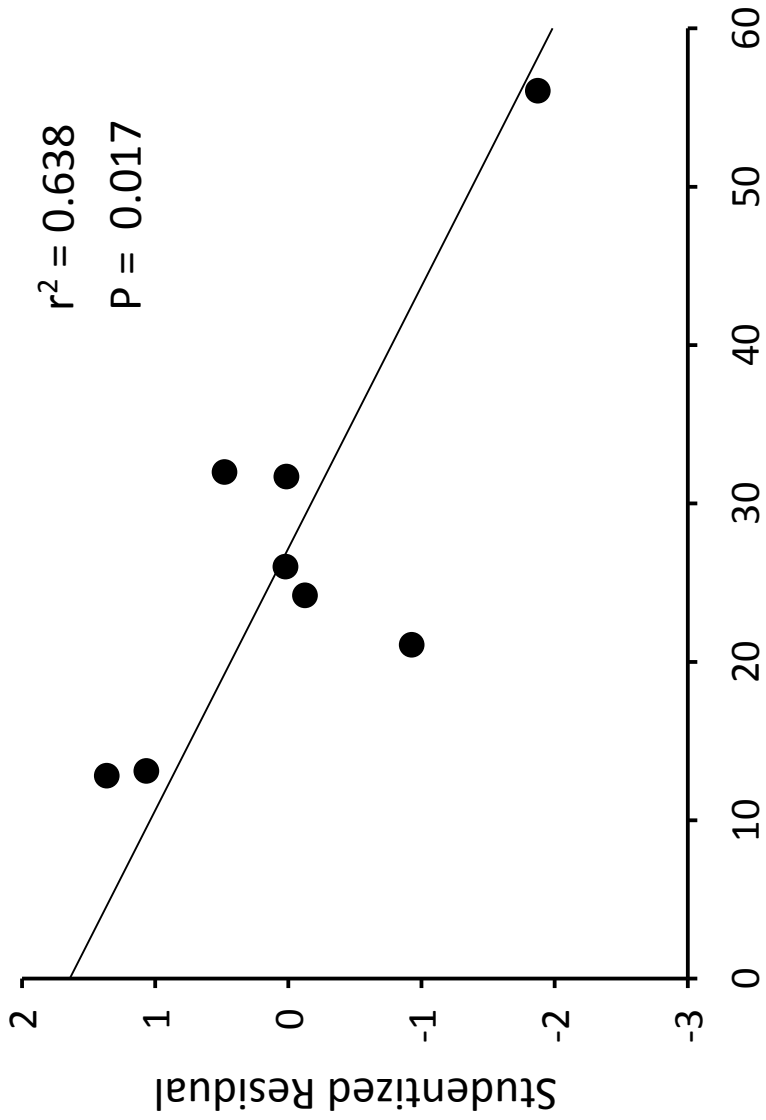
Table 1.13. The number of significant relationships between Smallmouth Bass, Rock Bass, and Northern Hogsucker recruitment (based on spawning and locomotion morphology traits) and the magnitude and variability of streamflows among streams in the Eastern Broadleaf Province of Minnesota. Significance level = 0.025 after Bonferroni Correction.

Hydrologic Parameter	Number of Stream Sites	Positive Relationships	Negative Relationships	No Relationship
Long-Term Magnitude	13	1	3	9
Short-Term Magnitude	13	0	0	13
		(Nest-Builder-Spawning Period)		
Long-Term Magnitude	1	0	0	1
Short-Term Magnitude	1	0	0	1
		(Benthic-Lithophil-Spawning Period)		
		(Cruiser-Rearing Period)		
Long-Term Variation	8	0	2	6
Short-Term Variation	8	0	1	7
		(Maneuverer-Rearing Period)		
Long-Term Variation	5	0	0	5
Short-Term Variation	5	0	0	5
		(Benthic-Hugger-Rearing Period)		
Long-Term Variation	1	0	0	1
Short-Term Variation	1	0	0	1

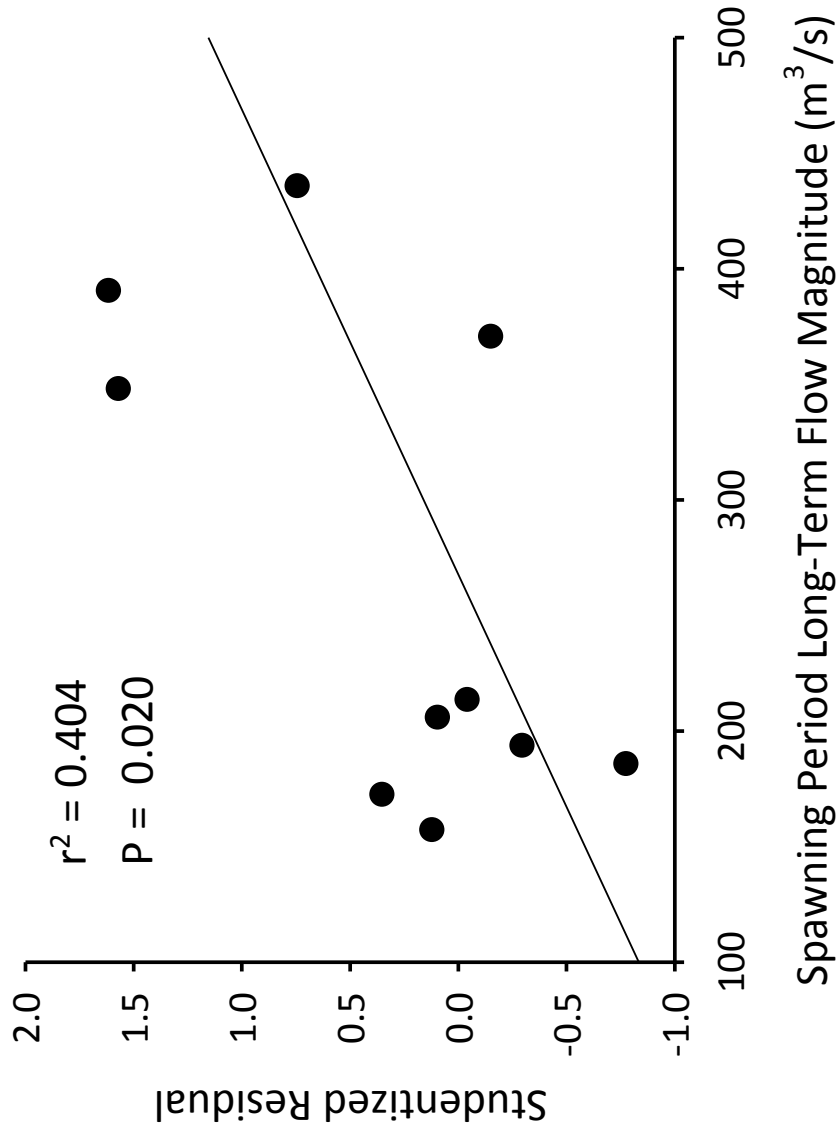
Recruitment among fishes displaying a nesting spawning strategy showed significant relationships with long term magnitude in the spawning period for only 4 of 13 populations (Table 1.13), which showed relatively strong support for the prediction that long-term flow magnitude during the spawning period would not influence recruitment of fishes. Long-term magnitude during the spawning period showed a significant negative relationship with Smallmouth Bass recruitment at the Root River ($r^2 = -0.638$; $P = 0.017$), but a positive relationship at the Mississippi River site at Monticello ($r^2 = 0.404$; $P = 0.020$; Figures 1.5, 1.6). Rock Bass recruitment showed negative relationships with long-term magnitude during the spawning period at the North Branch Root ($r^2 = -0.865$; $P = 0.022$) and Straight Rivers ($r^2 = -0.965$; $P = 0.018$; Figures 1.7, 1.8).

Recruitment of benthic lithophils (Northern Hogsuckers) was not significantly related to short-term flow magnitude ($r^2 = 0.139$; $P = 0.536$) in the spawning period at the Root River. The lack of a relationship between benthic lithophil recruitment and short-term spawning flows in the Root River did not support the prediction that benthic lithophil recruitment would be negatively related to short-term flow magnitude during their spawning period. Recruitment of benthic lithophils was also not significantly related to long-term flow magnitude ($r^2 = -0.028$; $P = 0.789$) in the spawning period at the Root River, which did support the prediction that benthic lithophil recruitment would show no relationship with long-term flow magnitude during the spawning period.

Recruitment of fish with cruiser morphology (Smallmouth Bass) showed a significant negative relationship with short-term rearing flow variability for 1 of 8 streams (*i.e.*, the Mississippi River near Saint Cloud; $r^2 = -0.623$; $P = 0.004$; Figure 1.9), but no relationships at the other seven streams (Table 1.13). Therefore, the data showed little support for the prediction that cruiser recruitment would be negatively related to short-term rearing flow variability.



Spawning Period Long-Term Flow Magnitude (m³/s)
 Figure 1.5. Relationship between Smallmouth Bass (year classes 2004-2011) recruitment for the Root River represented by studentized residuals from a weighted catch curve, and long-term flow magnitude from May-June (spawning period) represented by median flows from 2004-2011.



Spawning Period Long-Term Flow Magnitude (m³/s)
 Figure 1.6. Relationship between Smallmouth Bass (year classes 2000-2012) recruitment for the Mississippi River at Monticello represented by studentized residuals from a weighted catch curve, and long-term flow variation from May-June (spawning period) represented by median flows from 2000-2012.

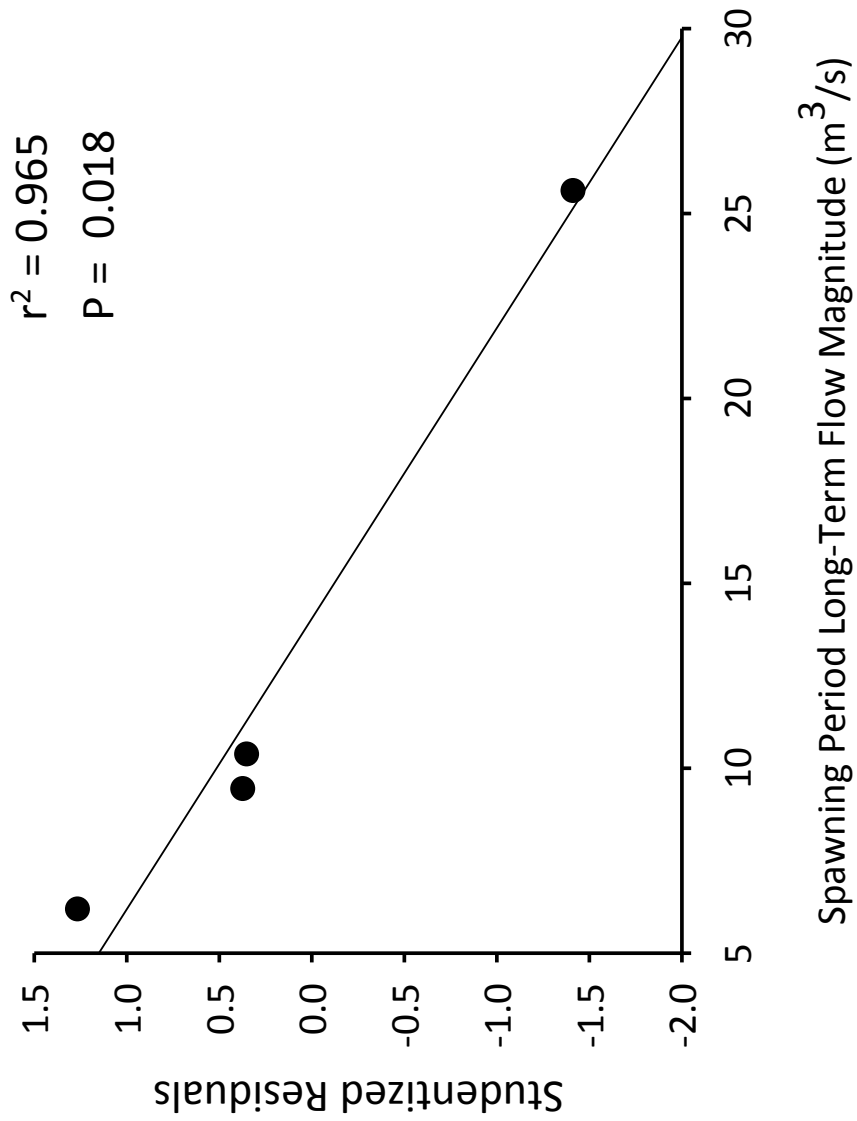
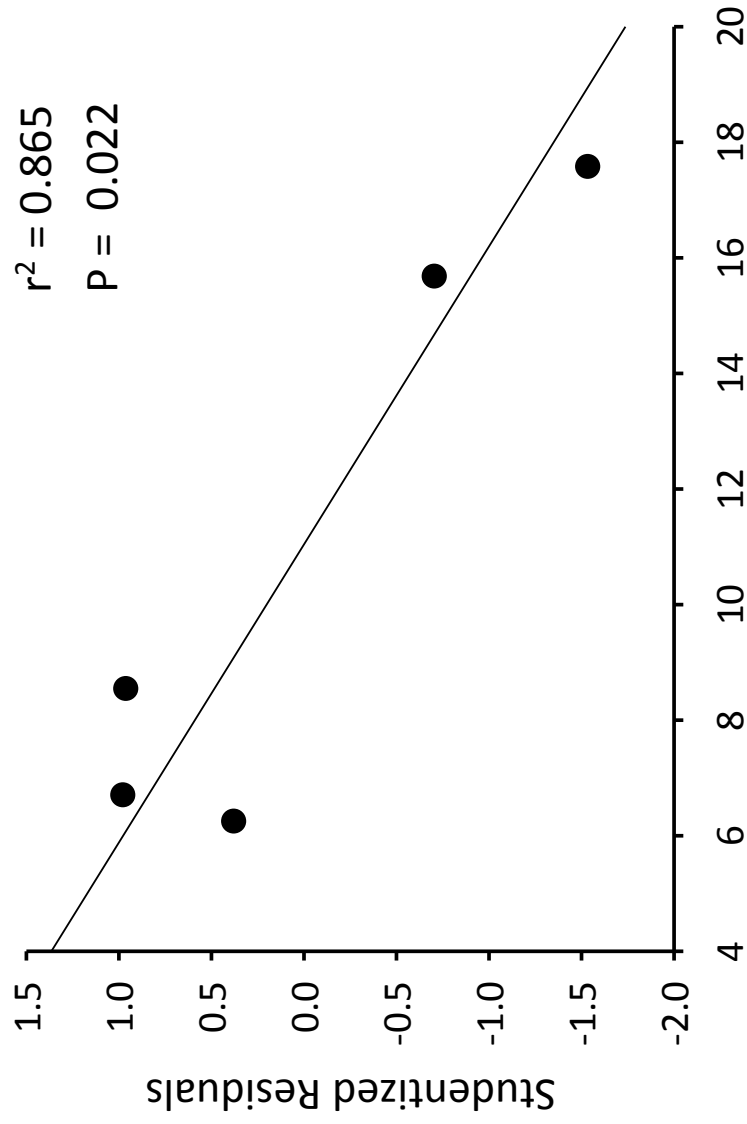
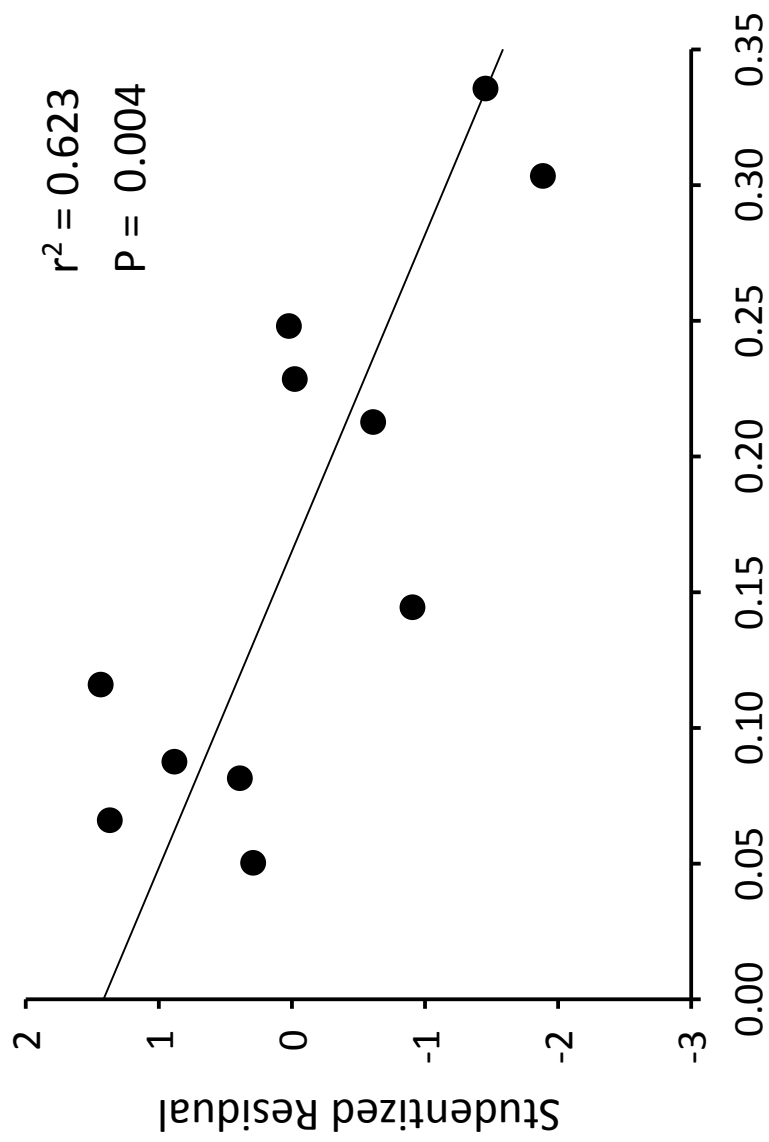


Figure 1.7. Relationship between Rock Bass (year classes 2009-2012) recruitment for the North Branch Root River represented by studentized residuals from a weighted catch curve, and long-term flow magnitude from May-June (spawning period) represented by mean discharge from 2009-2012.



Spawning Period Long-Term Flow Magnitude (m³/s)

Figure 1.8. Relationship between Rock Bass (year classes 2008- 2012) recruitment for the Straight River represented by studentized residuals from a weighted catch curve, and long-term flow magnitude from May-June (spawning period) represented by mean discharge from 2008-2012.



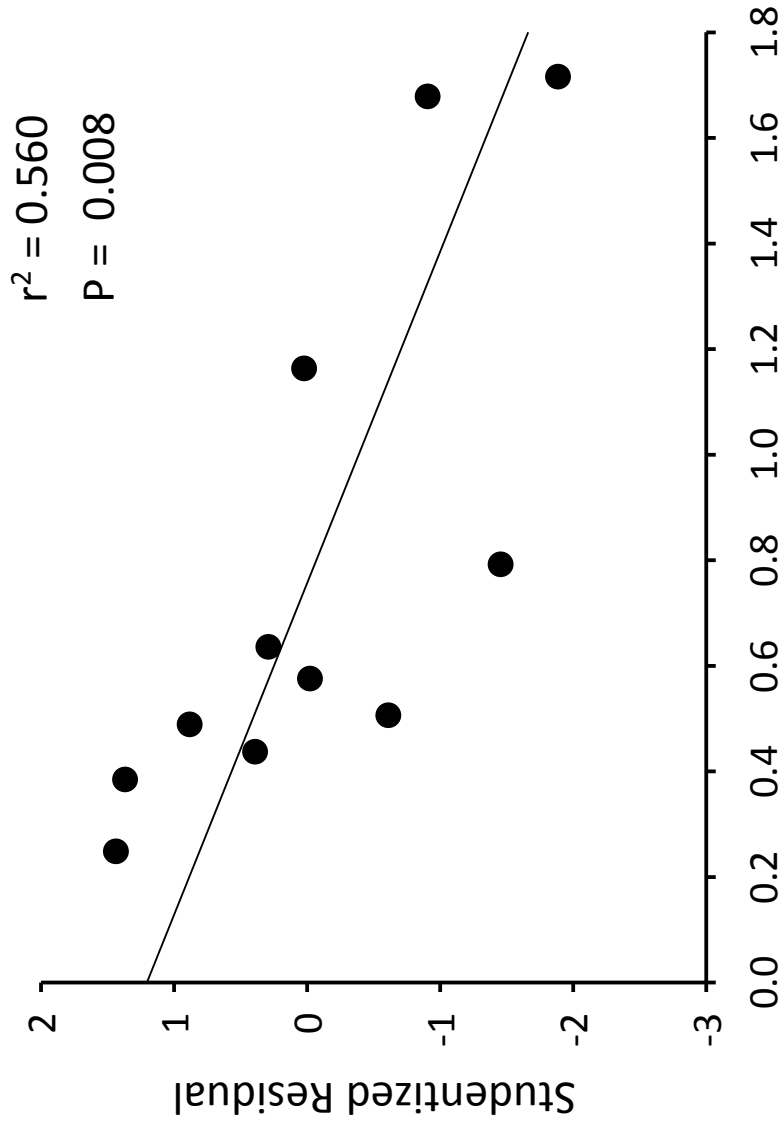
Rearing Period Short-Term Flow Variation

Figure 1.9. Relationship between Smallmouth Bass (year classes 2002-2012) recruitment for the Mississippi River near Saint Cloud represented by studentized residuals from a weighted catch curve, and short-term flow variation from July–November (rearing period) represented by the mean of the minimum 7 day interval coefficients of dispersion from 2002-2012. (See Table 3 for calculation of short term variation hydrologic variables).

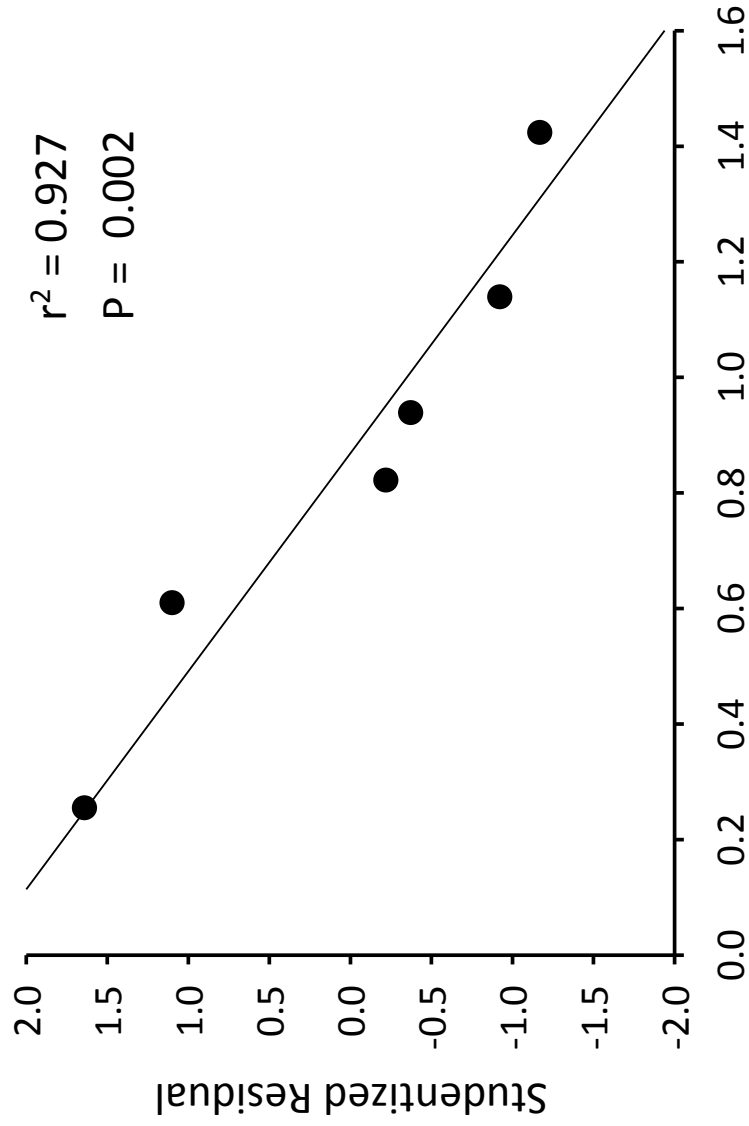
Cruiser fish recruitment was negatively related to long term variability during the rearing period in 2 of 8 streams (Table 1.13): Mississippi River sites near Saint Cloud ($r^2 = -0.560$; $P = 0.008$) and at Camp Ripley ($r^2 = -0.927$; $P = 0.002$; Figures 1.10, 1.11). The two negative relationships between cruiser recruitment and long-term rearing flow variability suggest weak support for the prediction that cruiser recruitment would be negatively influenced by long-term rearing flow variability.

Recruitment of fish displaying maneuverer (Rock Bass) morphology showed no significant relationships with short- or long-term flow rearing flow variability at any of the streams (Table 1.13). The data does not show support for the prediction that short-term rearing flow variability would be negatively related to maneuverer recruitment, but does show support for the prediction that long-term variability of rearing flows would show no relationship with maneuverer recruitment.

Benthic hugger (Northern Hogsucker) recruitment did not show a significant relationship with short- ($P = 0.943$) or long-term ($P = 0.739$) flow variability during the rearing period. This data shows support for the predictions that short-term and long-term-rearing flow variability would show no relationship with the recruitment of benthic huggers.



Rearing Period Long-Term Flow Variation
 Figure 1.10. Relationship between Smallmouth Bass (year classes 2002-2012) recruitment for the Mississippi River near Saint Cloud represented by studentized residuals from a weighted catch curve, and long-term flow variation from July-November (rearing period) represented by coefficients of dispersion from 2002-2012.



Rearing Period Long-Term Flow Variation

Figure 1.11. Relationship between Smallmouth Bass (year classes 2006-2011) recruitment for the Mississippi River at Camp Ripley represented by studentized residuals from a weighted catch curve, and long-term flow variation from July- November (rearing period) represented by coefficients of dispersion from 2006-2011.

Discussion

This study represents the first robust assessment for multiple species representing several populations across multiple rivers) of flow-ecology, fish-recruitment relationships in Minnesota. However, contrary to what others have found (Craven et al. 2010; Peterson and Shea 2014), I found little support for either long-term or short-term flow relationships with recruitment during the adult spawning and juvenile rearing periods. Predictions that were developed according to selected fish traits also showed little support among populations, suggesting minimal explanatory power for flow-recruitment relationships among stream fish in the study area.

Associations between spawning traits and spawning period hydrology

Recruitment of nest building fishes was predicted to show a positive relationship with short-term-spawning flow magnitude. Short-term-high magnitude spates during spawning can flush fine sediments and increase interstitial spaces that are important in protecting and oxygenating developing eggs (Craven et al. 2010). However, short-term-spawning flow magnitude was not significantly related to nest-building fish recruitment at any of my streams. The timing of short-term-high flow spates can often influence their effect on fish reproductive success, as high spates often initiate spawning cues for fishes (Poff et al. 1997; Craven et al. 2010). Although, if short-term-high flows during the spawning period do not coincide with optimal spawning temperatures they may have a minimal impact on fish reproductive success (Humphries et al. 1999). My findings differed from those of Peterson and Shea (2014), who found that short-term spawning period flows in streams of the Flint River Basin in Georgia had a positive effect on the recruitment of nest builders. However, dramatic increases in water withdrawals have occurred in the Flint River Basin since the 1970s to meet growing water demands of the metropolitan Atlanta area, as well as for agricultural irrigation in Southwestern Georgia (Richter et al. 2003). Water withdrawals can decrease flow magnitudes and decrease seasonal variability (Richter et al. 2003; Freeman and Marcinek 2006). Stable

flows and decreased flow magnitudes have been shown to increase the reproductive success of nesting building fish, such as centrarchids (Swenson et al. 2002; Smith et al. 2005).

Short-term spawning period flow magnitude was predicted to show a negative relationship with benthic lithophil recruitment. Due to a lack of parental care, egg and larval stages of broadcast spawning fishes, such as benthic lithophils are especially susceptible to displacement by high flow pulses (Weyers et al. 2003; Craven et al. 2010). Results of my study did not show a significant relationship between benthic lithophil recruitment and short-term flow magnitude, lending no support to the prediction that a negative relationship would be observed between benthic lithophil recruitment and short-term flow magnitude.

My findings conflicted with those of Craven et al. (2010) who found that broadcast spawners, including benthic lithophils, were negatively influenced by short-term-flow magnitude during their spawning periods. Craven et al. (2010) sampled fish in three rivers: the Kankakee River in Illinois, the Flint River in Georgia, and Tallapoosa River in Alabama. However, the majority of broadcast spawning species that Craven et al. (2010) captured were from the Kankakee River in Illinois. The Kankakee River and its tributaries have been channelized to a great degree from its headwaters in Indiana, until shortly before the Momence Wetlands Nature Preserve in Illinois (Kwak 1993). The channelization of the Kankakee River has made spring floods short and more intense than in non-channelized streams (Kwak 1993), which could decrease recruitment by limiting access to floodplain spawning and nursery areas, and displacing eggs and YOY fishes (Simonson and Swenson 1990; Weyers et al. 2003).

Long-term-spawning flow magnitude showed significant relationships with recruitment for only four of 14 populations of nest builders and benthic lithophils combined showing relatively strong support for the prediction that fish recruitment would show no relationship with long-term spawning flow magnitude. The lack of a relationship found between long-term spawning flow magnitude and fish recruitment

among many of failed to corroborate the findings of other studies that found a positive relationship between high spring-summer flows and fish recruitment (*e.g.*, Quist and Guy 1998; Phelps et al. 2010).

Many studies that found a positive relationship between fish recruitment and high flows were conducted on large floodplain rivers (*e.g.*, Raibley et al. 1997; Coutant 2004; Phelps et al. 2010). Predictable flooding in larger rivers (Strahler order >7) allows fishes access to floodplain spawning and nursery habitats and enhances recruitment (Junk et al. 1989; Schlosser 1991). The streams in this study were medium-sized streams and rivers (Strahler order 4-6) with the exception of larger Mississippi River sites. Short and unpredictable pulses in streams and rivers of lower orders make it more difficult for organisms to successfully use floodplain environments (Junk et al. 1989), which could lessen the importance of high flows for fish recruitment in such systems (Bunn and Arthington 2002).

Significant relationships between nest-builder recruitment and long-term - spawning flow magnitude were negative, with the exception of a positive relationship for the Mississippi River at Monticello. High-magnitude flows can scour nests and displace eggs and larvae of nest building fishes, leading to decreased reproductive success (Lukas and Orth 1995; Smith et al. 2005). The mechanism behind the positive relationship between long-term-spawning flows and nest-builder recruitment at the Mississippi River at Monticello was unclear. Recruitment of nest builders could have been influenced by warm-water discharge from a nuclear power plant that flows into the Mississippi River near the sampling area in Monticello. For example, Altena (2003) found that Smallmouth Bass below the warm water discharge near Monticello moved to spawning areas up to a week earlier than those upstream of the discharge. Additionally, in a study of Smallmouth Bass in the Mississippi near Monticello, Swenson et al. (2002) found strong interdependence of temperature and discharge that suggested that relationships to year class strength identified by linear regression could be due to the composite influence of several variables. Further research aimed at identifying multiple

variables contributing to year class strength of nest building fishes near Monticello could help explain the exact mechanisms affecting their recruitment.

Associations between locomotion morphology and rearing period hydrology

Cruiser recruitment was predicted to be negatively related to short-term-rearing flow variability. Cruiser fishes are often found in the water column where they are more likely to be displaced into unfavorable habitat (*e.g.*, drying pools, deeper pools with more piscivorous predators) during flashy flows, leading to death from causes such as suffocation and predation (Craven et al. 2010; Cocherell et al. 2011; Peterson and Shea 2014). However, recruitment of cruisers was only negatively related to short-term rearing flow variability in one of the eight populations in my study, while the remaining five populations did not show any relationship. These results show very little support for the prediction that cruiser recruitment would be negatively related to short-term rearing flow variability. My findings failed to corroborate with those of Craven et al. (2010), and Peterson and Shea (2014), who found negative relationships between cruiser recruitment and short-term rearing flow variability.

The river basins where Craven et al. (2010) and Peterson and Shea (2014) conducted their studies, namely the Kankakee, Tallapoosa, and Flint basins, are subject to increased amounts of water appropriation for municipal and agricultural uses (Kwak 1993; Irwin and Freeman 2002; Ruhl 2005). Water withdrawals can accelerate stream drying, which could lead to fish stranding mortality during sharp falls in stream flow (Grantham et al. 2012). It should be noted that some streams in my study also experienced water appropriations for agriculture (such as the Root River; Minnesota Pollution Control Agency 2012), however the intensity of these withdrawals may have been less severe in my streams than those examined by Craven et al. (2010) and Peterson and Shea (2014).

The only negative relationship found between short-term rearing flow variability and cruiser recruitment was in the Mississippi River near Saint Cloud. Hydropower

operations upstream of my study reaches near Saint Cloud could have intensified short-term variability in the rearing period. Flashy flows created by hydropower generation may reduce stable shallow water habitats that YOY fishes depend on for refugia, which could lead to decreased survival (Freeman et al. 2001).

I predicted that recruitment of fish with maneuverer locomotion morphology would be negatively related to short-term rearing flow variability. Fish species that exhibit maneuverer locomotion morphologies are not adapted to maintain position in turbulent currents created by flashy high flow pulses and may be displaced to unfavorable areas (Bernardo et al. 2003), which can reduce fish recruitment (Cocherell et al. 2011). Contrary to my prediction, my results showed that recruitment of fishes displaying maneuverer recruitment was not related to short-term rearing flow variability among streams. Some maneuverer fish, such as Rock Bass and some *Lepomis spp.* often use deeper, more structurally complex habitats that exhibit greater than average resiliency to stage declines and flashy flows, which could protect them from displacement into harsh habitats and increase survival rates (Probst and Rabeni 1984; Dutterer and Allen 2008).

Long-term-rearing flow variability was predicted to be negatively related to the recruitment of cruisers. Similar to my prediction for short-term-rearing flow variability and cruiser recruitment, the prediction of a negative relationship between cruiser recruitment and long-term-rearing flow variability was based on the assumption that cruiser species tend to occupy the water column and would be more easily displaced during flashy, high flows (Craven et al. 2010). My results showed negative relationships between cruiser recruitment and long-term-rearing flow variability for only two of eight populations, which did not support my prediction. Many fishes have adapted to long-term variability in stream flows, which is often related to the natural flow regime of a stream or river (*e.g.*, utilization of floodplain habitat for refugia, increased streamlining of body shapes). Such adaptations may make them less susceptible to reduced

recruitment from long-term flow variation during the rearing period (Lytle and Poff 2004; Brinsmead and Fox 2002).

Negative relationships found between long-term-rearing flow variability and cruiser recruitment were in the Mississippi River sites at Camp Ripley and near Saint Cloud. Long-term variation in streamflow in temperate streams and rivers is largely driven by seasonal floods and drought conditions that may vary in intensity on an inter-annual basis (Tockner et al. 2000). High flows during the rearing period of fishes may negatively impact their recruitment (Buynak and Mitchell 2002; Smith et al. 2005).

Long-term variability of rearing flows was not related to maneuverer recruitment in any of my streams, which supports my prediction. As previously discussed, many fishes have adapted to long-term variability in stream flows, which is often related to the natural flow regime of a stream or river. These adaptations may influence the behaviors and body shapes of fishes, making them less susceptible to long-term flow variation (Lytle and Poff 2004; Brinsmead and Fox 2002). Additionally, many maneuverers may use cover that is more resilient to the effects of flow variation, protecting them from any negative effects it may have on their recruitment (Dutterer and Allen 2008).

Benthic hugger recruitment showed no relationship to either long- or short-term-rearing flow variability, which supports my prediction. Peterson and Shea (2014) found that species displaying benthic-hugger-locomotion morphology were the least sensitive to rearing-flow variability when compared to species with other types of morphologies. Benthic fishes that have hugger morphology are often able to avoid swimming directly against the current by positioning themselves in the low flow boundary layer near the stream's bottom substrate, which can help them maintain position during sudden spikes in stream flow (Meyers and Belk 2014). Additionally, YOY benthic huggers often exploit cover provided by boulders and debris to avoid displacement into sub-optimal habitat (Kennedy and Vinyard 2006; White and Harvey 2003), such as areas prone to drying up in highly variable flows.

My results showed little evidence that flow magnitude and variability affected fish recruitment among selected streams in the Eastern Broadleaf Province of Minnesota. Factors such as the quantity and quality of available refuge and feeding habitats, as well as temperature regimes could have affected fish recruitment in the streams in this study (Schlosser 1991; 1995; Nunn et al. 2003). Additionally, aspects of the flow regime not quantified in this study, such as the timing, duration, and frequency of flows may have had an influence on recruitment among streams (Poff et al. 1997; Humphries et al. 1999; Durham and Wilde 2009). Further research may help to uncover the exact mechanisms driving fish recruitment in the streams of the Eastern Broadleaf Province.

CHAPTER II-FISH GROWTH RESPONSE TO HIGH FLOW DURATION

Introduction

The growth of fishes determines several aspects of their ecology, such as vulnerability to predation, sexual maturation, and recruitment into a population (Murphy and Willis 1996). Growth can be defined as the addition of biomass by individuals over a specific time interval (*e.g.*, daily, and annual growth). It can be accrued to the population, and is generally measured as an increase in length or a change in weight (Murphy and Willis 1996). During a fish's first year of life, faster growth can increase body size, and confer a host of advantages over slower growing conspecifics. At a time when mortality is typically high (Garvey et al. 1998), a larger size can reduce predation risk through improved swimming ability, reduce vulnerability to gape limited predators, and lower the risk of starvation through enhanced feeding opportunities. In northern latitudes, faster growth, leading to a larger fall body size of age-0 fishes, is especially important. Fish with a larger fall body size have more abundant energy reserves than smaller fish, which can aid survival through harsh winter conditions (Garvey et al. 1998; Graeb et al. 2004).

Minnesota fishes experience the largest amount of annual growth during summer, followed by progressively slower growth through fall, and into winter (Lux 1960; Dieterman et al. 2012). As a result, the window for age-0 fishes to grow to a body size sufficient for winter survival lies predominantly in the summer season (Simonson and Swenson 1990; Cunjak 1996). Factors such as food availability and temperature can affect inter-annual growth of age-0 fishes during the summer season (Neuheimer and Taggart 2007; Kaemingk et al. 2012). For example, Kaemingk et al. (2012) found that age-0 Bluegill Sunfish *Lepomis macrochirus* growth was significantly faster in a year with higher summer densities of *Daphnia* spp. compared to years with lower densities. An increase in the annual number of "growing degree days" can also affect fish growth.

A positive relationship exists between fish growth and the number of growing degree days, because a growing degree day represents a daily interval when temperatures are in the range where metabolic reaction rates are near linear functions of temperature (Neuheimer and Taggart 2007).

In lotic systems, stream flow has been identified as another important factor affecting fish growth (Buynak and Mitchell 2002; Jacquemin et al. 2014). Stream flow conditions can be defined by five components: magnitude, frequency, timing, duration, and rate of change of flow (Richter et al. 1996; 1997). Magnitude is the amount of water moving past a fixed location per unit time. Frequency refers to how many times a flow exceeds or falls below a certain magnitude (*e.g.*, overbank flooding) over a specified time interval. Timing is the Julian day when flows reach a given magnitude and help quantify the overall predictability of flows. Duration is the period of time that a specific flow magnitude lasts, and rate of change refers to how quickly flow rises or falls (*e.g.*, cubic feet/second/day). Magnitude, frequency, duration, timing, and rate of change of flows are used to characterize the entire range of flows, including specific hydrologic phenomena, such as low flows, high flows, and flood events (Figure 2.1; Poff et al. 1997).

High flows, defined as daily flows exceeding the 75th percentile, have been linked to increased growth among several species of stream dwelling fishes (Peterson and Jennings 2007; Grabowski et al. 2012, Quist and Spiegel 2012). High flows can inundate a river's floodplain and increase growth in some fishes by increasing access to floodplain feeding habitats and providing refuge from high velocities in the main river channel (Gutreuter et al. 1999; Sammons and Maceina 2009; Quist and Spiegel 2012). However, high flows can also lead to increased metabolic costs and reduced feeding efficiency in some fishes, leading to decreased growth (Grant and Noakes 1987; Weyers et al. 2003). Larval and juvenile fishes can be especially sensitive to high flows due to their weak swimming abilities and reduced metabolic reserves (Schlosser 1991; Weyers et al. 2003).

High flows may also be associated with increased suspended sediment concentrations (Bond and Downes 2003). High suspended sediment concentrations can decrease feeding efficiency of sight feeding fishes, and upon settling, can cover coarse substrates that makes important benthic habitat inaccessible for many invertebrate prey (Nerbonne and Vondracek 2001; Shaw and Richardson 2001; Robertson et al. 2006).

In the last three decades, many upper Midwestern rivers have exhibited an increase in the magnitude of most monthly median flows, along with an increase in the duration of those high flows (Lenhart et al. 2013). For example, Lenhart et al. (2013) found that the magnitude and duration of June and July high flows have greatly increased between the early 1980s and early 2000s for some Southern Minnesota streams. The state of Minnesota has an abundance and diversity of riverine resources that support important recreational fisheries, aquatic biodiversity, unique aquatic habitats, and ultimately economic and social benefits (Blann and Kendy 2012).

The Eastern Broadleaf Province of Minnesota is an especially important lotic region in the state. It is a transition zone between the prairie to the west and the mixed coniferous-deciduous forest to the northeast (Figure 2.1). Row crop agriculture is one of the major land uses in the province (Minnesota Department of Natural Resources 2006). The Eastern Broadleaf Province of Minnesota also includes many of the premiere recreational warmwater stream fisheries in the state for Smallmouth Bass *Micropterus dolomieu*, Rock Bass *Ambloplites rupestris*, and Walleye *Sander vitreus* (Thorn and Anderson 1999). Increasing amounts of land devoted to agriculture and urban development in the province has increased the magnitude and duration of high flows in early summer, and winter (Blann and Kendy 2012; Lenhart et al. 2011; 2013). However, the effects of land use change and associated stream flow alteration on stream fish growth in the province is unknown.

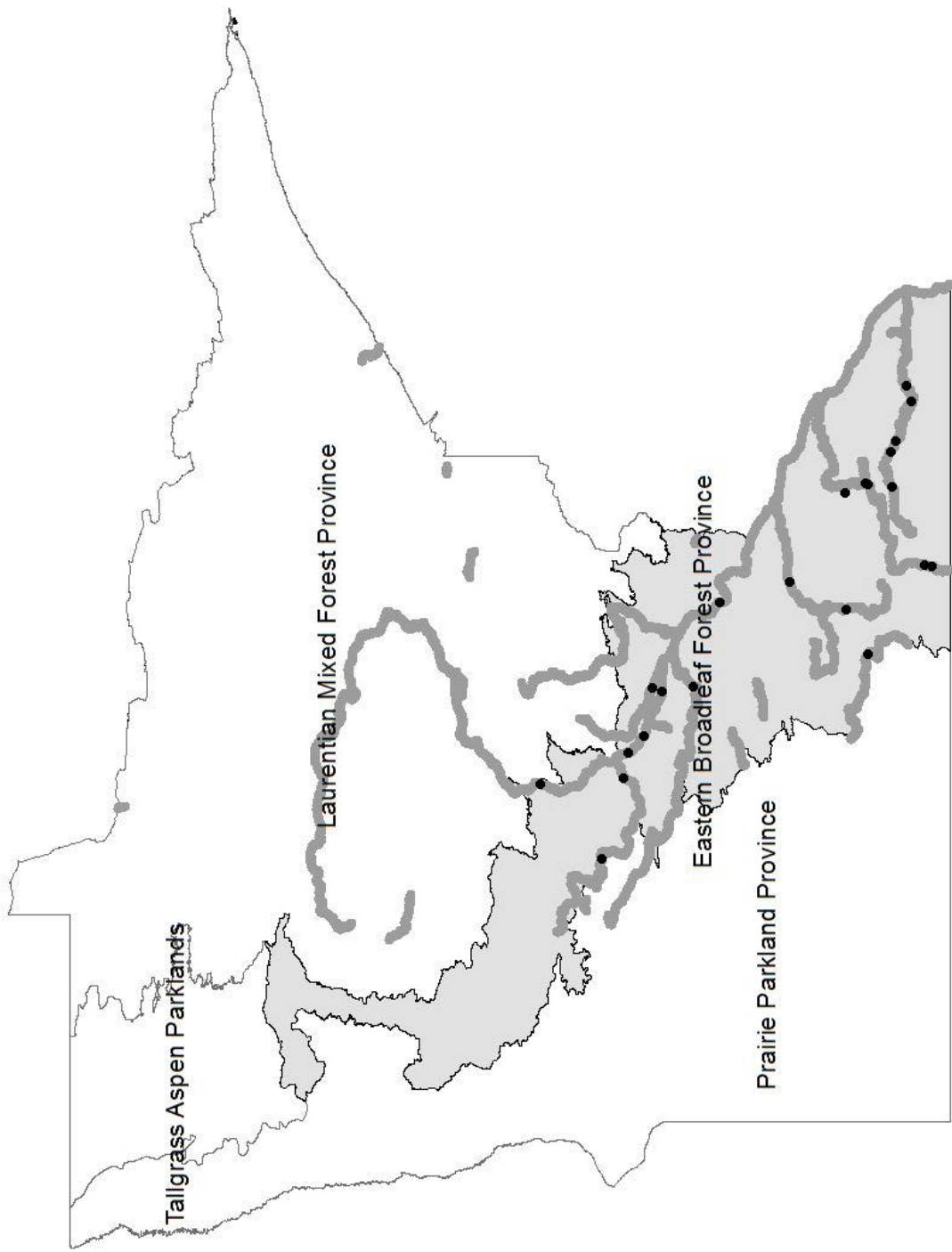


Figure 2.1. Map of the Ecological Provinces of Minnesota and the streams and stream sites (represented by black dots) sampled to assess stream fish growth in this study.

In light of the current trend in stream flow, water managers require information on the impact that land use influenced flow alterations has on fish population dynamics. Consequently, identification of relationships between fish growth and stream flow parameters is important for adequate water management to benefit fish populations. To identify these relationships I: 1) quantified inter-annual growth of selected stream fish populations, 2) quantified inter-annual duration of summer (June-September) high flows, and 3) assessed relationships between duration of summer high flows and inter-annual growth of selected fishes in several populations representative of streams within the Eastern Broadleaf Province of Minnesota.

Hypotheses:

- H₀: Fish growth will show no significant relationships with duration of summer high flows.
- H_{a1}: Fish growth will show significant positive relationships with duration of summer high flows at each stream regardless of species.
- H_{a2}: Fish growth will show significant negative relationships with duration of summer high flows at each stream regardless of species.

Methods

Study sites were chosen from representative streams and rivers within the Eastern Broadleaf Province that were publicly accessible, and were within 50 km of an adequate hydrologic gage. An adequate gage had discharge data for the years 2000-2012 and did not have a major dam between it and the study site. Discharge records from 2000-2012 were needed so that all growth years of fishes captured in this study were included within the hydrologic period of interest. Gages with a dam between them and the site of interest were excluded, as dams can often alter river hydrology (Braatne et al. 2008). However, I did include three sites that did not have an adequate gage, namely the Middle Fork Zumbro, Silver Creek, and Sauk River site near Melrose.

These sites were included to compare factors affecting stream-fish growth among sites in the same geographical region, but relationships between stream flow and fish growth were not investigated for the three sites. In some cases when more than one site was randomly selected on a particular river or stream within 50 river km, and not separated by a dam, fish growth data from those sites were combined to better represent the fish population. A total 18 sites were selected after combining sites within 50 river km (Table 2.1).

Smallmouth Bass, Rock Bass, and Northern Hogsuckers *Hypentelium nigricans* were the three species chosen to investigate relationships between fish growth and duration of summer high flows. These three species are common stream dwelling fish within the Eastern Broadleaf Province. Also, Smallmouth Bass and Rock Bass are considered to be important sport fish in Minnesota's rivers and streams.

To quantify inter-annual growth, stream fishes were captured with electrofishing gear; measured and a hard (calcified) part body structure was removed for aging. Sagittal otoliths were used to age Smallmouth Bass and Rock Bass, while pectoral fin rays were used to age Northern Hogsucker (Maceina and Sammons 2006; Reid 2007). Procurement of pectoral fin rays from Northern Hogsucker was possible without the need to sacrifice fish, but euthanasia was necessary to obtain sagittal otoliths from most Smallmouth Bass and Rock Bass. Fishes were euthanized by immersion in an overdose of MS-222 (tricaine-methanesulfonate; 250-500 mg/L; Topic-Popovic et al. 2012).

Incremental growth of individual fish was quantified using back calculated length at age, which was the proportion between the total length of the fish and the radius from the age structure focus to each annulus (Busacker et al. 1990). The Dahl-Lea method of back-calculation was used in this study, because it assumes a direct proportional (1:1) relationship between incremental increases in fish length and hard body part, which is applicable to the use for calcified structures that form at fish hatch (DeVries and Frie 1996).

Table 2.1. Stream site locations in the Eastern Broadleaf Province of Minnesota sampled in June-September of 2012 and 2013, including associated latitude and longitude coordinates (decimal degrees), 75th percentile of annual flows, upstream drainage area, and Gage I.D. (All gages are United States Geological Survey gaging stations, unless noted as a dam. NA = Not Available).

Stream Site	Location Description	Latitude and Longitude (dd)	75 th Percentile of Flows (m ³ /s)	Upstream Drainage Area (km ²)	Stream Width (m)	Gage I.D.
Cannon River	Upstream of Lake Bylesby	44.5042 -93.0776	607	2,478	30	Northfield Dam
Cedar River	Near Austin, MN	43.6372 -92.9744	344	1,033	26	05457000
Crow River	at Rockford, MN	45.1016 -93.7265	1,740	6,939	45	05280000
Elk River	Near Big Lake, MN	45.3588 -93.7382	330	1,435	19	05275000
Le Sueur River	Near Waseca, MN	44.0157 -93.5287	868	495	9	05320500
Middle Fork Zumbro River	Near Oronoco, MN	44.1525 -92.5201	NA	1,125	24	NA
Mississippi River	At Camp Ripley, MN	46.0600 -94.3397	6,045	28,852	175	05242300 + Sylvan Dam
Mississippi River	At Monticello, MN	45.2965 -93.7592	8,300	36,493	148	05270700
Mississippi River	At Pool 1	44.9356 -93.1991	12,250	51,291	237	Lower Saint Anthony Dam
Mississippi River	Near Saint Cloud, MN	45.5147 -94.1396	8,300	36,075	159	05270700
N.B. Root River	Near Cummingsville, MN	43.8710 -92.2599	445	600	22	05383950
Root River	Near Peterson, MN	43.7742 -91.8474	912	2,489	36	05385000
Rum River	Near Saint Francis, MN	45.3277 -93.3722	798	3,619	40	05286000
Sauk River	Near Saint Cloud, MN	45.5376 -94.2960	566	2,668	34	05270500
Sauk River	At Melrose, MN	45.6771 -94.7996	NA	1,642	19	NA
Silver Creek	At Rochester, MN	44.0285 -92.4543	NA	51	10	NA
South Fork Zumbro River	At Rochester, MN	44.0142 -92.4637	225	670	15	05372995
Straight River	Near Owatonna, MN	44.1483 -93.2448	351	649	20	05353800

The Dahl-Lea method back-calculates length at age according to the equation $L_i = (R_i/R_c)L_c$, where L_i = length at the i th increment, L_c = length at time of capture, R_i = radius of hard body part at the i th annulus, and R_c = radius of hard body part at time of capture (Dahl 1909; Lea 1910).

To estimate inter-annual growth of selected fish species, back-calculated values of incremental fish growth at age were entered into mixed effects growth models developed by Weisberg et al. (2010). The Weisberg Mixed-Effects Growth Model estimates growth more accurately than the Dahl-Lea model, because the mixed model accounts for growth effects due to individual fish, cohorts (year-classes), and years, instead of just accounting for age effects like the Dahl-Lea model. Weisberg et al. (2010) developed linear fixed-effects and mixed-effects (additive error terms) models to describe fish growth as a function of fish age and growth year. Independent variables used for the mixed models were fish age, growth year, an individual fish growth factor and cohort. Fish age accounts for differential growth rates among fishes of distinct age groups, and growth year quantifies growth of fishes in each year across age groups. The individual fish growth factor allowed each fish to have its own growth rate that applied to all growth increments for that fish, and was compared to the growth rates of all other individual fish in the model. Age was considered a fixed effect in the models, while growth year and the individual fish growth factor were considered random effects (Weisberg et al. 2010). Growth analyses were restricted to fish age 12 and less in the 2000-2012 year classes. Years with only one growth year data point (*i.e.*, one fish for a given year) were excluded.

Three candidate mixed-effects growth models were developed and compared for each species.

Model One: Growth \sim Age Effect + Individual Fish Effect

Model Two: Growth \sim Age Effect + Individual Fish Effect + Year Effect

Model Three: Growth \sim Age Effect + Individual Fish Effect + Year Effect + Cohort

Model One indicated that variation in fish growth was due to fixed age-effects (*e.g.*, younger fish growing faster than older fish), and random individual-effects only (*e.g.*, certain fish have a genetic predisposition to grow faster, and/or differences in growth between sexes). Model Two described growth variation in fishes due not only to age- and individual-effects, but also year-effects (*i.e.*, fishes, of all cohorts, grew faster in certain years; Nelson 2015). Model Three was a modification of a model presented by Weisberg et al. (2010), where a cohort-effect (age-year) was substituted for the interaction term. The model accounted for repeated measures of the same cohort (fish born in the same year) over time, and deflated growth impacts of cohort contribution. This cohort effect indicated that different age groups grew differently in each year (Nelson 2015).

Akaike's information criterion (AIC) was used to compare candidate models. To correct for small sample size and overfitting of models, a second-order bias correction (AICc) was applied when n/K was less than 40 for the model with the largest K (Burnham and Anderson 2004). Criterion differences (Δ_i) were considered meaningful for model selection of candidate models and were the difference between each model and that of the best approximating model (*i.e.*, the model with the lowest Δ_i ; Burnham and Anderson 2004; Nelson 2015). Criterion differences provide a ranking scheme for all models in comparison to the best model. Generally, models having Δ_i from 0 to 2 are showing similar levels of support, models with Δ_i values from 2 to 4 show some support, models having Δ_i from 4 to 7 show considerably less support, and models with $\Delta_i > 10$ essentially show no support (Burnham and Anderson 2004; Nelson 2015). Among competing candidate models, the model with the lowest AICc was selected, as it was considered to be the most parsimonious model. However, if AICc values were less than 2 for more than one model, the model with the fewest terms was selected.

The growth of each fish species was only tested in hydrologic models if the final selected growth model contained a year-effect (*i.e.*, model 2 or model 3). Growth results were interpreted as deviations (+/-) from a mean of zero, not as positive or

negative growth. By using this technique, all components of each growth model contribute to the predicted growth increment for each year and are the differences between the observed and predicted values (Davis-Faust 2012). A minimum of four years with a growth year-effect was required for testing relationships to hydrology variables to achieve adequate sample size for regression analysis.

To quantify inter-annual differences in duration of summer (June-September) high flows, daily discharge data near sampling sites was obtained from the U.S. Geological Survey's National Water Information System Website (<http://waterdata.usgs.gov/mn/nwis/rt>), and hydroelectric dam data from county databases. Summer high flow duration was quantified as the maximum number of consecutive days from June-September for which flow exceeded the 75th percentile of stream flow magnitude. Thresholds for the 75th percentile of stream flow magnitude were calculated from 20 years of continuous daily flow data for each site, with the exceptions of the Mississippi River site at Camp Ripley, Cannon River site, and the North Branch Root River, which were calculated with 16, 12, and 10 years of continuous daily flow data, respectively. Richter et al. (1997) recommended a period of at least 20 years for the assessment of current hydrologic conditions to dampen effects of inter-annual climatic variation. However, Poff et al. (2010) indicated that continuous daily discharge records of at least 10 years duration can be used to characterize current conditions when faced with an inadequate period of record.

To test associations between yearly growth estimates (dependent variables) and summer high flow duration (independent variables), I used univariate least squares regression. For each fish species, regressions were developed and tested independently for each population that exhibited a year effect to assess spatial repeatability of predictions. Years were replicates in all regressions. A Shapiro-Wilk test was used to detect significant departures from normality, and a Breusch-Pagan test was used to examine the constant variance assumptions for each regression analysis. An alpha value

of 0.10 was chosen to determine statistical significance. All regressions were performed using R 3.1.3 statistical software (R Core Team 2015).

Results

A total of 533 Smallmouth Bass, 317 Rock Bass, and 230 Northern Hogsuckers were captured across the 18 stream sites. Smallmouth Bass were captured at 14 of the 18 sites, but the minimum of five fish age one and older required to run growth models was only obtained at 12 of those 14 sites. The highest numbers of Smallmouth Bass were captured at the Mississippi River at Monticello and the lowest at the Cedar River near Austin. Smallmouth Bass lived longest at Mississippi River sites near Saint Cloud and Monticello, with age classes up to 11 and 12, respectively (Appendix 4). Rock Bass were captured at 14 of the 18 sites, however, the minimum of five fish age one and older was only obtained at 9 of those 14 sites. The greatest numbers of Rock Bass were captured at the Cedar River while the lowest numbers were captured at the Sauk River at Melrose. Rock Bass had the longest life spans at the Cedar River and the Mississippi River at Camp Ripley, which both had age classes up to age six (Appendix 5). Northern Hogsuckers were captured at 9 out of 18 streams, but only 7 of those 9 streams had the minimum of five fish age one and over. The highest numbers of Northern Hogsuckers were captured at the Root River and the lowest numbers were captured at the Cedar River. The Root River exhibited the greatest longevity for Northern Hogsuckers, with age classes up to eight (Appendix 6).

Growth

Smallmouth Bass growth was only influenced by age- and individual- effects (Model 1) in seven of 12 populations. The Crow River site, Mississippi River sites near Monticello, and at Pool 1, North Branch Root River, and Rum River all exhibited year-effects in growth (Table 2.2).

Table 2.2. Factors affecting Smallmouth Bass growth based on mixed effects growth models with associated K (number of model parameters), AICc, Δ AIC, and AICc Weights. The model with the best fit is bolded, while models with growth year effects are highlighted in gray.

Stream	Model	K	AICc	Δ AIC	AICc Wt
	Growth=Age+Individual	7	465.99	0.00	0.72
Cannon River	Growth=Age+Individual+Year	8	468.30	2.31	0.23
	Growth=Age+Individual+Year+Cohort	9	471.17	5.18	0.05
	Growth=Age+Individual	7	149.45	0.00	1.00
Cedar River	Growth=Age+Individual+Year	8	161.58	12.13	0.00
	Growth=Age+Individual+Year+Cohort	9	179.78	30.33	0.00
Crow River	Growth=Age+Individual+Year	7	295.01	0.00	0.85
	Growth=Age+Individual+Year+Cohort	8	298.46	3.45	0.15
	Growth=Age+Individual	6	312.46	17.35	0.00
Middle Fork Zumbro River	Growth=Age+Individual	13	586.75	0.00	0.80
	Growth=Age+Individual+Year	14	589.86	3.11	0.17
	Growth=Age+Individual+Year+Cohort	15	593.09	6.34	0.03
Mississippi River at Camp Ripley	Growth=Age+Individual	11	707.81	0.00	0.74
	Growth=Age+Individual+Year	12	710.60	2.79	0.18
	Growth=Age+Individual+Year+Cohort	13	712.24	4.43	0.08
Mississippi River at Monticello	Growth=Age+Individual+Year+Cohort	17	3236.55	0.00	1.00
	Growth=Age+Individual+Year	16	3264.90	28.34	0.00
	Growth=Age+Individual	15	3287.96	51.40	0.00
Mississippi River at Pool 1	Growth=Age+Individual+Year	11	1012.40	0.00	0.72
	Growth=Age+Individual+Year+Cohort	12	1014.83	2.43	0.21
	Growth=Age+Individual	10	1017.16	4.76	0.07
Mississippi River near Saint Cloud	Growth=Age+Individual	14	1687.77	0.00	0.71
	Growth=Age+Individual+Year	15	1690.09	2.32	0.22
	Growth=Age+Individual+Year+Cohort	16	1692.43	4.66	0.07
North Branch Root River	Growth=Age+Individual+Year	10	845.50	0.00	0.70
	Growth=Age+Individual+Year+Cohort	11	847.22	1.72	0.30
	Growth=Age+Individual	9	862.81	17.31	0.00
Root River	Growth=Age+Individual	11	1244.22	0.00	0.63
	Growth=Age+Individual+Year	12	1245.79	1.57	0.29
	Growth=Age+Individual+Year+Cohort	13	1248.19	3.96	0.09
Rum River	Growth=Age+Individual+Year	16	809.74	0.00	0.81
	Growth=Age+Individual+Year+Cohort	17	812.72	2.97	0.18
	Growth=Age+Individual	15	821.84	12.10	0.00
Sauk River near Saint Cloud	Growth=Age+Individual	15	808.12	0.00	0.54
	Growth=Age+Individual+Year	16	809.06	0.93	0.34
	Growth=Age+Individual+Year+Cohort	17	811.05	2.93	0.12

Model 3 was selected for the Mississippi River site at Monticello, suggesting that variation in growth was due to age-effects, individual-effects, year-effects, and that different cohorts grew differently in each year. Model 2 was selected for the Crow River site, Mississippi River site at Pool 1, North Branch Root River, and Rum River sites, indicating that variation in Smallmouth Bass growth at these sites was due to a combination of age-, individual-, and year-effects (Table 2.2).

Smallmouth Bass growth appeared to decrease consistently with age, and by age four, incremental growth decreased at all sites by 50 percent or more from what it was at age one (Table 2.3). The Mississippi River sites near Saint Cloud, Monticello, and at Camp Ripley, as well as the Sauk River near St. Cloud had particularly high incremental growth from ages one to four when compared to other sites. Conversely, the Cedar River, North Branch Root River, and Root River had particularly low incremental growth from ages one to four when compared to other sites (Table 2.3).

Similar to Smallmouth Bass growth model selection, Model 1 was selected for Rock Bass growth at a majority of stream sites. Consequently, variation in Rock Bass growth for most stream sites seemed to be mainly due to age- and individual-fish effects (Table 2.4). The Cedar River, Mississippi River site at Camp Ripley, and Straight River were the only sites that displayed year-effects among the nine sites where mixed-growth models were made for Rock Bass. Model 2 was selected for the Cedar River and Straight River site, while Model 3 was selected for the Mississippi River site at Camp Ripley (Table 2.4).

As with Smallmouth Bass growth, the incremental growth of Rock Bass decreased consistently with age, and by age four, incremental growth decreased at all sites by 50 percent or more from what it was at age one (Table 2.5). The Mississippi River sites near Saint Cloud, and at Camp Ripley, along with the Sauk River near Melrose had particularly high incremental growth from ages one to four, while the South Fork Zumbro River, North Branch Root River, and Root River site showed relatively low incremental growth for the same age range (Table 2.5).

Table 2.3. Smallmouth Bass incremental growth (mm) estimates, ± 1 standard error, for 12 stream sites in the Eastern Broadleaf Province of Minnesota, obtained from mixed effects growth models.

Stream site	Smallmouth Bass												
	Age 1	Age 2	Age 3	Age 4	Age 5	Age 6	Age 7	Age 8	Age 9	Age 10	Age 11	Age 12	
Cannon River	114 \pm 3	68 \pm 3	48 \pm 5	40 \pm 5									
Cedar River	88 \pm 7	66 \pm 8	64 \pm 9										
Crow River	126 \pm 9	74 \pm 10	63 \pm 11										
M.F. Zumbro River	117 \pm 3	64 \pm 3	66 \pm 3	46 \pm 3	40 \pm 5	25 \pm 5	13 \pm 7	13 \pm 12					
Miss. at Pool 1	116 \pm 3	73 \pm 3	49 \pm 3	36 \pm 4	27 \pm 4	24 \pm 6							
Miss. near St. Cloud	129 \pm 2	97 \pm 2	65 \pm 2	33 \pm 2	22 \pm 3	19 \pm 3	18 \pm 4	12 \pm 5	7 \pm 7	7 \pm 7	9 \pm 7		
Miss. near Monticello	139 \pm 3	85 \pm 3	58 \pm 3	37 \pm 4	25 \pm 4	19 \pm 4	15 \pm 5	12 \pm 5	16 \pm 6	10 \pm 7	10 \pm 8	14 \pm 8	
Miss. at Camp Ripley	146 \pm 4	82 \pm 4	71 \pm 5	54 \pm 6	42 \pm 7	42 \pm 8							
N.B. Root River	108 \pm 6	74 \pm 6	57 \pm 7	54 \pm 8	37 \pm 11								
Root River	100 \pm 2	58 \pm 2	41 \pm 3	34 \pm 4	25 \pm 4	28 \pm 5	25 \pm 6	29 \pm 8					
Rum River	116 \pm 4	85 \pm 4	80 \pm 5	56 \pm 6	41 \pm 6	40 \pm 9							
Sauk River near St. Cloud	137 \pm 4	96 \pm 4	75 \pm 4	38 \pm 4	23 \pm 4	17 \pm 5	7 \pm 7	8 \pm 10	9 \pm 10				

Table 2.4. Factors affecting Rock Bass growth based on mixed effects growth models with associated K (number of model parameters), AICc, Δ AIC, and AICc Weights. The model with the best fit is bolded, while models with growth year effects are highlighted in gray.

Stream	Model	K	AICc	Δ AIC	AICc Wt
Cedar River	Growth=Age+Individual+Year	10	1938.66	0.00	0.60
	Growth=Age+Individual+Year+Cohort	11	1939.45	0.79	0.40
	Growth=Age+Individual	9	1949.60	10.94	0.00
Elk River	Growth=Age+Individual	7	331.69	0.00	0.78
	Growth=Age+Individual+Year	8	334.64	2.94	0.18
	Growth=Age+Individual+Year+Cohort	9	337.74	6.05	0.04
Mississippi River at Camp Ripley	Growth=Age+Individual+Year+Cohort	10	700.31	0.00	0.65
	Growth=Age+Individual+Year	9	701.57	1.26	0.34
	Growth=Age+Individual	8	709.01	8.70	0.01
Mississippi River near Saint Cloud	Growth=Age+Individual	6	158.36	0.00	0.93
	Growth=Age+Individual+Year	7	163.54	5.18	0.07
	Growth=Age+Individual+Year+Cohort	8	169.76	11.40	0.00
North Branch Root River	Growth=Age+Individual	6	610.60	0.00	0.71
	Growth=Age+Individual+Year	7	612.96	2.36	0.22
	Growth=Age+Individual+Year+Cohort	8	615.38	4.78	0.07
Root River	Growth=Age+Individual	9	401.73	0.00	0.59
	Growth=Age+Individual+Year	10	403.79	2.06	0.21
	Growth=Age+Individual+Year+Cohort	11	403.85	2.12	0.20
Sauk River near Melrose	Growth=Age+Individual	10	221.23	0.00	0.93
	Growth=Age+Individual+Year	11	226.54	5.31	0.07
	Growth=Age+Individual+Year+Cohort	12	232.51	11.28	0.00
South Fork Zumbro River	Growth=Age+Individual	7	249.99	0.00	0.81
	Growth=Age+Individual+Year	8	253.17	3.18	0.16
	Growth=Age+Individual+Year+Cohort	9	256.57	6.57	0.03
Straight River	Growth=Age+Individual+Year	8	478.93	0.00	0.78
	Growth=Age+Individual+Year+Cohort	9	481.60	2.66	0.21
	Growth=Age+Individual	7	487.53	8.59	0.01

Table 2.5. Rock Bass incremental growth (mm) estimates, ± 1 standard error, for nine stream sites in the Eastern Broadleaf Province of Minnesota, obtained from mixed effects growth models.

Stream Site	Rock Bass					
	Age 1	Age 2	Age 3	Age 4	Age 5	Age 6
Cedar River	56 \pm 1	36 \pm 1	31 \pm 2	28 \pm 2	23 \pm 3	16 \pm 4
Elk River	58 \pm 1	45 \pm 2	32 \pm 3	31 \pm 4	22 \pm 4	
Miss. near Saint Cloud	71 \pm 3	56 \pm 4	39 \pm 5	22 \pm 7		
Miss. at Camp Ripley	70 \pm 3	49 \pm 3	39 \pm 4	32 \pm 5	20 \pm 6	21 \pm 8
N.B. Root River	54 \pm 1	37 \pm 1	35 \pm 2	23 \pm 2		
Root River	54 \pm 1	40 \pm 1	31 \pm 1	19 \pm 3		
Sauk River near Melrose	83 \pm 3	58 \pm 3	41 \pm 3	26 \pm 6	23 \pm 6	
S.F. Zumbro River	52 \pm 2	35 \pm 2	37 \pm 2	26 \pm 2	17 \pm 3	
Straight River	57 \pm 3	49 \pm 3	46 \pm 3	35 \pm 4	24 \pm 5	

For Northern Hogsuckers, Model 1 was selected for four of the seven of the stream sites. Three out of the seven sites had growth-year effects, namely the North Branch Root River, Root River, and the South Fork Zumbro River site. Model 2 was selected for Northern Hogsucker growth at all three sites (Table 2.6).

Northern Hogsucker incremental growth did not decrease consistently as was the case with Smallmouth Bass and Rock Bass. Age two growth was similar to age three growth, with faster age 3 growth in some cases. However, apart from the lack of a decrease in incremental growth from age two to age three, growth seemed to decrease consistently as age increased (Table 2.7).

Growth-Year Effects on Populations

Smallmouth Bass growth showed similarities among years for the five streams that exhibited year-effects. For example, all streams showed slower than average growth in 2012, and each of the streams except for the Crow River showed slower than average growth in 2011. Conversely, each of the five stream sites except for the Rum River showed faster than average growth in 2010 (Table 2.8).

Among the three sites that showed growth year-effects for Rock Bass, there were some similarities in certain years. The Cedar River, Mississippi River at Camp Ripley, and Straight River all showed a negative year-effect for Rock Bass growth in 2011. Additionally, all three streams exhibited faster than average growth in 2008, although the positive year-effect on growth at the Cedar River was fairly weak (Table 2.8).

Northern Hogsucker growth showed similarities among years for the three stream sites that had year-effects. The Root River, North Branch Root River, and South Fork Zumbro River all showed negative growth year-effects in 2009 and 2010. Additionally, the two sites that had growth data for 2012, the North Branch Root River, and South Fork Zumbro River, both had positive growth year-effects for that year (Table 2.8).

Table 2.6. Factors affecting Northern Hogsucker growth based on mixed effects growth models with associated K (number of model parameters), AICc, Δ AIC, and AICc Weights. The model with the best fit is bolded, while models with growth year effects are highlighted in gray.

Stream	Model	K	AICc	Δ AIC	AICc Wt
	Growth=Age+Individual	9	526.33	0.00	0.79
Cannon River	Growth=Age+Individual+Year	10	529.30	2.98	0.18
	Growth=Age+Individual+Year+Cohort	11	532.41	6.09	0.04
	Growth=Age+Individual	7	146.94	0.00	0.94
Le Sueur River	Growth=Age+Individual+Year	8	152.57	5.63	0.06
	Growth=Age+Individual+Year+Cohort	9	161.07	14.13	0.00
	Growth=Age+Individual+Year	12	1549.71	0.00	0.76
North Branch Root River	Growth=Age+Individual+Year+Cohort	13	1552.05	2.34	0.24
	Growth=Age+Individual	11	1561.80	12.09	0.00
	Growth=Age+Individual+Year	11	3334.76	0.00	0.74
Root River	Growth=Age+Individual+Year+Cohort	12	3336.89	2.13	0.25
	Growth=Age+Individual	10	3344.28	9.52	0.01
	Growth=Age+Individual	8	210.63	0.00	0.96
Silver Creek	Growth=Age+Individual+Year	9	216.79	6.16	0.04
	Growth=Age+Individual+Year+Cohort	10	224.43	13.80	0.00
	Growth=Age+Individual+Year	10	226.55	0.00	0.80
South Fork Zumbro River	Growth=Age+Individual	9	229.44	2.89	0.19
	Growth=Age+Individual+Year+Cohort	11	234.21	7.67	0.02
	Growth=Age+Individual	7	196.67	0.00	0.93
Straight River	Growth=Age+Individual+Year	8	202.05	5.38	0.06
	Growth=Age+Individual+Year+Cohort	9	208.42	11.75	0.00

Table 2.7. Northern Hogsucker incremental growth (mm) estimates, ± 1 standard error, for seven streams sites in the Eastern Broadleaf Province of Minnesota, obtained from mixed effects growth models.

Stream Site	Northern Hogsuckers							
	Age 1	Age 2	Age 3	Age 4	Age 5	Age 6	Age 7	Age 8
Cannon River	98 \pm 6	90 \pm 6	90 \pm 6	46 \pm 7	32 \pm 9	29 \pm 15		
Le Sueur River	65 \pm 3	53 \pm 3	50 \pm 4	43 \pm 4				
N.B. Root River	80 \pm 4	65 \pm 4	71 \pm 5	55 \pm 6	29 \pm 8	11 \pm 10		
Root River	89 \pm 3	46 \pm 3	51 \pm 3	42 \pm 3	38 \pm 3	33 \pm 4	24 \pm 6	20 \pm 9
Silver Creek	69 \pm 8	57 \pm 8	74 \pm 8					
S.F. Zumbro River	69 \pm 8	42 \pm 8	69 \pm 9	41 \pm 11	23 \pm 11			
Straight River	97 \pm 6	53 \pm 6	56 \pm 6	71 \pm 11				

Table 2.8. Growth year effects (mm) from mixed effects growth models for Smallmouth Bass, Rock Bass, and Northern Hogsuckers at stream sites in the Eastern Broadleaf Province in Minnesota. (Only sites that had growth year effects (i.e., sites where Model 2 or 3 was selected) were included in the table; Bolded values are maximums and underlined values are minimums in growth among populations.)

Stream site	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Smallmouth Bass												
Crow River										3.13	16.12	<u>-25.33</u>
Miss. near Monticello	7.33	<u>-10.32</u>	2.98	9.40	1.46	3.59	-1.59	-7.00	0.40	3.81	-1.31	-6.55
Miss. at Pool 1							5.30	4.10	2.50	5.30	<u>-6.00</u>	-5.30
N.B. Root River								-7.74	-11.75	0.17	-7.12	<u>-14.89</u>
Rum River						5.67	12.02	10.23	0.71	-3.52	<u>-13.14</u>	
Rock Bass												
Cedar River						2.49	-0.21	0.55	1.39	0.62	<u>-3.67</u>	
Miss. at Camp Ripley						1.01	-0.19	3.51	-1.51	0.48	<u>-3.30</u>	
Straight River								10.25	2.37	-1.35	-4.50	<u>-6.77</u>
Northern Hogsuckers												
Root River				-0.15	-2.62	1.27	6.38	6.00	-3.20	-2.68	<u>-4.98</u>	
N.B. Root River			8.84	0.57	-0.52	4.75		<u>-6.38</u>	-6.31	-4.73	<u>-6.38</u>	10.16
S.F. Zumbro River								-12.19	<u>-15.96</u>	-15.54	9.45	21.23

Hydrology

Duration of summer high flows varied among streams and years (Table 2.9). However, similarities existed among streams in certain years. Nine of 15 streams had their longest high flow durations in 2011, and a majority of streams had their shortest durations in 2009. High flow duration was greatest in 2011 in the Sauk River, Elk River, Crow River, Rum River, and Pool 1 of the Mississippi River. In all five rivers, high flows persisted for about 90 of the 122 summer days in 2011. Conversely, in 2009 there were no high flows in the Elk River, Rum River, or any of the Mississippi River sites. Also, high flows only lasted for one to three days in the Root and Cannon rivers, respectively. Additionally, high flows had relatively long durations in 2008 and 2012 and relatively short durations in 2006 and 2007 among streams.

Associations between Growth and Hydrology

Growth year-effects for Smallmouth Bass showed significant negative relationships with summer-high-flow duration for 2 of 5 regressions, namely the Mississippi River at Pool 1 ($r^2 = -0.84$; $P = 0.01$) and the Rum River ($r^2 = -0.69$; $P = 0.04$; Table 2.10, Figures 2.3, 2.4). The strongest negative growth year-effects in the Mississippi River at Pool 1 (-6.00 mm) and the Rum River (-13.14 mm) were observed in 2011, a year that also showed the longest duration of summer high flows among the two streams (Table 2.9).

A significant negative relationship existed between summer-high-flow duration and Rock Bass growth for the Cedar River ($r^2 = -0.69$; $P = 0.04$; Figure 2.5). However, the other two streams that showed growth year-effects, the North Branch Root and Straight rivers, showed no such relationship (Table 2.10). Similar to Smallmouth Bass growth in the Mississippi River at Pool 1 at Pool 1 and the Rum River, the strongest negative growth year effects for Rock Bass in the Cedar River (-3.67 mm) occurred in 2011, the year with the longest duration of summer high flows (Table 2.9).

Table 2.9. Maximum duration of summer high flows (maximum number of days in a row with flows > 75th percentile) for 15 streams in the Eastern Broadleaf Province of Minnesota. (Bold values are maximums and underlined values are minimums for each stream; the Middle Fork Zumbro River, Silver Creek, and Sauk River site near Melrose were not included, as there was no adequate gage to quantify hydrology; The presence of species specific growth year effects among populations are denoted for each stream in superscript, where SMB = Smallmouth Bass, RKB = Rock Bass, and NHS = Northern Hogsuckers).

Stream site	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
<i>Cannon River</i>								22	<u>3</u>	17	56	
<i>Cedar River</i> ^(RKB)									<u>19</u>	25	36	
<i>Crow River</i> ^(SMB)									33	94	40	
<i>Miss. at Camp Ripley</i> ^(RKB)					2	13	26	<u>0</u>	<u>0</u>	<u>0</u>	47	
<i>Miss. near Monticello</i> ^(SMB)	38	37	28	7	40	<u>0</u>	9	20	<u>0</u>	<u>0</u>	42	63
<i>Miss. at Pool 1</i> ^(SMB)							<u>0</u>	20	<u>0</u>	8	89	54
<i>Miss. near St. Cloud</i>		37	28	7	40	<u>0</u>	9	20	<u>0</u>	<u>0</u>	42	63
<i>N.B. Root River</i> ^(SMB, NHS)								50	18	25	38	<u>0</u>
<i>Root River</i> ^(NHS)				25	9	14	33	70	<u>1</u>	4	<u>1</u>	
<i>Rum River</i> ^(SMB)						<u>0</u>	<u>0</u>	26	<u>0</u>	46	97	
<i>Sauk River near St. Cloud</i>				11	35	<u>0</u>	<u>0</u>	23	9	16	103	20
Elk River								25	<u>0</u>	44	99	34
S.F. Zumbro River ^(NHS)								33	7	19	26	<u>5</u>
Straight River ^(RKB)								23	<u>7</u>	30	23	13
Le Sueur River									<u>6</u>	37	45	11

Table 2.10. Relationships between fish growth and the magnitude and the duration of summer high flows among populations in nine streams in the Eastern Broadleaf Province of Minnesota with associated statistics. Significant relationships are in gray. Significance level = 0.10.

Stream site	DF	Slope	Intercept	F-Value	r^2	P-Value
Smallmouth Bass						
Crow River	2	0.42	-25.6	0.8	0.45	0.535
Miss. near Monticello	11	-0.12	3.03	2.18	0.18	0.171
Miss. at Pool 1	5	-0.13	4.81	21.71	0.84	0.01
N.B. Root River	4	2.33	-14.69	2.22	0.43	0.233
Rum River	5	-0.2	7.73	8.94	0.69	0.04
Rock Bass						
Cedar River	5	-0.19	4.23	8.72	0.69	0.042
Miss. at Camp Ripley	5	-0.04	0.53	0.38	0.09	0.57
Straight River	4	0.06	-1.17	0.02	0.01	0.894
Northern Hogsuckers						
Root River	7	0.16	-3.08	17.28	0.74	0.006
N.B. Root River	5	-0.19	4.01	1.26	0.24	0.325
S.F. Zumbro River	4	-0.39	4.33	0.24	0.07	0.657

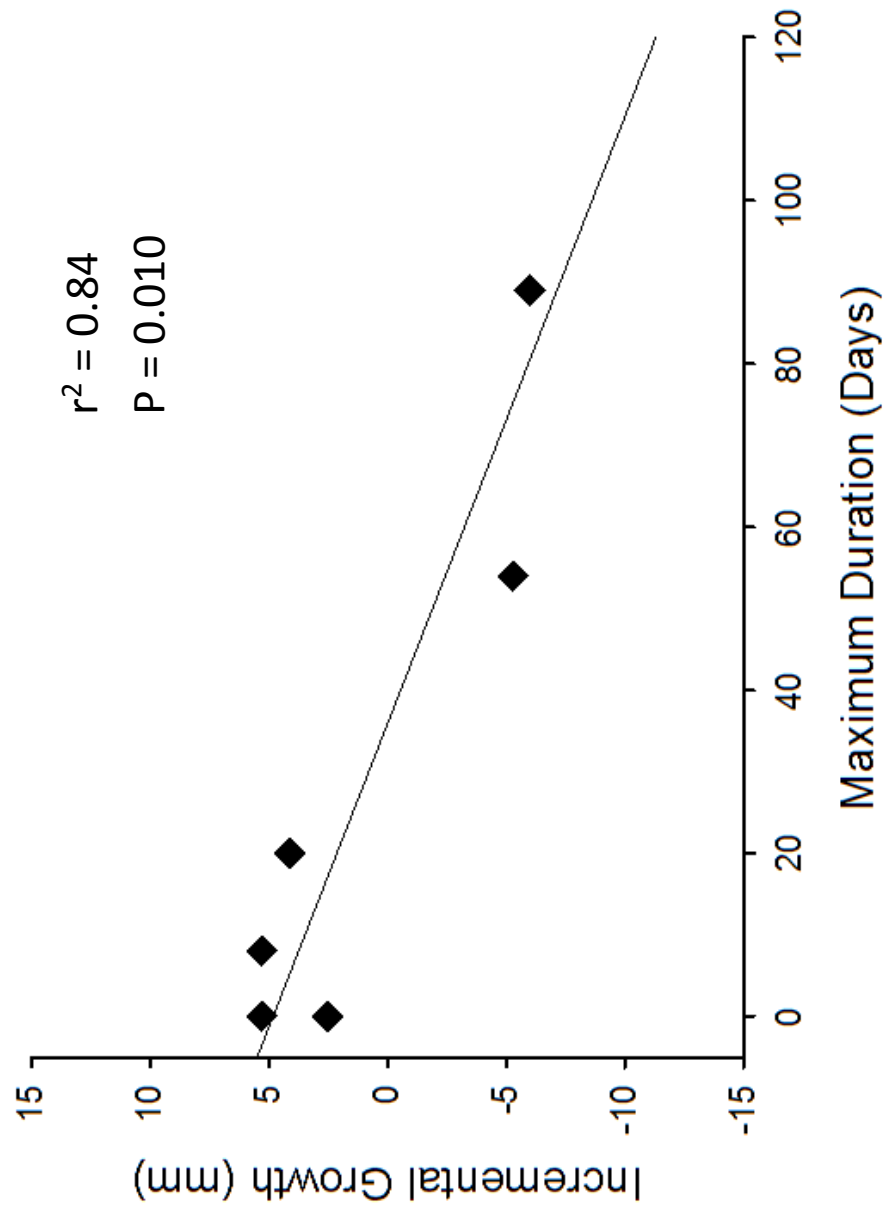


Figure 2.2. Relationship between Smallmouth Bass growth and the duration of summer high flows at the Mississippi River at Pool 1 from 2007-2012.

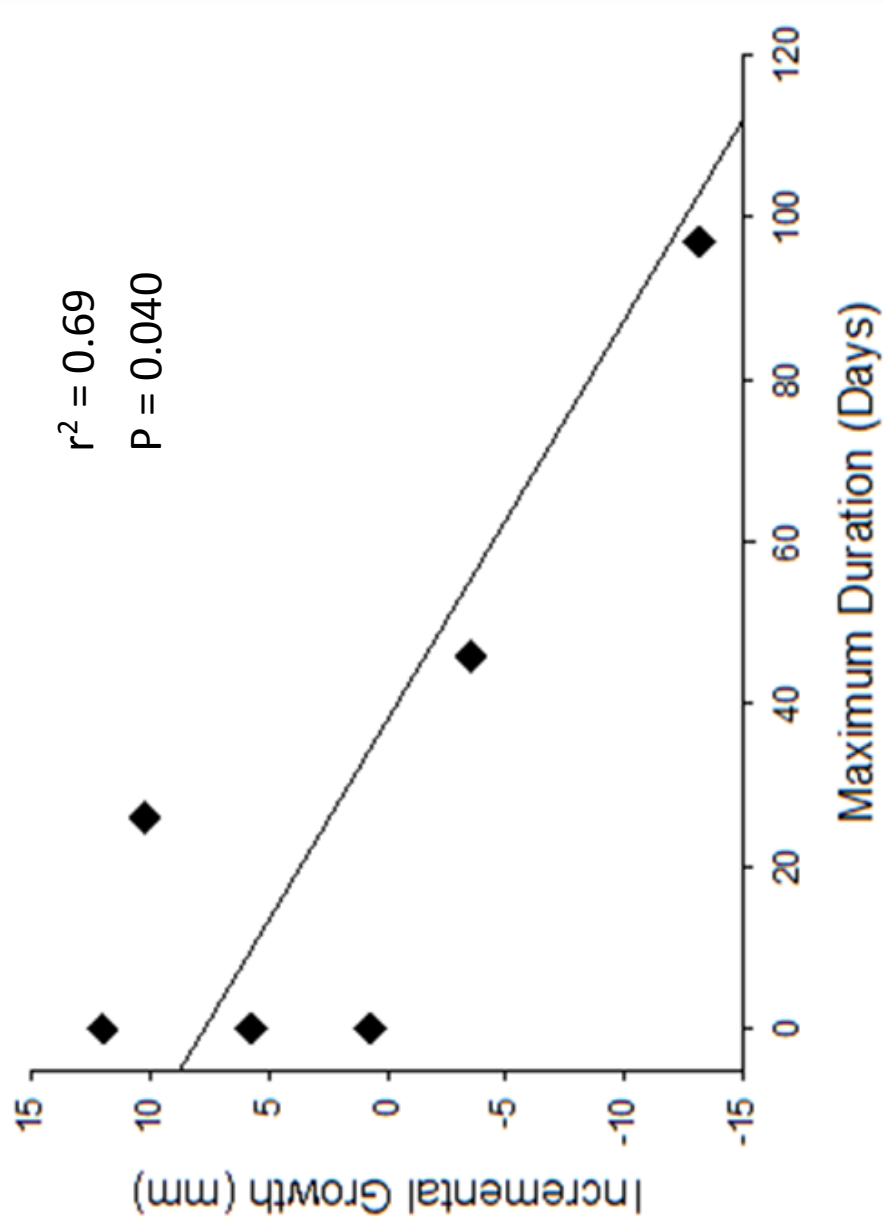


Figure 2.3. Relationship between Smallmouth Bass growth and the duration of summer high flows at the Rum River from 2006-2011.

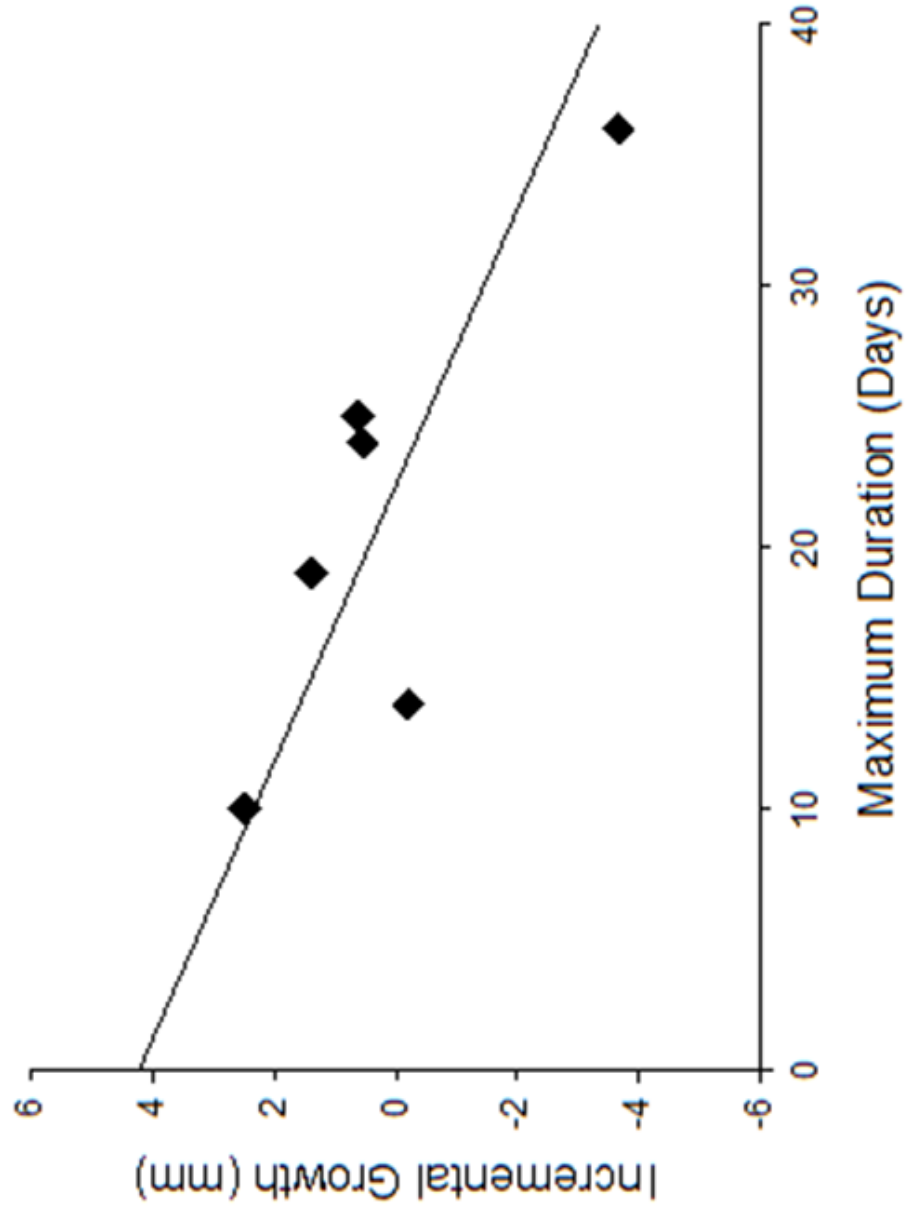


Figure 2.4. Relationship between Rock Bass growth and the duration of summer high flows at the Cedar River from 2006-2011.

Growth-year effects for Northern Hogsuckers showed a significant positive relationship with summer high flow duration at the Root River ($r^2 = 0.74$; $P = < 0.01$; Figure 2.6). The other two streams, which were the North Branch Root and South Fork Zumbro Rivers, did not show any relationships between Northern Hogsucker growth-year effects and duration of summer high flows (Table 2.10). The strongest positive growth year effect in the Root River (6.38, 6.00 mm) occurred in 2007 and 2008, respectively, years with the longest duration of summer high flows (Table 2.9).

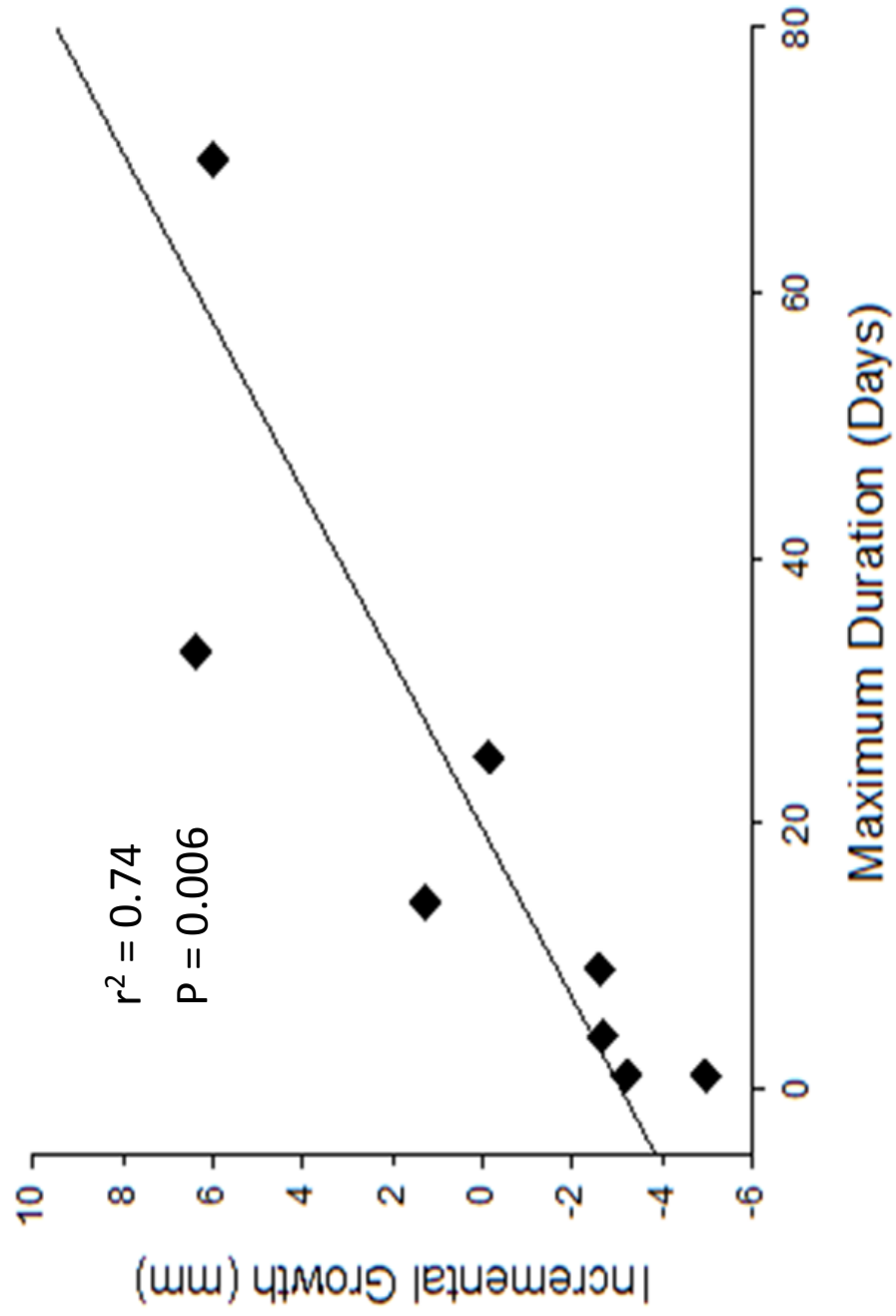


Figure 2.5. Relationship between Northern Hogsucker growth and the duration of summer high flows at the Root River from 2004-2011.

Discussion

Growth year-effects for Smallmouth Bass, Rock Bass, and Northern Hogsucker populations were negligible among several of the streams in this study as evidenced by the selection of Model 1 (Growth = Age Effects + Individual Fish Effects). In most fish populations growth is highly dependent on age, as growth rates tend to decline in a linear fashion as fish approach maximum longevity (Maceina 1992; Sammons and Maceina 2009). Additionally, individuals may show variation in growth due to genetics and/or sex, which may influence population level estimates (Reynolds and Gross 1992; Bhatta et al. 2012; Jacquemin et al. 2014).

Under stable environmental conditions characterized by low amounts of temporal variability, growth is more likely to be controlled by biotic factors, such as those related to differences in age, genetics, and sex (Egna and Boyd 1997; Szczepkowski 2009; Beesley and Prince 2010). However, the maximum duration of summer high flows varied considerably among years for streams where Model 1 was selected, suggesting that they were not stable systems (Table 2.9). Not surprisingly, since northern temperate streams often show a high degree of temporal variability in physical habitat (Schlosser 1991). Consequently, I posit that in streams where Model 1 was selected, the influence of age- and individual- fish effects on growth was strong enough to overwhelm year-effects to an inconsequential level. Further research of these streams is needed to uncover the specific mechanisms that allow age- and individual- effects such as, sex selective or genetic differences, to have such a strong effect on fish growth.

Cohort-effects on growth were only observed for the population of Smallmouth Bass at the Mississippi River at Monticello, and the population of Rock Bass at the Mississippi River at Camp Ripley. Different growth rates among cohorts can occur due to inter-annual variability in the physical environment as well as density-dependent factors during years with strong recruitment (Marschall and Crowder 1995). Annual variation in stream flow and temperature regimes can affect the reproductive success

and survival of YOY fishes (Schlosser 1991), which can in turn affect abundance within cohorts (Cattaneo et al. 2002). For example, optimal spawning conditions produced by favorable coupling of flow and temperature have been shown to increase year class abundance of fishes (Swenson et al. 2002; Nunn et al. 2003). In cohorts with high abundance, feeding and refuge habitats may become a limiting factor due to intra-specific competition resulting in decreased fish growth (Lobon-Cervia 2005; Finstad et al. 2009).

Growth model selection differed among co-occurring populations of Smallmouth Bass and Rock Bass in the Cedar River, North Branch Root River, and the Mississippi River at Camp Ripley, which was somewhat surprising because the two species are ecologically similar (Probst and Rabeni 1984; Roell and Orth 1993). Rock Bass showed growth year-effects in the Cedar River and Mississippi River at Camp Ripley, whereas Smallmouth Bass did not, and Rock Bass showed no growth year-effects in the North Branch Root River, whereas growth year-effects were observed there for Smallmouth Bass. The exact mechanisms that led to differences between factors affecting Smallmouth Bass growth and Rock Bass growth in co-occurring populations are unknown. However, inter-specific competition can affect the relative strength of factors influencing growth in co-occurring populations of ecologically similar fish species (Hearn 1987).

Smallmouth Bass and Rock Bass have similar affinities for habitat and prey types, which could lead to interspecific competition (Probst and Rabeni 1984; Roell and Orth 1993). At times of high environmental disturbance (*e.g.*, floods and droughts) competition is of minimal intensity, but may become more severe during stable periods when population densities of competing species increase (Hearn 1987). Under such a scenario, increased intensity of inter-specific competition could result in a significant reduction in growth and condition of one species depending on growth year conditions (Townsend et al. 1997). Studies exploring the niches that Smallmouth Bass and Rock

Bass occupy in sympatric populations in Minnesota streams could ascertain the effect that interspecific competition has on their growth.

A total of eleven populations had growth year-effects among fish species. Inter-annual variation in growth was not significantly related to duration of summer high flows for seven of the eleven populations. Temporal variation in water temperatures, and other aspects of the flow regime such as timing, magnitude, frequency, and rate of change of flows could have had a greater influence on fish growth in those streams (Schlosser 1991; Neuheimer and Taggart 2007; Peterson and Jennings 2007). Interactions between temperature and flow regime can be especially influential on the growth of fishes (Gutreuter et al. 1999; Swenson et al. 2002; Quist and Spiegel 2012). For example, Swenson et al. (2002) found that first year growth of Smallmouth Bass was highest during years with a combination of warmer growth season temperatures and lower stream discharge. Years with warmer growing season temperatures can increase the metabolic capacity for growth, and when coupled with lower discharge levels, perhaps lower than the 75th-percentile quantified in this study, can also minimize metabolic costs from swimming, subsequently increasing fish growth rates (Swenson et al. 2002). The lack of a relationship between inter-annual growth and duration of summer high flows for seven of the 11 fish populations lends relatively strong support to the null hypothesis that inter-annual growth of fishes would not be influenced by summer high flow duration.

Results in my study suggesting the lack of a relationship between high flow duration and fish growth conflicted with the findings of other studies that have found positive relationships between the two (Sammons and Maceina 2009; Quist and Spiegel 2012). Positive relationships between the duration of high flows and fish growth are often associated with flows sufficient to inundate a river's floodplain, which can increase fish feeding habitat and serve as flow refugium for younger fish (Gutreuter et al. 1999; Sammons and Maceina 2009). It is possible that my use of the 75th percentile of flows as an explanatory variable for fish growth failed to adequately capture this

relationship. Return intervals for flood discharges can vary from one to ten years in different streams depending on basin area, sediment character, basin geomorphology, channel slope and channel entrenchment (Poff and Ward 1989). Therefore, they can often only be accurately determined from field based measurements (Williams 1978; Johnson and Heil 1996; Olsen et al. 1997) which were beyond the scope of this study. Consequently, it was unknown how my 75th percentile flows related to floodplain inundation flows in the various streams examined in my study area. Further research exploring relationships between the extent and duration of floodplain inundation and fish growth in the streams of the Eastern Broadleaf Province may help identify other important hydrology drivers effecting fish growth.

Populations of Smallmouth Bass in the Mississippi River at Camp Ripley and Rum River, as well as populations of Rock Bass at the Cedar River showed significant negative relationships between inter-annual growth and duration of summer high flows. Increased duration of high flows can lead to increased metabolic costs and reduced feeding efficiency in some fishes, leading to decreased growth (Grant and Noakes 1987; Weyers et al. 2003). The negative relationships between Smallmouth Bass and Rock Bass inter-annual growth and the maximum duration of summer high flows at three streams showed some evidence to support the hypothesis that the inter-annual growth of fishes would be negatively related to the maximum duration of summer high flows, but the evidence was relatively weak.

The population of Northern Hogsuckers in the Root River showed a significant positive relationship between growth and duration of summer high flows. A couple of different mechanisms may drive this relationship. Large precipitation events associated with high flow pulses can transport substantial amounts of nutrients into streams, especially in watersheds with relatively high amounts of agriculture, like the Root River watershed (Royer et al. 2006; Duff et al. 2008; Minnesota Pollution Control Agency 2012). Increased phosphorus and nitrogen loads can increase stream productivity, causing bottom up effects that could increase fish growth (Harvey et al. 1998).

Although, under such a scenario, bottom up effects caused by increased phosphorus and nitrogen loads would have been expected to increase the growth of Smallmouth Bass and Rock Bass in the Root River as well, this was not the case. It is possible that the lower trophic position of Northern Hogsuckers relative to Smallmouth Bass and Rock Bass could have allowed them to benefit more directly from increased production at lower trophic levels (Lyons 1992; Davis et al. 2010, Schmitt et al. 2011). Northern Hogsuckers are benthic omnivores, and feed mainly on aquatic invertebrates and organic matter from the stream bottom, whereas Smallmouth Bass and Rock Bass feed on aquatic invertebrates and smaller fishes (Probst et al. 1984; Schmitt et al. 2011). Inefficient energy transfer between trophic levels can lead to disproportionate levels of production that often favor organisms at lower trophic positions (Gibson and Cutting 1993; Davis et al. 2010). Additionally, the fin morphology and concave head of Northern Hogsucker can serve as hydrofoils, pressing them to the substrate and making them less susceptible to high flows (Matthews 1998; Meyers and Belk 2014), which could allow them to conserve energy for growth during high flow spates. The significant positive relationship between Northern Hogsucker growth and duration of summer high flows provides some support for the hypothesis that fish growth increases with longer duration of summer high flows.

This study showed little evidence that high flow duration affected fish growth among selected streams in the Eastern Broadleaf Province of Minnesota. Inter-annual variability in temperatures along with the timing, magnitude and frequency of flows may have contributed to differences in the annual growth of fishes in some streams (Schlosser 1991; Neuheimer and Taggart 2007; Peterson and Jennings 2007). However, minimal growth year-effects observed at the majority of my sites suggests that biotic factors (*e.g.*, fish age, genetic differences) may play a large role in determining the growth rates of fishes within the streams of the study area.

MANAGEMENT IMPLICATIONS

This study provided recruitment and growth measures for populations of Smallmouth Bass, Rock Bass, and Northern Hogsuckers in a number of streams in the Eastern Broadleaf Province of Minnesota. Inter-annual variability of the magnitude and duration of stream flows were also quantified for a number of streams in the province. Additionally, mixed effects models identified factors affecting Smallmouth Bass, Rock Bass, and Northern Hogsucker growth for several populations among streams in the study area. Key findings of this study are summarized below.

- Recruitment of Smallmouth Bass, Rock Bass, and Northern Hogsuckers was highly variable among streams and years.
- Magnitude and duration of stream flows were highly variable among streams and years during the spawning and rearing periods of Smallmouth Bass, Rock Bass, and Northern Hogsuckers.
- Little support was found for either long-term or short-term flow effects on recruitment during the adult spawning and juvenile rearing periods.
- Age and individual fish effects were the primary factors affecting growth for a majority of the populations of Smallmouth Bass, Rock Bass, and Northern Hogsuckers among streams.
- The maximum duration of summer high flows (75th flow percentile) did not show a significant relationship with the inter-annual growth of Smallmouth Bass, Rock Bass, and Northern Hogsuckers for most populations among streams.

Recruitment and growth measures from this study, particularly those for Smallmouth Bass and Rock Bass, can be used in the assessment of several stream fisheries in the Eastern Broadleaf Province. Specifically, these measures could be used as a baseline status for future studies.

Additionally, during the course of this study I encountered several stream flow gages with long gaps in long-term discharge data. Although the maintenance and status

of stream flow gages are often dictated by budget constraints, the importance of long-term flow data for studies such as mine cannot be understated. Therefore, whenever possible, funding should be made available for the continued operation of gages to ensure adequate long-term discharge records for future studies.

I found little evidence that the duration of high flows, and the magnitude and variability of flows affected the growth and recruitment of Smallmouth Bass, Rock Bass, and Northern Hogsuckers. Consequently, future studies focusing on different factors that may affect fish growth and recruitment, such as temperature and habitat regimes, and timing and frequency of flows may help to explain the inter-annual variability found for the fish populations in this study.

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APPENDICES

CHAPTER I

Appendix 1. Smallmouth Bass age class frequency for streams in the Eastern Broadleaf Province of Minnesota sampled to assess recruitment among populations.

Stream Site	Age 0	Age 1	Age 2	Age 3	Age 4	Age 5	Age 6	Age 7	Age 8	Age 9	Age 10	Age 11	Age 12	Age 13
<i>Miss. at Camp Ripley</i>	2	3	6	3	3	2	4			1				
<i>Miss. at Saint Cloud</i>	26	6	9	11	6	4	3	5	1			2		
<i>Miss. at Monticello</i>	34	16	10	2	2	10	2	3	2	2	1	1	2	
<i>Miss. at Pool 1</i>	12	2	6	10	10	4	4		1					
<i>Rum River</i>	7	4	7	8	2	3	2							
<i>Elk River</i>	19	1	1											
<i>Cannon River</i>	3	7	3	6	1									
<i>Straight River</i>	1													
<i>N.B. Root River</i>	9	52	8	7	9	1	1							
<i>Root River</i>	1	12	18	16	2	4	3	2	2					
<i>Cedar River</i>	3	4	1	2										

Appendix 2. Rock Bass age class frequency for streams in the Eastern Broadleaf Province of Minnesota sampled to assess recruitment among populations.

Stream Site	Age 0	Age 1	Age 2	Age 3	Age 4	Age 5	Age 6	Age 7
<i>Miss. at Camp Ripley</i>		19	10	6	3	2	2	2
<i>Miss. at St. Cloud</i>		2	3	2		1		
<i>Miss. at Monticello</i>		2	1					
<i>Rum River</i>			2	1				
<i>Elk River</i>	8	17	4	2		3		
<i>Straight River</i>		8		5	9	1		
<i>N.B. Root River</i>		14	4	10	9			
<i>Root River</i>			1	15	2			1
<i>Cedar River</i>		24	31	37	16	9	8	1

Appendix 3. Northern Hogsucker age class frequency for streams in the Eastern Broadleaf Province of Minnesota sampled to assess recruitment among populations.

Stream Site	Age 0	Age 1	Age 2	Age 3	Age 4	Age 5	Age 6	Age 7	Age 8	Age 9	Age 10
<i>Miss. at St. Cloud</i>						1	2	3	2	1	1
<i>Cannon River</i>		1		1	5	4	1	1			
<i>Straight River</i>				4	1	1					
<i>N.B. Root River</i>	1	11	14	19	12	6	5				
<i>Root River</i>		5		7	27	25	18	6	4		
<i>Cedar River</i>		1		2	4						

Appendix 4. The number of significant relationships between Smallmouth Bass and Rock Bass recruitment (based on spawning and locomotion morphology traits) and the magnitude and variability of streamflows among streams in the Eastern Broadleaf Province of Minnesota. Significance level = 0.025 after Bonferroni Correction.

Stream Site	DF	Nest-builder Spawning Period		Cruiser morphology Rearing Period	
		Long Term Magnitude	Short Term Magnitude	Long Term Variability	Short Term Variability
<i>Mississippi River-Camp Ripley</i>	5	$r^2 = -0.260$ P = 0.302	$r^2 = -0.062$ P = 0.635	$r^2 = -0.927$ P = 0.002	$r^2 = -0.005$ P = 0.895
<i>Mississippi River-Saint Cloud</i>	10	$r^2 = -0.104$ P = 0.333	$r^2 = -0.213$ P = 0.153	$r^2 = -0.560$ P = 0.008	$r^2 = -0.623$ P = 0.004
<i>Mississippi River-Monticello</i>	12	$r^2 = -0.404$ P = 0.020	$r^2 = 0.374$ P = 0.026	$r^2 = 0.262$ P = 0.074	$r^2 = 0.104$ P = 0.282
<i>Mississippi River-Pool 1</i>	5	$r^2 = -0.124$ P = 0.494	$r^2 = -0.330$ P = 0.233	$r^2 = -0.161$ P = 0.430	$r^2 = -0.748$ P = 0.026
<i>Rum River-Saint Francis</i>	5	$r^2 = -0.700$ P = 0.038	$r^2 = -0.021$ P = 0.783	$r^2 = 0.033$ P = 0.729	$r^2 = -0.150$ P = 0.448
<i>Cannon River</i>	4	$r^2 = 0.002$ P = 0.935	$r^2 = 0.026$ P = 0.795	$r^2 = -0.639$ P = 0.105	$r^2 = -0.056$ P = 0.702
<i>North Branch Root River</i>	3	$r^2 = -0.424$ P = 0.349	$r^2 = -0.136$ P = 0.631	$r^2 = -0.011$ P = 0.895	$r^2 = -0.350$ P = 0.408
<i>Root River-Peterson</i>	7	$r^2 = -0.638$ P = 0.017	$r^2 = -0.387$ P = 0.099	$r^2 = -0.005$ P = 0.868	$r^2 = 0.125$ P = 0.391

Appendix 4. continued-- The number of significant relationships between Smallmouth Bass and Rock Bass recruitment (based on spawning and locomotion morphology traits) and the magnitude and variability of streamflows among streams in the Eastern Broadleaf Province of Minnesota. Significance level = 0.025 after Bonferroni Correction.

Stream Site	DF	Nest builder Spawning Period		Maneuverer morphology Rearing Period	
		Long Term Magnitude	Short Term Magnitude	Long Term Variation	Short Term Variation
<i>Mississippi River-Camp Ripley</i>	5	$r^2 = 0.043$ P = 0.694	$r^2 = 0.136$ P = 0.472	$r^2 = < -0.001$ P = 0.990	$r^2 = 0.309$ P = 0.252
<i>Elk River</i>	4	$r^2 = 0.236$ P = 0.407	$r^2 = 0.453$ P = 0.213	$r^2 = -0.369$ P = 0.277	$r^2 = 0.071$ P = 0.665
<i>Straight River</i>	4	$r^2 = -0.865$ P = 0.022	$r^2 = -0.596$ P = 0.126	$r^2 = -0.621$ P = 0.113	$r^2 = 0.084$ P = 0.637
<i>North Branch Root River</i>	3	$r^2 = -0.965$ P = 0.018	$r^2 = -0.548$ P = 0.260	$r^2 = -0.080$ P = 0.718	$r^2 = -0.013$ P = 0.887
<i>Cedar River</i>	6	$r^2 = -0.213$ P = 0.297	$r^2 = 0.060$ P = 0.596	$r^2 = -0.015$ P = 0.792	$r^2 = 0.189$ P = 0.330

CHAPTER II

Appendix 5. Smallmouth Bass age class frequency for streams in the Eastern Broadleaf Province of Minnesota sampled to assess growth among populations.

Stream Site	Age 0	Age 1	Age 2	Age 3	Age 4	Age 5	Age 6	Age 7	Age 8	Age 9	Age 10	Age 11	Age 12
<i>Miss. at Camp Ripley</i>	2	3	6	3	3	2	4			1			
<i>Sauk River at Saint Cloud</i>			2		1	5	3	3		1			
<i>Miss. at Saint Cloud</i>	26	6	9	11	6	4	3	5	1			2	
<i>Miss. at Monticello</i>	34	16	10	2	2	10	2	3	2	2	1	1	2
<i>Miss. at Pool 1</i>	12	2	6	10	10	4	4		1				
<i>Rum River</i>	7	4	7	8	2	3	2						
<i>Crow River</i>	10		9	4	1								
<i>Cannon River</i>	3	7	3	6	1								
<i>Middle Fork Zumbro River</i>				2	7	2	2	1				1	
<i>N.B. Root River</i>	9	52	8	7	9	1	1	1					
<i>Root River</i>	1	12	18	16	2	4	3	2	2				
<i>Cedar River</i>	3	4	1	2									

Appendix 6. Rock Bass age class frequency for streams in the Eastern Broadleaf Province of Minnesota sampled to assess growth among populations.

Stream Site	Age 0	Age 1	Age 2	Age 3	Age 4	Age 5	Age 6	Age 7
<i>Miss. at Camp Ripley</i>	19	10	6	3	2	2		
<i>Sauk River Near Melrose</i>		1	3			1		
<i>Miss. at St. Cloud</i>	2	3	2			1		
<i>Elk River</i>	8	17	4	2		3		
<i>Straight River</i>		8		5	9	1		
<i>South Fork Zumbro River</i>		1		2	4	3		
<i>N.B. Root River</i>		14	4	10	9			
<i>Root River</i>			1	15	2			1
<i>Cedar River</i>		24	31	37	16	9	8	1

Appendix 7. Northern Hogsucker age class frequency for streams in the Eastern Broadleaf Province of Minnesota sampled to assess growth among populations.

Stream Site	Age 0	Age 1	Age 2	Age 3	Age 4	Age 5	Age 6	Age 7	Age 8	Age 9	Age 10
<i>Cannon River</i>		1		1	5	4	1	1			
<i>Straight River</i>				4	1	1					
<i>Lesueur River</i>			1	1	3	1					
<i>Silver Creek</i>				6			1				
<i>South Fork Zumbro River</i>	1		1	3		1		1			
<i>N.B. Root River</i>	1	11	14	19	12	6	5				
<i>Root River</i>		5		7	27	25	18	6		4	
<i>Cedar River</i>		1		2	4						