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Hydrologic and Temperature Regime Influence on Growth and Recruitment of Fishes in an Upper Midwest Riverine Ecosystem

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Hydrologic and Temperature Regime Influence on Growth and Recruitment of Fishes in an Upper Midwest Riverine Ecosystem

By

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Endorsement Date: ________________

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Abstract

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The natural flow regime is often identified as the primary driver of ecological integrity in rivers. The Minnesota River basin is characterized by a row-crop agricultural landscape with an extensive network of drainage tiles and ditches to improve land productivity. Intensive surface and subsurface drainage alters flow regimes, increasing the magnitude and frequency of high flows. Changes in river hydrology lead to alterations in geomorphology, including increased bank erosion, channel widening, and downward incision that can lead to floodplain disconnection. Disruption of historical hydrology can alter energy flow and connection to specialized habitats subsequently affecting important aquatic communities and populations valued by humans.

To conceptualize flow regimes, three concepts are of interest: 1) the flood pulse, 2) low flow recruitment, and 3) intermediate flow concepts, all of which differ by flow magnitude, timing, and duration. Therefore, the objective of this research was to assess growth and recruitment of selected fishes in relation to various flow and temperature regimes defined by riverine concepts to determine the applicability of each concept to the Minnesota River from 2001-2011.

Variation in fish growth was obtained from linear mixed models. Recruitment was assessed using catch-curve regression. To test relationships of fish growth and recruitment in relation to hydrology and temperature, linear regression was used. Dependent variables included growth-year effects from mixed models and residuals from catch curves. Independent variables included a variety of flow and temperature parameters used to define each riverine concept.

Results indicated the importance of backwater and active floodplain connections to Minnesota River fish growth and recruitment. In particular, backwater connection duration coupled with optimal growing temperature was the top-ranking model for Channel Catfish *Ictalurus punctatus*, Flathead Catfish *Pylodictis olivaris*, and Freshwater Drum *Aplodinotus grunniens*. Active floodplain connection duration parameters and combinations of other flow magnitudes were important for Channel Catfish, Walleye *Sander vitreus*, and Freshwater Drum. To some extent, every riverine concept or flow threshold was beneficial for at least one species, suggesting that a natural flow regime (*i.e.*, with variation) should be maintained. Backwater and active floodplain connections were important to many fishes, therefore, maintaining and restoring these connections should be a high priority for Minnesota River managers.

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Abbreviations

AFCD .... active floodplain connection duration
AIC .... Akaike information criterion
BOD .... biological oxygen demand
BWCD .... backwater connection duration
BWCF .... backwater connection frequency
°C .... degrees Celsius
Chl-a .... chlorophyll-a
cm .... centimeter
DO .... dissolved oxygen
EFC .... Environmental Flow Components
ELFD .... extreme low flow duration
ET .... evapotranspiration
FPC .... flood pulse concept
GBERB .... Greater Blue Earth River Basin
HR .... hydrological reversals
Hz .... hertz
IHA .... Indicators of Hydrologic Alteration
K .... model parameters
L .... liter
LFR .... low-flow recruitment
LMPF .... left marginal pectoral fin
ln .... natural logarithm
LPS .... left pectoral spine
m^3/s .... cubic meter per second
MN DNR .... Minnesota Department of Natural Resources
MPCA .... Minnesota Pollution Control Agency
MRBDC .... Minnesota River Basin Data Center
NOAA .... National Oceanic and Atmospheric Administration
OGD .... optimal growing days
OSD .... optimal spawning days
P .... probability of occurrence
RKM .... river kilometer
R^2 .... coefficient of determination
s .... second
SDS .... second dorsal spine
SE .... standard error
SO .... sagittal otolith
spp .... multiple unidentified species

TL..total length
TP..total phosphorus
µg ....micrograms
USGS ....U.S. Geological Survey
VIF ....variance inflation factor
YOY..young-of-year

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CHAPTER I: INTRODUCTION

Today, most large rivers have been altered by human activities (Welcomme 1985; Dynesius and Nilsson 1994; Galat and Frazier 1996). In Minnesota, nearly 50 percent of rivers and streams have been modified via channelization, ditching, and straightening (MPCA 2014). Humans have altered physical river templates, channel and tributary hydraulic dynamics, and basin land-use characteristics to an extent that substantial and complex impacts to aquatic species have occurred (Bayley 1995). In such disturbed systems, management is often targeted to restore altered system features to desired levels of quality (*e.g.*, support designated uses) and conservation of river features that still exhibit desirable conditions (Flotemersch et al. 2006).

Of the available freshwater in the biosphere, freshwater rivers and their floodplains contain only a fraction, yet are of utmost importance physically, chemically, and biologically (Allen and Flecker 1993). Rivers are crucial in the water cycle, transporting minerals and nutrients from higher to lower elevations and eventually to lakes, reservoirs, larger rivers, or oceans (Allen and Castillo 2007). Rivers serve many human necessities as well, such as potable water, harvestable food items, travel and shipping routes, waste removal, and a renewable energy source (Allen and Flecker 1993). Rivers also provide human recreational opportunities, aesthetic enjoyment, and spiritual renewal (Allen and Castillo 2007). Large riverine ecosystems, however, are strongly influenced by what occurs in their watersheds and receive both beneficial and harmful cumulative impacts of upstream activities (Flotemersch et al. 2006; Jelks et al. 2008). Like many rivers today, the Minnesota River is highly impacted by human development.

The Minnesota River has often been criticized as being one of the most polluted rivers in the nation, primarily from nonpoint sources (MRBDC 2009). For instance, the Minnesota River is a major contributor of pollution downstream to the Mississippi River. An estimated 80 to 90 percent of sediment entering Lake Pepin comes from glacial deposits originating from the Minnesota River basin (Kelley and Nater 2000).

As of 2012, the Minnesota River basin had 336 listed impairments, with 108 on the main stem (*e.g.,* dissolved oxygen, bacteria, turbidity, un-ionized ammonia, and biota; MPCA 2012). Sixteen mainstem impairments, including high turbidity, low dissolved oxygen, and excessive un-ionized ammonia negatively affect aquatic life (MPCA 2012). Payne (1994) stated that major riverine stressors are excessive inputs of sediments and nutrients (mainly during rainfall and snowmelt), oxygen-demanding substances, and habitat degradation from channelization. Common nonpoint pollution sources include septic tank discharges and stormwater runoff from roads, parking lots, construction sites, lawns, agricultural fields, feedlots, and mining and forest harvesting operations (Payne 1994). As a result of these stressors, Minnesota River biological communities have been adversely impacted (Stauffer et al. 1995). Abundance of many fish species is lower today than under historic conditions. For example, 12 of the 104 fish species previously documented in the Minnesota River have not been seen for more than three decades, and are likely extirpated (Schmidt and Proulx 2007).

Vast resources have been dedicated to address degraded water and watershed quality in the Minnesota River basin. From 1992-2002, about $1.2 billion dollars were spent to implement conservation measures or retire land from agricultural use (Sigford 2002). As a result, some water quality conditions have improved over the past three decades (Schmidt and Proulx 2007). Over the past thirty years, decreasing trends have been reported for total suspended solids and total phosphorus, while nitrate-N concentrations have increased over the past decade (Musser et al. 2009).

Natural systems, such as rivers, are extremely complex due to numerous factors interacting simultaneously to influence biological communities. Many efforts have been made to understand how riverine biota respond to these environmental factors (*e.g.,* Ward and Stanford 1983). Most river ecologists recognize five broad components that interact to determine population dynamics and biotic assemblages in rivers. These five components are water quality, hydrology, physical habitat and geomorphology, connectivity and energy flow, and biological interactions (Annear et al. 2004; Dauwalter et al. 2010). Due to complex riverine interactions, single-component restorations, such as water quality, may not translate into direct benefits to riverine biota, including fishes. The other four components may need to be restored or managed as well.

The five components provide an excellent basis for understanding rivers, however, each is often too broad to explain smaller-scale complexities and interactions that typically differ within and among flowing water corridors (Vannote et al. 1980; Fisher et al. 1998). To provide a better understanding of these smaller-scale complexities and interactions, river ecologists have synthesized several observations across the five components, and across river systems, to formulate riverine concepts about how rivers work. Concepts that have been identified permit a better understanding of specific management actions needed to restore a river with subsequent benefits to the humans that use that resource. But before a riverine concept can be used to guide management of a specific river, the concept needs to be tested for its applicability to that river. The

Minnesota River is a waterway in need of better management approaches that an understanding of current riverine concepts might facilitate. However, almost no current riverine concepts have been tested for applicability to the Minnesota River.

Research Objectives

The broad goal of this research was to test tenets of three primary riverine concepts: 1) the flood pulse, 2) low-flow recruitment, and 3) intermediate flows (hydrologic variation). Of particular interest was assessing growth and recruitment of selected Minnesota River fishes in the context of flood flows, low flows, and intermediate flows coupled with temperature. Goal assessment was accomplished through the completion of five primary objectives:

1) Provide a review of the literature concerning the large river ecology concepts (Chapter II).

2) Provide an overview of the Minnesota River basin's geology, climate, land use, hydrologic impacts, nutrients, and fishes (Chapter III).

3) Describe the current hydrology (2001-2011) of the Minnesota River and quantify selected hydrologic variables to test riverine concepts (Chapter IV).

4) Describe population characteristics of eight Minnesota River fishes important to river managers and quantify selected population characteristics to test hypotheses predicted by large river ecology concepts (Chapter V).

5) Provide an overview of primary research findings, management implications, and future research needs (Chapter VI).

CHAPTER II: A LITERATURE REVIEW OF RIVER-FLOODPLAIN ECOLOGY

Large River Ecology

A river's flow regime was termed the "Master Variable" by Poff et al. (1997) because hydrology interacts with and influences the other four components of river systems (*i.e.*, water quality, geomorphology and fish habitat, connectivity and energy flow, and biotic interactions; Figure 2.1). Flow regime is defined by five primary aspects: magnitude, frequency, duration, timing, and rate of change. A river's flow regime often varies temporally from hours to years and influences everything from chemical composition to aquatic organism community structure and function. Flow is a major determinant for river habitat conditions and serves as master variable for aquatic life, dictating what can live in an aquatic system (Flotemersch et al. 2006). Riverine flow regimes often exhibit variability, ranging from periods of extreme low-flow or intermittent periods to spates overtopping riverbanks (Poff et al. 1997). As such it is a key component in many if not most riverine concepts as well, including the flood pulse, low-flow recruitment and intermediate flow concepts. The goal of Chapter II is to provide an overview of three large river ecological concepts including the flood pulse, low flow recruitment, and intermediate flows.

Flood Pulse and Flood Recruitment

An important flow-regime component is the point where river channels are no longer able to contain the volume of water passing downstream (*i.e.*, above bankfull level) and laterally expand onto the floodplain ('flood pulse', Welcomme 1979; Tockner et al. 1999). In large rivers with substantial floodplains (*e.g.*, tropical rives such as the

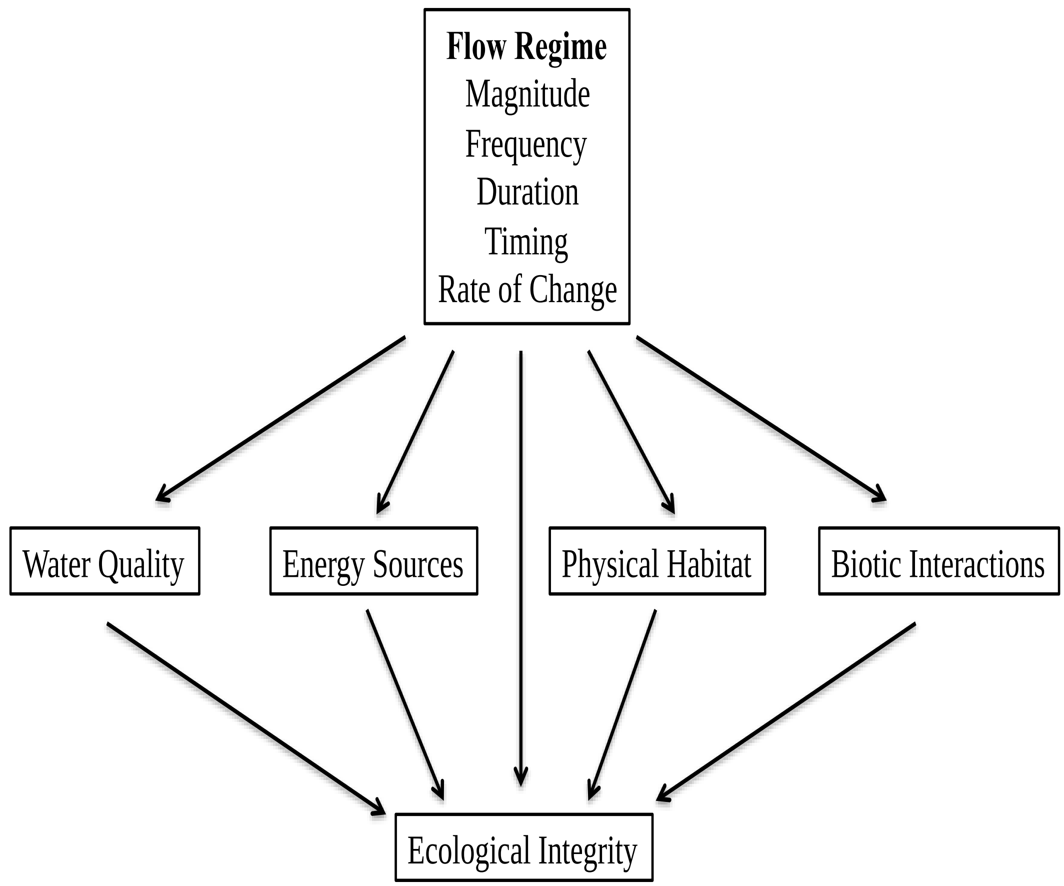

Figure 2.1. Flow regime depicted as the "master variable" in sustaining the ecological integrity of riverine ecosystems. The five aspects of flow regime are magnitude, frequency, duration, timing, and rate of change both directly and indirectly influence integrity, through effects on other regulators of integrity (Adopted from Karr 1991).

Amazon), annual flood pulses are perhaps the most important hydrologic feature governing year-to-year changes in ecosystem productivity and biological diversity (Junk et al. 1989; Ward 1989). One of the primary hypotheses describing riverine function is the flood-pulse concept (FPC). The FPC, proposed by Junk et al. (1989), postulates that discharge pulses are a major controlling force in river-floodplain systems and that lateral exchanges of nutrients both directly and indirectly impact biota.

Over-bank flooding facilitates lateral exchange of nutrients, organic matter, and organisms between the main channel and associated floodplains (Benke and Meyer 1988; Sparks et al. 1990; Poff et al. 1997; Strauss et al. 2006). Materials transported in rivers are in dissolved and particulate forms and can be altered during a flood event. During high discharge periods, previously mineralized nutrients in the floodplain become dissolved and mix with nutrients associated with floodwaters and as such, concentrations generally increase with discharge and suspended particulate matter (Bayley 1995). In tropical floodplains and backwaters, nitrogen and phosphorus limit primary productivity and therefore, floodplain inundation is the mechanism that often replenishes nutrients to isolated autogenic floodplain waters (Junk et al. 1989). Tockner et al. (1999) referred to overbank flooding as a transport phase marked by high nutrient levels and low primary productivity, where floodplains are open cycling with the main river channel.

During flood events, nutrients are transferred from the river into riparian areas and catalyze increased primary production. Flood pulse duration is very important because short pulses (*i.e.*, rapid rise and fall of the hydrograph) can transport organic matter and nutrients from the floodplain to the main channel at a higher rate than what is being delivered, having little benefit to floodplain production (Junk et al. 1989; Bayley 1991). Welcomme (1985) reported that phytoplankton abundance often peaks during the dry season, then diminishes during floods in main-channel and floodplain habitats, likely from dilution. As floodwaters recede, materials entering floodplain depressions may be stored, altered by chemical or biological forces, or discharged by flow or atmospheric interactions (Johnston et al. 1997). Lateral exchange of nutrients and organic matter between the floodplain and main river channel typically result in increased productivity of aquatic plants, plankton, invertebrates – all of which in turn are food for fishes (Junk et al. 1989; Figure 2.2).

Increased fish production (*i.e.*, improved growth and recruitment) resulting from flood pulses is referred to as a “flood pulse advantage” (Bayley 1991). Off-channel habitats provide large abundance of prey items essential for fish growth and survival (Harris and Gehrke 1994). During periods of floodplain inundation, fish consume mainly terrestrial organisms (Reimer 1991; Fisher et al. 2001). For example, burrowing crayfish Cambaridae live in dry floodplains, but provide a significant portion of the diet for some riverine fishes during inundation (Lowe-McConnell 1975; Flotemersch and Jackson 2003). Welcomme and Halls (2001) reported that 75 percent of annual growth occurs during inundation periods or rising flows due to relative lack of food during low water periods. Quist and Spiegel (2011) stated that growth of multiple sucker species (Family: Catostomidae) was positively correlated with discharges rates (*i.e.*, flooding across reaches) in Iowa rivers. Water level increases accompanied by a combination of long duration, high magnitude flood, and gradually warming temperature improves fish recruitment and is known as flood recruitment (Welcomme 1979; Bayley 1991;

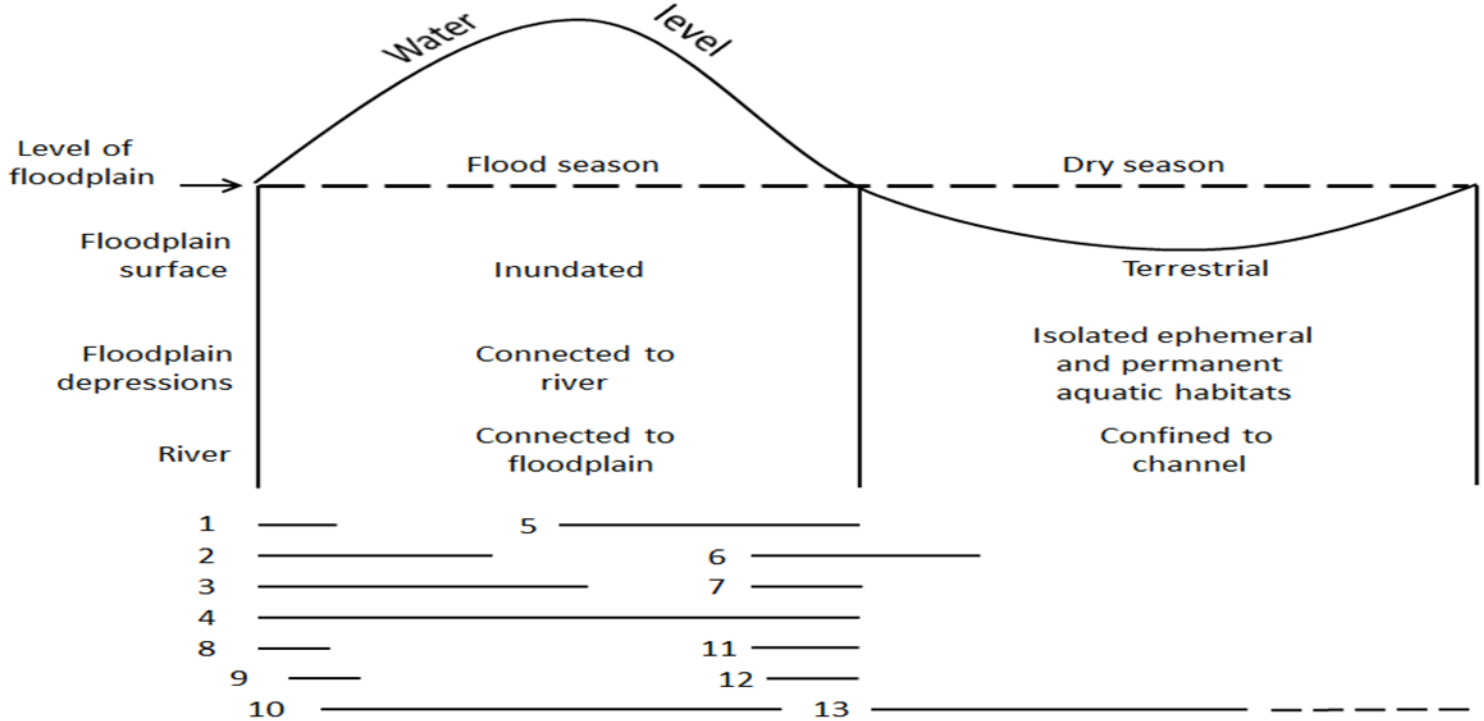

Figure 2.2. Schematic of changing water levels in a floodplain river system throughout a flood and dry season. 1, nutrients released in newly flooded areas; 2, nutrient transfer from riverine flood water; 3, rapid growth of aquatic plants and invertebrates in floodplain habitats; 4, high floodplain detrital processing; 5, export of dissolved organic matter and fine particulate matter to the river; 6, high production of plankton is floodplains; 7, plankton, benthos, and macrophytes drift to river; 8, fishes enter floodplains from river; 9, fishes spawn on floodplain; 10, maximum fish growth occurs; 11, fishes enter the river from floodplains;12, heavy fish predation at mouth of drainage channels; 13, fishes become stranded in floodplains leading to high mortality rates (Ward 1989; Galat et al. 1996).

King et al. 2003; King 2004). Thus, strong recruitment is expected when a rise in water level and optimal spawning temperatures coincide, and have a negative impact on recruitment when floodplain inundation and temperature are decoupled (King et al. 2003; Figure 2.3). Many lotic fishes (*e.g.,* Paddlefish *Polyodon spathula* and Lake Sturgeon *Acipenser fulvescens*) rely on rising discharge coupled with increased water temperature to increase the likelihood of a successful spawn and strong recruitment (Miller et al. 2008; T. Heinrich, MNDNR Large Lake Specialist, personal communication). Numerous lower Missouri River fishes have been shown to spawn when floodplain connections coincide with temperatures between 15 and 25 °C (Galat et al. 1998). Northern Pike *Esox lucius* and Bigmouth Buffalo *Ictiobus cyprinellus* also show increased reproduction during floods by spawning on newly flooded vegetation (Becker 1983; Edwards 1983). In addition to increased spawning habitat availability, inundated floodplain habitats are also beneficial to young fishes (Gorski et al. 2011).

Floodplain wetlands and backwater lakes provide important nursery habitat for fishes and are believed to be essential for survival of certain species. High wetland and backwater productivity is often directly linked with fish production (Poff et al. 1997). Slipke et al. (2005) reported that backwater habitats are more conducive to larval fish production than main channel lotic habitats in the Demopolis River, Alabama. Similar findings were reported in Pool 13 of the upper Mississippi River where more larvae were captured in backwater habitats than in main channel habitats (Sheaffer and Nickum 1986). Prolonged periods of inundation can also increase habitat availability and lessen

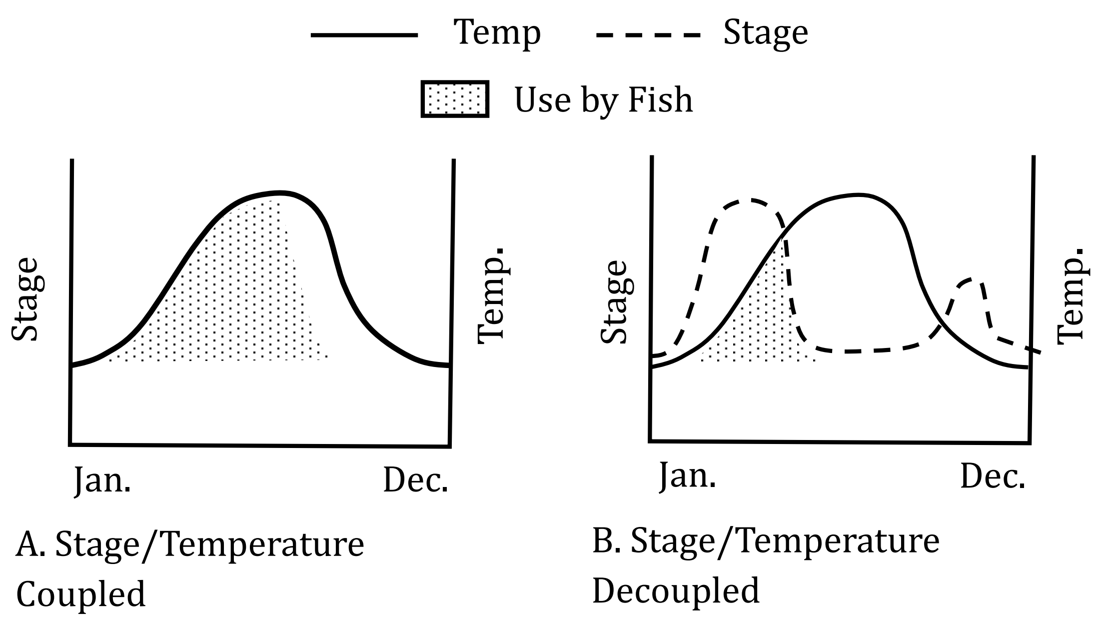

Figure 2.3.Schematic of coupling and decoupling of river stage and temperature in temperate floodplain ecosystems. A. Represents a coupling of temperature and flood stage. B. Represents an early spring flood and decoupled from temperature regime (Adopted from Junk et al. 1989 and Galat et al. 1996).

density-dependent factors such as cannibalism, competition, and predation (Peterson and Jennings 2007). Backwater-associated primary production has been linked to enhanced growth and recruitment in main channel fishes when high flow transports nutrients, organic matter, and potential prey items back to the main channel (Junk et al. 1989). For instance, Olmsted (1981) reported that washout of backwater habitats reduced pre-flood limnetic rotifer densities from 560,000 organisms/m^3 to 48,000 organisms/m^3 during peak discharge. Export of organic matter and/or potential prey items has been shown to benefit traditional fluvial species as well. Jones and Noltie (2007) reported enhanced growth in Flathead Catfish *Pylodictis olivaris* in the middle Mississippi River after the 1993 flood, and suggested increased production of invertebrate and small fish prey was a primary factor. Schramm and Eggleton (2006) concluded that growth of Blue Catfish *Ictalurus furcatus* and Flathead Catfish was positively related to duration of floodplain inundation when water temperature exceeded the minima for active feeding in the lower Mississippi River. Quist and Guy (1998) concluded growth of Channel Catfish *Ictalurus punctatus* was greatest during the high water of 1993 in the Kansas River, Kansas. Although numerous studies have indicated positive fish growth and recruitment in relation to floodplain inundation, contradictory data are also published, and some species have responded quite differently.

White Bass *Morone chrysops* growth did not differ between flood years and low-flow years in the upper Mississippi River, whereas, growth of littoral species such Largemouth Bass *Micropterus salmoides* and Bluegill *Lepomis macrochirus* increased during warm-season floods only (Gutreuter et al. 1999). Rutherford et al. (1995) reported growth of Blue Catfish, Channel Catfish, Freshwater Drum *Aplodinotus grunniens*, and

Gizzard Shad *Dorosoma cepedianum* was inversely related to the magnitude of discharge and positively related to length of growing season in the lower Mississippi River.

In temperate river systems, certain riverine fishes exploit flood pulse production and exhibit increased growth and strong recruitment; however, absence or lack of synchronization between temperature and water level rise can reduce recruitment success (Bayley 1991; Gutreuter et al. 1999; Halls and Welcomme 2004). Humphries et al. (1999) placed an emphasis on timing and duration of flood pulses, because short duration floods may not provide long enough periods of optimal habitat for spawning or rearing of young. In the Ovens River, Australia the only larval fish species to increase after the flood peak was Common Carp *Cyprinus carpio* and abundance peaked during a rapidly declining hydrograph in isolated backwater habitats (King et al. 2003). However, in absence of high flushing flows, species with life stages that are sensitive to sedimentation, such as eggs and larvae of many invertebrates and fishes often suffer high mortality rates (Poff et al. 1997). Tockner et al. (2002) suggested that flows substantial enough to connect backwaters will favor fish migration and post-pulse primary production because active overland flow may produce nutrient pulses and allow migration into backwater habitats, but depress primary production via strong current velocities during the pulse.

Flooded habitats are temporary and a risk may be associated with lateral movement of biota onto the floodplain for short periods (Humphries et al. 1999). In many rivers, floods can be unpredictable and may not be advantageous for fish species that are nest builders or exhibit parental care (Humphries et al. 1999). Due to the temporary nature of flooded habitats, low dissolved oxygen (DO) concentrations and adverse water quality conditions may make floodplain habitats less desirable for certain species (Humphries et al. 1999). Some species, such as temperate gars (Family: Lepisosteidae), evolved physiological and anatomical adaptations to inhabit hypoxic conditions (Sparks 1995)

Life history adaptations of riverine fauna to hydrological aspects, such as timing and duration of flooding, will control the response of river fish fauna (King 2004). Most information gathered for the FPC is on large pristine tropical rivers with a predictable flood pulse of long duration (Bayley 1995; Junk 1997). Tockner et al. (2000) suggested the importance of extending the FPC to temperate rivers situated in upper and middle reaches with a wide range of fluvial dynamics to further understand functional riverine processes. Growing concern over how applicable the FPC was to temperate rivers spurred other ideas on energy flow and riverine production in the absence of a flood pulse.

Low-Flow Recruitment

If flooding and warm temperatures do not coincide, certain fishes may find it more beneficial to spawn during predictable low-flow periods. Humphries et al. (1999) reported that some fishes inhabiting the Murray-Darling Basin in Australia spawn in mid-summer, when flooding likelihood is low, but predictability of high temperature and low flow is high. Humphries et al. (1999) went on to propose the low-flow recruitment hypothesis (LFR) that certain riverine fishes spawn and recruit during stable and predictable low-flow periods. Junk and Wantzen (2004) reported that when warm temperature, extended periods of light, and increased concentrations of nutrients coincide, main channels show considerable primary production, where conditions favorable for floodplain production can be hindered.

Low-flow periods typically less turbidity, increased stream temperatures, and elevated primary production that likely increases survival and growth during critical early life stages (Moore and Thorp 2008). During low flow periods, appropriate-sized prey are concentrated and tend to facilitate rapid development of young fishes. For example, during low flows of the Illinois River, zooplankton and macroinvertebrate densities were present at levels sufficient to support a functional food web, particularly for young fishes (Dettmers et al. 2001). Summer low flow periods coincide with the “critical period” and “match-mismatch” hypotheses, again emphasizing the importance and timing of larval feeding and development (Hjort 1914; Cushing 1969; Humphries et al. 1999).

Faster growth of young fishes during low flows may also be attributed to reduced energy costs of maintaining position in swift current. Flood events or rapid flow increases may dislodge individuals or force organisms to expend energy to maintain position (Allen and Castillo 2007). Harvey (1987) reported that some minnows (Family: Cyprinidae) and sunfishes (Family: Centrarchidae) smaller than 10 mm in length were susceptible to downstream displacement that likely impact growth and recruitment. In Jordan Creek Illinois, juvenile abundance of species breeding later in the year (minnows and sunfish) is associated with differences in hydrologic regime, with large increases in abundance during stable to low flow conditions (Schlosser 1995). Schlosser (1995) reported high stream magnitude had little influence on juvenile abundance of White Sucker *Catostomus commersonii* and Northern Hogsucker *Hypentelium nigricans* and several darter (Family

Percidae). In contrast, larval abundance of age-0 carpsuckers *Carpiodes* spp. was inversely related to periods of high discharge in the Oconee River, Georgia (Peterson and Jennings 2007). After young rheophilic fish (*i.e.*, species with a preference for flowing water) attain larger (35-40 mm in length) sizes, they tend to shift habitat use to stream areas with faster velocities (Schiemer and Spindler 1989). As suggested by Humphries et al. (1999), there are also disadvantages for riverine fishes during low-flow conditions.

Periods of low flow could result in high stream temperature and organic content leading to low DO concentrations and physiological stress (Schlosser 1991; Mason et al. 2007). Other direct and indirect impacts of low flow periods include dewatering via loss of longitudinal and lateral connectivity resulting in changing habitats and increased competition for food resources (Lake 2003). For instance, Grabowski and Isely (2007) reported that over the course of the spawning season in 2005 on the Savanna River, South Carolina, over 50 percent of observed nest sites for Robust Redhorse *Moxostoma robustum* were either completely dewatered or in extreme low flow conditions for several days leading to high mortality rates among proto-larvae and larvae. In addition to the physical stressors caused by low water levels, decreased water volume can also concentrate predators and potentially increase mortality (Humphries et al. 1999). Contrasting both the FPC and LFR, some researchers suggest that intermediate flows may therefore be the most beneficial to certain fishes.

Intermediate Flow Conditions

Temperate rivers are often marked by less predictable floods of shorter duration, or expansion-contraction events below bankfull called flow pulses (Puckridge et al. 1998;

Tockner et al. 2000). Moore and Thorp (2008) found young-of-year (YOY) fish survival in the Kansas River improved during intermediate flows that maximized habitat heterogeneity and slackwater patches (*e.g.,* ephemeral sandbars and wood snags). Higher densities of YOY fish, zooplankton, and invertebrates are often found in slackwaters with low turbidity and high temperatures (Thorp and Delong 1994; Moore and Thorp 2008). Intermediate flow pulses are beneficial for transporting food, oxygen, nutrients, organic matter and wastes (Roach et al. 2009). Intermediate flow pulses also increase riffle and raceway habitat via expansion and flushing. Riffle and raceway habitats are used by many spawning fishes, such as Walleye *Sander vitreus*, suckers, darters, dace Cyprinidae and stonerollers *Campostoma* spp. (Aadland et al. 1991; Aadland 1993).

In essence, aquatic organisms exhibit a dynamic equilibrium with predictable flood pulses of moderate duration (Johnson et al. 1995). However, erratic changes in discharge, such as hydrologic reversals, may result in increased physical stress on organisms from rapid changes in current velocity, turbulence, turbidity, and bed movement (Roach et al. 2009). Given the documented fish community responses to a range of flow conditions, it is apparent that no single flow model can be used for all riverine environments. However, previously discussed models describe three somewhat distinct flow conditions – high, low, and intermediate.

CHAPTER III: MINNESOTA RIVER ECOSYSTEM

Minnesota River Basin Overview

The Minnesota River is a warmwater system that encompasses 43,434 km^2 and drains portions of southwestern Minnesota, eastern South Dakota, northern Iowa, and southeastern North Dakota (Figure 3.1). The Minnesota River basin encompasses close to 20 percent of Minnesota's landmass and drains 38,435 km^2 (Kudelka et al. 2010). Made up of all or parts of 37 counties and 13 major watersheds, the Minnesota River is the largest tributary of the Mississippi River in Minnesota (Senjem 1997; Kudelka 2010). The Minnesota River flows through three distinct ecoregions, including the Northern Glaciated Plains, Western Corn Belt Plains, and North Central Hardwood Forest that are differentiated by land use, geology, vegetation, and to a lesser extent, precipitation (Omernik 1987). The goal of Chapter III is to provide an overview of the Minnesota River basin's geology, climate, and land use because these influence hydrology and nutrients which in turn influence fishes.

Geology

Sudden draining of Lake Agassiz about 10,000 years ago carved out what is now the Minnesota River valley. Following the retreat of the Des Moines Lobe of the Laurentide ice sheet, the Minnesota River basin was left with a landscape covered by glacial deposits (Winterstein et al. 1993, Senjem 1997). Today, the Minnesota River cuts though glacial deposits of the Des Moines Lobe and follows the course of Glacial River Warren along a deep and long valley that drops ~ 0.143 m/km over its entire length (Kirsch et al. 1985; Magner and Alexander 1994; Payne 1994). Post-glacial width of the

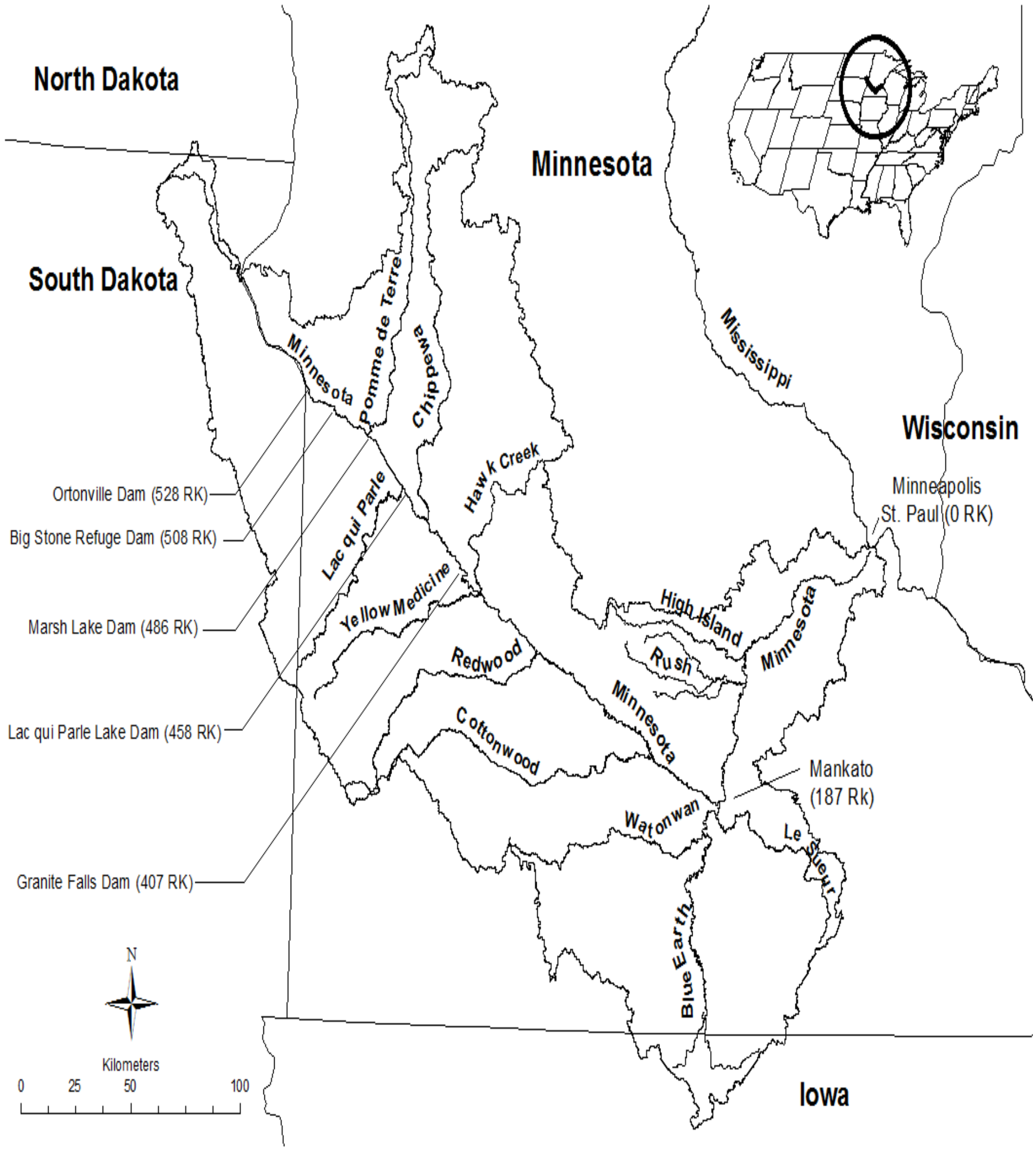

Figure 3.1**.** Map of Minnesota River basin showing all major tributaries and dams.

river channel varies from 14 to 107 m, with primary substrates being sand, gravel, and silt (Kirsch et al. 1985). Hydrologic characteristics of the basin are driven by moraines of accumulated glacial deposits and till plains that consist of unconsolidated glacial deposits (Senjem 1997). The Minnesota River follows the peripheral margins of highland moraines (Magner and Alexander 1994) and include areas of steep slopes with knickpoints near the mainstem and expanses of relatively flat and poorly drained landscapes in the upstream watershed (Downing et al. 1999).

The Minnesota River basin is described as two distinct geological portions (west and east; Payne 1994) The western portion of the Minnesota River basin is primarily dominated by the Northern Glaciated Plains and Western Corn Belt Plains Ecoregions. The western portion of the basin is covered by Cretaceous sediments that overlie crystalline Precambrian rock and is higher in total dissolved solids than the eastern portion of the basin (Magner and Alexander 1994; Payne 1994). Magner and Alexander (1994) noted that some of the oldest rocks in the world can be found near Granite Falls and Morton along the Minnesota River. The western portion of the basin also has the Coteau des Prairies. The Coteau des Prairies, a glacial moraine in the upper reaches of the basin, is characterized by an abrupt rise in land surface that is 293 m at the base and more than 610 m at the summit (Payne 1994). In the upper reaches of the Minnesota River Valley, three natural impoundments were formed from alluvial deposits of tributaries entering the Minnesota River (Big Stone Lake/Whetstone River – RKM 533, Marsh Lake/Pomme de Terre River RKM 488, and Lac qui Parle Lake/Lac qui Parle River – RKM 464; Magner and Alexander 1994).

Near the city of Mankato, the Minnesota River makes an abrupt turn to the northeast that was likely due to the course of an earlier stream developed while the Des Moines Lobe was in retreat (Jennings 2007). Just upstream of the abrupt turn in Mankato, the Watonwan and Le Sueur Rivers join the Blue Earth River. This area is characterized as the start of the eastern portion of the basin (Magner and Alexander 1994). The eastern portion of the Minnesota River basin includes portions of the Western Corn Belt Plains and North Central Hardwood Forest Ecoregions. The watersheds of the Watonwan, Blue Earth, and Le Sueur rivers are collectively known as the Greater Blue Earth River Basin (GBERB).

The GBERB drains the areas of the Minnesota River basin that that receives the highest rainfall. As a result, long-term stream discharge records show that the Blue Earth River accounts for 46 percent of the Minnesota River flow at Mankato (Payne 1994). A change in water chemistry also takes place between Judson and Courtland just upstream of Mankato (Downing et al. 1999). Glacial tills comprised of sandstones, limestones, and shales cover Cambrian and Ordovician rocks in the eastern portion of the Minnesota River basin and are high in magnesium bicarbonate (Magner and Alexander 1994). Poorly drained clay-rich till and weathered clay loams resulted in a landscape dominated by wetlands or lakes (Magner and Alexander 1994; Downing et al. 1999). Large differences in hydraulic head can be seen in the eastern basin where there is over 60 m of topographic relief adjacent to the river (Magner and Alexander 1994).

Climate

Midwest climate and weather are determined by regional characteristics, such as location (*i.e.,* latitude and longitude), topography, and land use. Continental climates in the upper Midwest experience four distinct seasons that can be variable from year-to-year. During winter months, outbreaks of cold continental polar air masses are carried via polar jet stream, with frequent storm systems and variable winds (Senjem 1997). Average January temperature is -10 °C and July average temperature is 23 °C (MPCA 2015). Midwest summers are hot and humid resulting from warm air pushed northward from the Gulf of Mexico and southwestern United States (MRBDC 2015). The freeze-free (*i.e.*, air temperature above 0°C) growing season generally starts mid-May and ends the first week of October (Senjem 1997).

About two-thirds of the total annual precipitation in the basin occurs during the cropping season (May-October), often marked by unpredictable short-duration rainfall and thunderstorms (Magner and Alexander 1994; Senjem 1997). Precipitation increases across the basin from 56 cm in the west to 76 cm in the east (Winterstein et al. 1993). In the western portion of the basin, nearly 90 percent of the annual precipitation is returned to the atmosphere via evapotranspiration, whereas about 84 percent is returned to the atmosphere in the eastern portion (Anderson et al. 1974). Conditions of moderate drought are expected once in four to five years, while severe to extreme drought is expected once every eight years and can persist for several years in succession (Senjem 1997).

Land Use and Hydrologic Impacts

Arrival of early European settlers to the Minnesota River basin dramatically altered the landscape. Prior to European settlement, 40 to 60 percent of the basin was covered with wetlands, whereas by 1992, that percentage had dropped to less than 20, with several areas approaching 0 percent (Senjem 1997). Over the past 150 years, much of the original prairie wetlands and deciduous forests have been converted to agricultural production. About 80 to 90 percent of the original wetlands have been drained for other uses, primarily agriculture (Leach and Magner 1992; Senjem 1997; Musser et al. 2009). About 76 percent of the total land acres are now used for production of grain crops, primarily corn and soy beans (Senjem 1997; Musser et al. 2009).

Wetland and aquatic habitat loss is often positively related to the extent a landscape has been altered by agricultural drainage (Blann et al. 2009). Wetlands are locations of surface water storage and groundwater recharge and wetland loss may contribute to river flooding (Allen and Castillo 2007). Precipitation that would normally be lost via evaporation from small swales or depressions now adds water to stream discharge (Magner et al. 2004).

Agricultural land conversion has catalyzed the increase in ditches, tile drainage, and surface tile inlets. As a result, land drainage has notably increased hydraulic efficiency of the stream channel network and increased streamflow, regardless of increased or decreased peak flows (Miller 1999; Renwick and Eden 1999, Blann et al. 2009, Lenhart et al. 2011). Downing et al. (1999) reported that the installation of drainage tiles and ditches throughout the Minnesota River basin has resulted in a flashier flow regime with faster and more severe responses to storm events**.** Robinson and Rycroft (1999) reported that open surface drainage carries water away more quickly, resulting in increased maximum flow rates, while subsurface using pipes will encourage infiltration and lower peak flows. Antecedent water storage and rainfall characteristics also influence runoff and total flows (Robinson and Rycroft 1999).

Artificial drainage has replaced an immature lake-wetland environment with an unstable mature fluvial landscape over a short period of time that is characterized by excessive degradation and aggradation (Quade 1981). Magner and Alexander (1994) reported that hydrology has shifted from one dominated by deeper less extensive local drainage to shallower and more extensive regional flow patterns. Prairie land conversion to agriculture can decrease soil infiltration and result in increased overland flow, channel incision, floodplain isolation, and headward erosion of stream channels (Prestegaard 1988; Poff et al. 1997).

In agricultural landscapes, crops often replace forests and prairie. Evapotranspiration (ET) from crops can have an impact on flow regime (Dingman 2002). Zhang and Schilling (2006) reported that conversion of perennial vegetation to row crops such as corn and soybeans in the Mississippi River basin reduced ET, increased groundwater recharge, and thus increased baseflow and streamflow. Schottler et al. (2013) noted that conversion to soybean agriculture resulted in a greater proportion of precipitation entering rivers in early spring because row crops are planted in late spring and replace forage crops and small grains that actively grow earlier in the spring.

Similar conditions have been reported in the Minnesota River basin where streamflow-to-precipitation ratios are increasing substantially, resulting in greater flow volumes, especially during fall and winter (Lenhart et al. 2011; Figure 3.2).

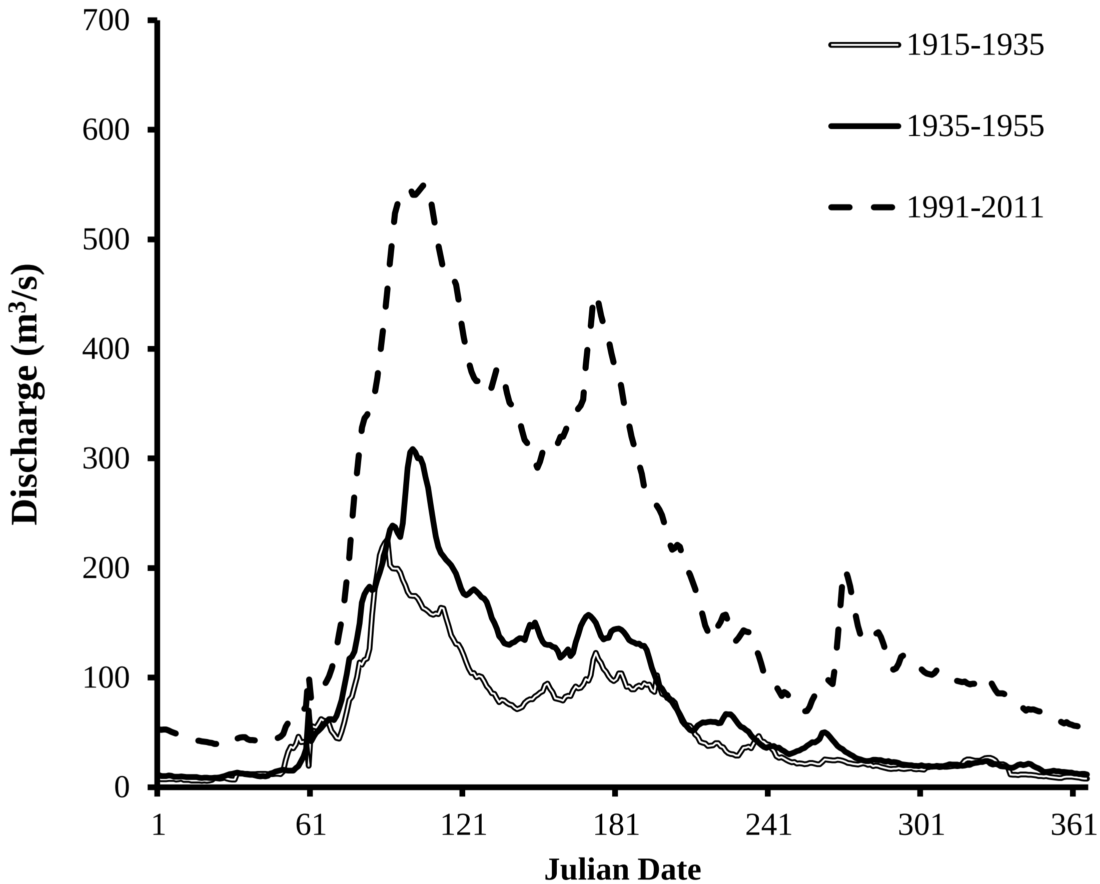

Figure 3.2. Flow history for the Minnesota River at Mankato, MN based on long-term mean annual discharge m^3/s.

The result of increased hydraulic efficiency is increased total runoff and more storm event responsive runoff patterns (Stauffer et al. 1995; Downing et al. 1999). High flow events are often responsible for channel forming conditions. Schottler et al. (2013) reported that increases in annual water yield increase channel widths. Increases in water yield for Minnesota River tributaries have been associated with 10 to 42 percent increases in channel widths since the late 1930s (Schottler et al. 2013). In combination, geology, climate, and land use ultimately impact hydrology and water quality and riverine habitats in the Minnesota River basin (Senjem 1997).

Nutrients

In landscapes dominated by agricultural drainage, less water is stored in the soil and increased overland flow ultimately increases sediment loads and nutrient concentrations (Blann et al. 2009). For example, total phosphorus (TP) concentrations in the Blue Earth River, a major tributary of the Minnesota River, were correlated with flow, suggesting strong nonpoint phosphorus contributions (Heiskary and Markus 2003). During periods of low flow, soluble phosphorus is derived primarily from wastewater treatment plants and decrease with increasing discharge and nonpoint phosphorus loading (James and Larson 2008). Payne (1994) also noted that soluble phosphorus found during non-runoff periods could be due to the release from channel sediments. Additionally, the GBERB area is considered the primary source of nitrate loading to the Minnesota River (Payne 1994). As a result, biological oxygen demand (BOD) is often statistically correlated with levels of instream production of algae, indexed by the levels of chlorophyll-a (chl-a; Payne 1994; Hatch 2002). One of the highest chl-a concentrations for large rivers worldwide was recorded near the Minnesota-Mississippi River confluence (Van Nieuwenhuyse and Jones 1996). Excessive amounts of macronutrients can also have undesirable indirect impacts on the Minnesota River ecosystem.

In the Minnesota River, nutrient/phytoplankton concentration is strongly regulated by discharge. Total phosphorus levels often exceed 200 μg/L can range from 40 to 480 μg/L, increase 2 to 5 times during runoff events, and are not limiting to phytoplankton growth (Payne 1994; Senjem 1997; Downing et al. 1999; Hatch 2002; James and Larson 2008). Similar characteristics have been recorded in the lower Minnesota River for dissolved inorganic nitrogen where concentrations ranged from 2.82 to 7.09 mg/L over 18 years (Hatch 2002). High levels of algal production can be seen throughout the mainstem of the Minnesota River, especially during low flow summer months. Dense levels of algae typically coincide with high levels of soluble orthophosphorus. During periods of high discharge algal concentration significantly decreases in the Minnesota River, likely due to shading and abrasion from physical turbidity (Payne 1994).

Biogeochemical cycle alterations can lead to cultural eutrophication in agricultural landscapes where application of fertilizer, manure, and decaying vegetation is used to enhance crop yields (Blann et al. 2009). Excessive macronutrient inputs can enhance production of photosynthetic biota as well as overall ecosystem production (Elser et al. 1990; Sharpley et al. 1994; Smith et al. 1999). Excessive algal and plant growth can lead to large diurnal fluctuations in DO and pH from daytime photosynthesis and nighttime respiration (Senjem 1997). Senescence and decomposition of dead and decaying organisms can also lead to oxygen shortages via increased BOD (Carpenter et al. 1998). Mason et al. (2007) reported that periods of low flow result in high stream temperature and organic content leading to low DO concentrations.

Nutrient enrichment can also shift species composition and biomass, especially algal and diatom assemblages that represent the foundational diets for many macroinvertebrates (Miltner and Rankon 1998; Blann et al. 2009). Increases in primary production noted during periods of low flow may shift the fish community from one dominated by insectivores and top predators to one dominated by niche generalists, omnivores, and detritivores, such as, insectivorous minnows, redhorse *Moxostoma* and black basses to Creek Chub *Semotilus atromaculatus*, Bluntnose Minnow *Pimephales promelas*, White Sucker, Common Carp and Green Sunfish *Lepomis cyanellus* (Fajen and Layzer 1993; Rankin et al. 1999). Major changes in lower trophic levels ultimately affect higher trophic levels and overall food web structure (Blann et al. 2009). Overproduction of algae can also limit light penetration and reduce overall quality of habitat for macroinvertebrates, periphyton, and fishes (Correll 1998; Blann et al. 2009).

Phosphorus can influence aquatic fauna metabolic rates. Dodson (2005) reported that fishes have lower metabolic rates when undernourished and at least in moderation, enrichment can increase game fish production (McDaniel 1993). For instance, Smallmouth Bass *Micropterus dolomieu* and Largemouth Bass growth has been shown to be positively correlated with total phosphorus (Yurk and Ney 1989; Putman et al. 1995).

However, in the Minnesota River basin, excessive algal blooms during low-flow periods favor omnivorous species that have the ability to digest both plants and animals and switch between food sources when one type is disrupted (Heiskary and Markus 2003).

Fishes of the Minnesota River

Biological communities of the Minnesota River are adversely impacted by land use practices (Stauffer et al. 1995). Many fish populations are less abundant than historical conditions and some species have not been recorded for more than three decades and may be extirpated (Schmidt and Proulx 2007). Talmage et al. (2002) reported 88 fish species in the Minnesota River basin; however, 104 fish species from 24 families have been documented in counties adjacent to the Minnesota River (Schmidt and Proulx 2007). In 2005, 60 species of fish were documented in the Minnesota River during a survey targeting threatened, special concern, or rare species (Proulx 2005; Schmidt and Proulx 2007). In 1992, 1998, and 2004 routine fish population assessments documented 64, 68 and 64 species, respectively (Stauffer et al. 1995; Chapman 2000; Chapman 2004).

A quality recreational fishery exists in the Minnesota River. Recreational species include Flathead Catfish, Channel Catfish, Walleye, Sauger *Sander canadensis*, Northern Pike, and White Bass (Schmidt and Proulx 2007). A 1998 angler creel survey reported that the two most sought after fishes were Channel Catfish (25 harvested fish/mile) and Flathead Catfish (6 harvested fish/mile). An estimated 49,311 hours of angling pressure were expended from 1 May to 31 October (Chapman 2001).

Rare large riverine species such as Paddlefish *Polyodon spathula*, Lake Sturgeon, Blue Sucker *Cycleptus elongatus*, and Black Buffalo *Ictiobus niger* have also been documented in the lower free-flowing reaches of the Minnesota River (Schmidt and

Proulx 2007). Shovelnose Sturgeon *Scaphirhynchus platorynchus* and Smallmouth Bass increased in abundance between the early 1990s and 2007 (Lundeen and Koschak 2011).

Since the 1980s, a substantial amount of information has been collected regarding fish species diversity and abundance in the Minnesota River (Stauffer et al. 1995). Previous surveys documented population dynamics of important recreational species, including recruitment, age and growth, mortality and movement (Stauffer et al. 1995; Stauffer et al. 1996; Chapman 2000; Chapman 2004, Shroyer 2011). Aside from presence/absence and relative abundance, however, little work has been done on population dynamics of nongame fishes. Also, few studies have attempted to identify physicochemical factors influencing population dynamics of game and nongame fishes in the context of large river ecology.

Eight common Minnesota River fishes were examined in the present study, including Common Carp, Bigmouth Buffalo, River Carpsucker *Carpiodes carpio,* Shorthead Redhorse *Moxostoma macrolepidotum*, Channel Catfish, Flathead Catfish, Walleye, and Freshwater Drum. Channel Catfish, Flathead Catfish, Walleye, and Freshwater Drum were included due to recreational importance. Fishes of commercial significance were Bigmouth Buffalo and Common Carp. Shorthead Redhorse and River Carpsucker account for a considerable biomass in the Minnesota River, yet little is known about population dynamics of either. These eight fishes encompass an array of functional feeding groups, habitat preferences, reproductive behaviors, and temperature preferences (Table 3.1).

Table 3.1. Trophic classification (O/D – omnivore/detritivore, PK – planktivore, IN – insectivore, PI – piscivore), optimal growing temperature (+/- 4 degrees Celsius), reproductive classification (NG- non guarder, G – guarder), optimal spawning temperature (+/- 4 degrees Celsius), and approximate spawning months for all target species. Listed is source for temperature preferences and approximate spawning months.

Common Name	Trophic Guild	Optimal Growing Temperature (+- 4 degrees Celsius)	Reproductive Guild	Optimal Spawning Temperature (+- 4 degrees Celsius)	Spawning Months
Common Carp	O/D	27 (23-31) - Wismer and Christie (1987)	NG, Phytolithophil	19 (15-23) - Wismer and Christie (1987)	March-June
Bigmouth Buffalo	PK	28 (24-32) - Edwards (1983)	NG, Lithopelagophil	20 (16-24) - Edwards (1983)	March-June
River Carpsucker	O/D	22 (18-26) - Wismer and Christie (1987)	NG, Lithopelagophil	21 (17-25) - Kay et al. (1994)	April-July
Shorthead Redhorse	IN	26 (22-30) - Wismer and Christie (1987)	NG, Lithophil	12 (8-16) - Sule and Skelly (1985)	March-June
Channel Catfish	O/D	25 (21-29) - Coutant (1977)	G, Speleophil	26 (22-30) - Scott and Crossman (1973)	May-August
Flathead Catfish	PI	27 (23-31) - Lee and Terrel (1987)	G, Speleophil	22 (18-26) - Lee and Terrel (1987)	May-August
Walleye	PI	22 (18-26) - McMahon et al. (1984)	NG, Lithopelagophil	10 (6-14) - Becker (1983)	March-June
Freshwater Drum	IN	22 (18-26) - Edsall (1967)	NG, Pelagophil	20 (16-24) - Wallus and Simon (2006)	April-July

CHAPTER IV: MINNESOTA RIVER HYDROLOGIC AND THERMAL REGIMES

Introduction

The flood pulse, low-flow recruitment, and intermediate flow concepts were proposed, in part, to help river managers understand the pervasive influence of hydrologic regimes on aquatic habitat and riverine biota (Junk et al. 1989; Humphries et al. 1999; Moore and Thorp 2008). Thus, quantifying a river's hydrologic regime is a fundamental requirement to understanding and testing the applicability of these concepts to a particular system. There are five key elements that comprise a river's hydrologic regime: 1) magnitude, 2) frequency, 3) duration, 4) timing, and 5) the rate of change of high and low flow conditions (Richter et al. 1996; Poff et al. 1997; Allen and Castillo 2007) and each of these needs to be quantified.

In addition to stream flow, temperature is an integral part of the flood pulse and low-flow recruitment concepts. Temperature is a key property driving ecological processes such as production of food organisms, fish feeding rates, metabolic rates, and spawning cues for fishes (Tonolla et al. 2010). In terms of growth and development, especially for ectotherms, a specific thermal preference exists. One of the most widely used thermal parameters is growing degree-day or the daily temperature measured below, between, or above some temperature threshold (Nueheimer and Taggart 2007). In addition, temperature is an important reproductive cue for many fishes (Junk et al. 1989). Like hydrology, optimal thermal conditions for fish growth and spawning need to be quantified, and where necessary, coupled with appropriate hydrology measures.

Several hydrologic and thermal elements are key to understanding and quantifying the flood pulse concept for rivers. These include 1) defining two primary flood levels: the discharge magnitude at which backwater habitats (termed high flows) or the active floodplain (termed small floods) become connected to the main river channel, 2) the frequency and duration of these two connections and 3) the duration of these connections that were simultaneously coupled with appropriate temperatures for either fish spawning or growth. For instance, optimal spawning temperature for Common Carp often occurs during spring and early summer, and has been reported as 15 to 25 °C in the Red River of the North along the Minnesota and North Dakota border (Resseguie and Kelsch 2008). Resseguie and Kelsch (2008) also noted that peak spawning temperature appeared to coincide with discharge spikes, suggesting discharge magnitude was likely a synchronizing cue that triggered spawning.

Similar to the flood pulse concept, the low-flow recruitment concept requires an extreme low-flow threshold be defined for each river and that selected indices of the frequency and duration of extreme low flows are calculated. Extreme low flows that are coupled with important water temperatures (*e.g.*, for growth or reproduction) will also need to be determined to test the importance of water temperature to this concept. Humphries et al. (1999) noted that several Australian fishes spawned in midsummer when temperatures were high and flows were low. Humphries et al. (1999) also suggested that summer low flow spawning was advantageous in that concentrations of appropriate-sized prey, such as rotifers and benthic microcrustaceans are greatest at this time.

In contrast with the flood pulse and low flow recruitment concepts, the intermediate flows concept suggests that optimal conditions for spawning and YOY growth for prairie river fishes occurs when flows provide maximum in-channel habitat heterogeneity and ample slackwater patches (*i.e.*, areas of minimal current velocity) (Thorp and Casper 2002; Moore and Thorp 2008). In-channel slackwater patches often have low turbidity and high temperatures resulting in high densities of YOY fishes (Moore and Thorp 2008). In addition, YOY prairie fishes are capable of persisting through periods of extreme hydrologic variability (Moore and Thorp 2008). A corollary benefit of hydrologic variability is flushing of sediments from coarse substrate used for spawning by many river fishes (Aadland et al. 1991; Aadland 1993).

Similar to the flood pulse and low flow recruitment concepts, specific flow thresholds, or magnitudes, need to be identified to permit quantification of frequency and duration of intermediate flows. Frequency and duration of intermediate flows that are coupled with important spawning and growing temperatures may be important to this concept. Lastly, the intermediate flow concept suggests that YOY prairie fishes are able to cope with hydrologic variability that consequently may produce high abundances of YOY when flows are more variable (Moore and Thorp 2008). The overall goal of this chapter is to describe the current hydrological patterns in the Minnesota River and quantify selected hydrological and thermal aspects associated with the three riverine concepts.

Chapter Objectives

Specific objectives for this chapter are

1) Describe the current hydrology (1991-2011) of the Minnesota River
2) Quantify selected annual characteristics of the flood pulse concept between 2001 and 2011 at two primary flood levels by completing a-d below,
   a) Quantify the number of high flow events, their fall rate, and their duration each year that allowed access to secondary habitats (*i.e.*, backwater lakes, secondary channels, slackwater) as described by the flood pulse concept,
   b) Quantify the total duration of days each year that the active floodplain (>small floods) or secondary habitats (high flows) were inundated that might have allowed a productivity burst to enhance fish growth,
   c) Quantify the total degree-days for growing and spawning for selected Minnesota River fishes,
   d) Quantify the number of days each year that the active floodplain (>small floods) or secondary habitats (high flows) were inundated and coupled with preferred spawning and growing temperatures for fishes,
3) Quantify selected annual characteristics of the low-flow recruitment concept between 2001 and 2011 by completing a-b below,
   a) Quantify the number of days each year with extreme low flow conditions,
   b) Quantify the number of days each year when extreme low flow conditions were coupled with preferred spawning or growing temperatures of selected Minnesota River fishes,
4) Quantify selected annual characteristics of the intermediate flows concept between 2001 and 2011 by completing a-c below,
   a) Quantify the number of intermediate flow days that may have flushed riffle habitats for spawning or downstream drift of food organisms,
   b) Quantify the number of days each year that intermediate flows were also coupled with preferred spawning and growing temperatures for fishes, and
   c) Quantify the rate and frequency of hydrologic reversals each year that might have placed physical stress on young fishes.

Methods

To describe the current hydrology of the Minnesota River, discharge data (m^3/s) were obtained from the United States Geological Survey (USGS) gauging station (05325000) in Mankato, Minnesota and analyzed with the Indicators of Hydrological Alteration (IHA; Version 7.1, The Nature Conservancy 2009) software program (Richter et al. 1996). The IHA program calculates two sets of hydrologic parameters. The first set calculates 33 IHA parameters and the second set, called Environmental Flow Components (EFC) calculates 34 parameters (Tables 4.1 and 4.2).

The 33 IHA parameters quantify several aspects of the magnitude, frequency, duration, timing and rate of change of river flows (Table 4.1). The IHA parameter set includes summaries of monthly flows, magnitude and duration of 1-day, weekly (7-day), and seasonal (90-day) time periods, and the rate and frequency of water condition changes. Whereas the 33 IHA variables represent hydrology more broadly, the 34 EFC parameters (Table 4.2) represent a series of ecologically relevant hydrology variables needed to sustain a river's ecological integrity (*e.g.*, extreme low flow, low flow, high flow, small flood and large flood; IHA 2009).

Extreme low flows were defined as flows falling below 19 m^3s, or below the 10th percentile of daily flows from 1991-2011 (Figure 4.1). In the Minnesota River, low flows were calibrated to flows between 19 m^3/s and the high flow threshold (see below). All EFC low flows represent normal flows within the Minnesota River channel and are functionally equivalent to intermediate flows described in the intermediate flow concept and will be referred to as such henceforth. High flows were defined as flows exceeding

Table 4.1 Indicators of Hydrologic Alteration (IHA) parameters that were quantified to define the current hydrology (1991-2011) of the Minnesota River at Mankato, MN.

Group	Parameters	Definition/unit of measurement	Example Ecosystem Influences
(1) Magnitude of monthly conditions	January median flows	m^3/s	Habitat availability for Minnesota River fishes Influences water temperature and dissolved oxygen levels
	February median flows	m^3/s	
	March median flows	m^3/s	
	April median flows	m^3/s	
	May median flows	m^3/s	
	June median flows	m^3/s	
	July median flows	m^3/s	
	August median flows	m^3/s	
	September median flows	m^3/s	
	October median flows	m^3/s	
	November median flows	m^3/s	
	December median flows	m^3/s	
(2) Magnitude and duration of annual extreme water conditions	Lowest annual 1-day flow	m^3/s	Influences duration of stressful conditions such as low oxygen levels, high temperatures, or high chemical concentrations Duration of high flows influences waste disposal, formation of instream physical habitat and connections to floodplain habitats
	Lowest annual 3-day flow	m^3/s	
	Lowest annual 7-day flow	m^3/s	
	Lowest annual 30-day flow	m^3/s	
	Lowest annual 90-day flow	m^3/s	
	Highest annual 1-day flow	m^3/s	
	Highest annual 3-day flow	m^3/s	
	Highest annual 7-day flow	m^3/s	
	Highest annual 30-day flow	m^3/s	
	Highest annual 90-day flow	m^3/s	
	Number of zero-flow days	Number	
	Baseflow index	7-day minimum flow/mean flow for the year	
(3) Timing of annual extreme water conditions	Julian date of each annual 1-day maximum flow	Julian date	Spawning cues for fishes Timing of access to floodplain habitats
	Julian date of each annual 1-day minimum flow	Julian date	
(4) Frequency and duration of high and low flow pulses	Count of low flow pulses	Number	Nutrient and organic matter exchanges Access to floodplain habitats
	Duration of low flow pulses	Days	
	Count of high flow pulses	Number	
	Duration of high flow pulses	Days	
(5) Rate and frequency of water condition changes	Rise rates	$m^3/s/day$	Fish entrapment in floodplain habitats
	Fall rates	$m^3/s/day$	
	Number of reversals	Number of times flow shifts from rising to falling or vice versa	

Table 4.2. Environmental Flow Component (EFC) parameters that were quantified to define the current hydrology (1991-2011) of the Minnesota River at Mankato, MN and where indicated (in bold), to quantify selected hydrologic aspects of three riverine concepts to test for applicability to the Minnesota River hydrosystem.

Group	Parameters	Definition/Unit of Measurement	Example Ecosystem Influences
(1) Monthly low flow conditions (Intermediate flows)	January low flows	m^3/s	Minimum aquatic habitat available for Minnesota River fishes Maintenance of suitable water temperature and dissolved oxygen Maintenance of water table levels in floodplains Minimum flows to keep buoyant fish eggs suspended
	February low flows	m^3/s	
	March low flows	m^3/s	
	April low flows	m^3/s	
	May low flows	m^3/s	
	June low flows	m^3/s	
	July low flows	m^3/s	
	August low flows	m^3/s	
	September low flows	m^3/s	
	October low flows	m^3/s	
	November low flows	m^3/s	
	December low flows	m^3/s	
(2) Extreme low flows (daily flows lower than the 10^{th} percentile of all daily flows between 1991-2011)	Extreme low flow peak (magnitude)	Minimum flow during the event (m^3/s)	Indicator of drought conditions May be beneficial to fishes that spawn during low flow conditions
	Extreme low flow duration	Days	
	Extreme low flow timing	Julian date of 1-day lowest extreme low flow	
	Extreme low flow frequency	Number of extreme low flow events each year	
(3) High flows (daily flows higher than 200 m^3/s, a discharge at which backwater habitats become connected to the main channel)	High flow peak (magnitude)	Maximum flow during the event (m^3/s)	Connections to backwaters and off-channel habitats in the floodplain (e.g., oxbows) but not the floodplain itself Aerate fish eggs in spawning gravels, prevent siltation
	High flow duration	Days	
	High flow timing	Julian date of 1-day peak flow	
	High flow frequency	Number of high flow events each year	
	High flow rise rate	$m^3/s/day$	
	High flow fall rate	$m^3/s/day$	
(4) Small floods (daily flows higher than the 2-year flood return interval)	Small flood peak (magnitude)	Maximum flow during the small flood event (m^3/s)	Allow fish access to the floodplain for spawning, feeding and juvenile nursery Allow lateral exchange of nutrient between the floodplain and in-channel habitats
	Small flood duration	Days	
	Small flood timing	Julian date of 1-day peak small flood flow	
	Small flood frequency	Number of small flood events each year	
	Small flood rise rate	$m^3/s/day$	
	Small flood fall rate	$m^3/s/day$	

Table 4.2. Continued.

Group	Parameters	Definition/Unit of Measurement	Example Ecosystem Influences
(5) Large floods (daily flows higher than the 10-year flood return interval)	Large flood peak (magnitude)	Maximum flow during the large flood event (m^3/s)	Allow fish access to the floodplain for spawning, feeding and juvenile nursery Allow lateral exchange of nutrient between the floodplain and in-channel habitats Shape riverine habitats and substrates
	Large flood duration	Days	
	Large flood timing	Julian date of 1-day peak large flood flow	
	Large flood frequency	Number of large flood events each year	
	Large flood rise rate	$m^3/s/day$	
	Large flood fall rate	$m^3/s/day$	
(6) Intermediate flows (all flows less than high flows (200 m3/s) and higher than extreme low flows; analogous to low flows in IHA program)	**Duration of intermediate flows**	Days	In-channel flows representing the dominant hydrologic condition in most rivers Determines amount of aquatic habitat available for most of the year
	Number of reversals	Number	

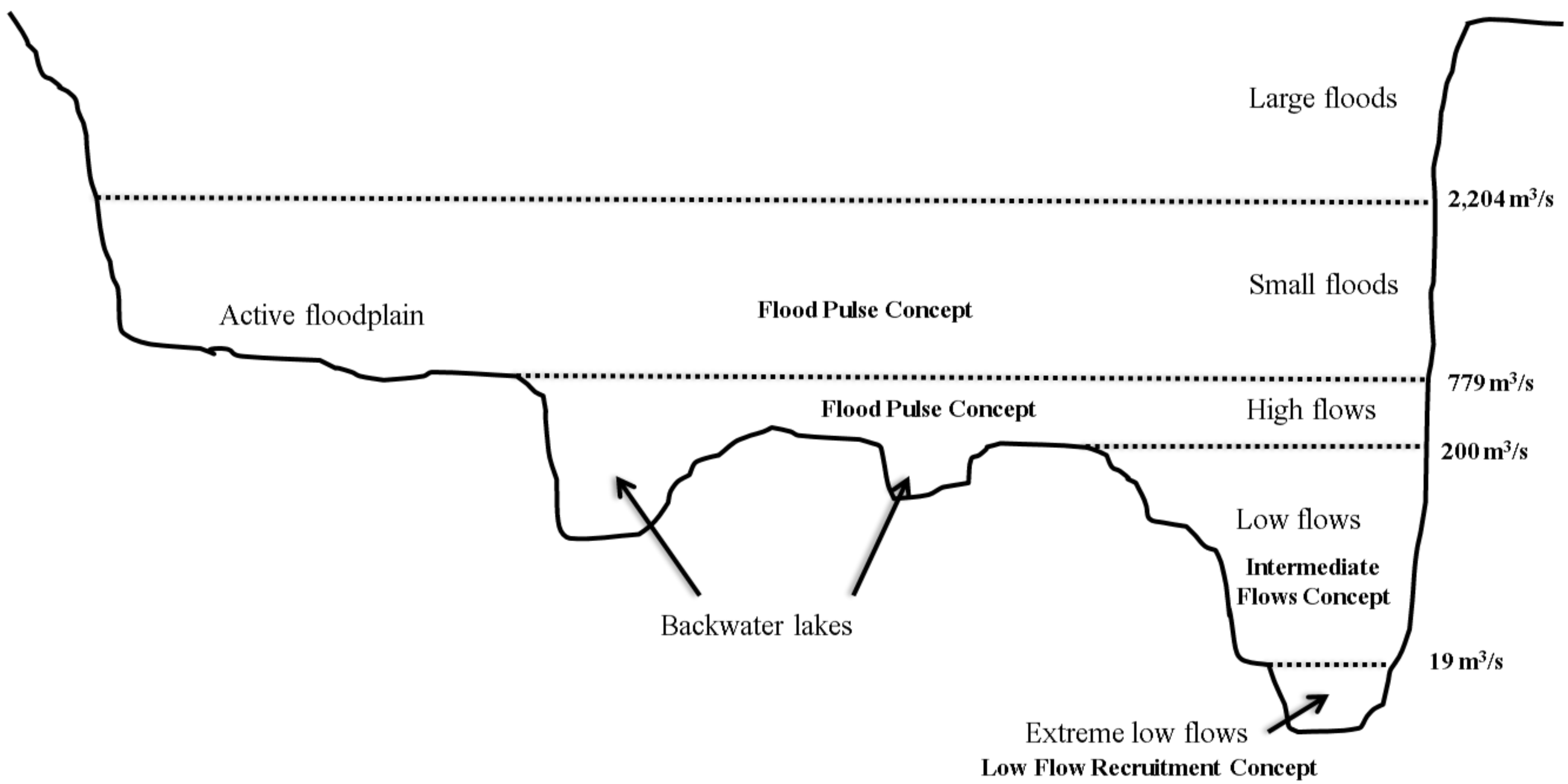

Figure 4.1. Hypothetical cross-section of the Minnesota River. Threshold discharge for extreme low flows in the Minnesota River is 19 m^3/s. and is the 10th percentile of all flows. Threshold discharge for low (intermediate) flows in the Minnesota River is 19 m^3/s to 200 m^3/s. Threshold discharge for high (backwater connection) flows in the Minnesota River is 200 m^3/s to 779 m^3/s. Threshold discharge for small floods (active floodplain connection) in the Minnesota River is 779 m^3/s to 2,204 m^3/s or flows greater than bankfull but less than the 10-year flood interval (*i.e.*, 2-year flood interval). Threshold discharge for large floods in the Minnesota River is flows > 2,204 m^3/s or flows equal to or greater than the 10-year flood interval.

200 m^3/s because this was the observed minimum discharge for backwater lake connections in the study area in a concurrent Minnesota River project (Nickel 2014). Small flood flows were set from a 2-year return interval at 779 m^3/s. Large floods were based on a 10-year return interval at a discharge of 2,204 m^3/s.

To characterize the current range of variation in a river's flow regime, a minimum of twenty years of record should be used (Richter et al. 1997). Annual values for each of the 33 IHA and 34 EFC parameters, over the minimum 20-yr time period, were compiled and the 25th, 50th, and 75th percentiles were calculated. The 25th and 75th percentiles are commonly used to describe the current range of reference hydrologic conditions that future hydrology can be compared to (Richter et al. 1997). Because of the non-normal distribution of hydrologic data, all IHA and EFC parameters were calculated using non-parametric analyses (IHA 2009). Non-parametric statistics analyze flow data using percentile statistics, whereas parametric analyses calculate mean and standard deviation (IHA 2009). To tabulate duration for EFC parameters, daily flow values were categorized as one of four specific EFC components: 1) extreme low flows, 2) intermediate flows, 3) backwater connection flows, and 4) active floodplain connection flows.

Hydrologic and thermal characteristics of the river ecology concepts are only presented here for the years 2001-2011 because this was the extent of fish population data assessed in subsequent chapters. The EFC parameters for high flow events (frequency, fall rate, and duration) and flows greater than small flood events (duration) were used to quantify hydrologic aspects of the flood pulse concept (Table 4.2). High flow events represented hydrologic connections to off-channel backwaters and oxbow lakes but not direct connections to the active floodplain and will be termed backwater connection flows. Small flood events represented connections to the active floodplain. All flows greater than small floods were termed active floodplain connection. To incorporate temperature effects, air temperatures were used as a surrogate for water temperatures because residuals between the two measurements are typically well correlated with each other (Kothandaraman 1972). Air temperature data were obtained from the National Oceanic and Atmospheric Administration (NOAA) weather station in Mankato, Minnesota.

Temperature was assessed as length of growing season and optimal spawning conditions (Rutherford et al. 1995). Length of growing season was reported as the number of optimal growing days (OGD) for each species based on thermal preference, plus and minus 4 degrees. Optimal spawning days (OSD) were reported as number of days with optimal spawning temperatures, plus and minus 4 degrees (see Table 3.1) based on species thermal preferences. Thermal preferences were typically during spring and summer, therefore, fall temperatures were not included in the total day counts. Optimal growing/spawning temperatures were then coupled with EFC components specified above.

To quantify selected aspects of the low flow recruitment concept, I used the EFC in the IHA program for extreme low flow (Table 4.2). To determine the number of days (duration) each year that extreme low flow conditions were present and coupled with optimal spawning and growing temperatures for fishes, a count was tallied for each day that temperatures and extreme low flows coincided on an annual basis.

To quantify selected aspects of the intermediate flow concept, I used the EFC parameters in the IHA program that specifically identified days with intermediate flows. The number of days (duration) each year that had intermediate flow conditions was enumerated. To determine the number of days each year with intermediate flows that coupled with optimal spawning and growing temperature for fishes, a count was tallied for each day that temperatures and intermediate flows coincided. The number of hydrological reversals, is an IHA parameter and represents daily changes in flow that were either positive or negative.

Results

Hydrology of the Minnesota River: 1991-2011

Minnesota River hydrology is typified by a mostly spring snowmelt and rainfall-driven unimodal flood-pulse followed by low flows in mid- to late summer. More specifically, flows are often lowest in mid- to late winter (January and February), increase and peak during spring (April), and then gradually subside to low levels in August and September (Figures 4.2 and 4.3; Appendix A). Low flow in late summer may be followed by a second smaller flow pulse in October or November before falling back to winter low flow conditions. Maximum 1-day flows currently range from 606 to 1,390 m^3/s and 1-day minimum flows from 8 to 27 m^3/s (Appendix A). Maximum flows peaked on average at about 779 m^3/s on April 29, but the current normal range of variation could be any day between April 7 and June 12. Flows currently reach their one-day minimum level anytime between October 5 and the following February 5. On average, the river rises and falls at a similar rate of 4 m^3/s per day, with the current range of hydrologic reversals varying from 56 to 74 each year.

Several ecologically-relevant hydrologic variables [EFCs] were also calculated to further describe the current hydrology of the Minnesota River (Appendix A). Extreme low flows for the Minnesota River do not occur every year but have increased in occurrence since 1998. On average, extreme low flows peak at 17 m^3/s and occur in early November. Median duration of extreme low flows is 48 days, but lasted up to 179 days in 2003. The current range of extreme low flow duration varies from 19 to 79 days.

Monthly

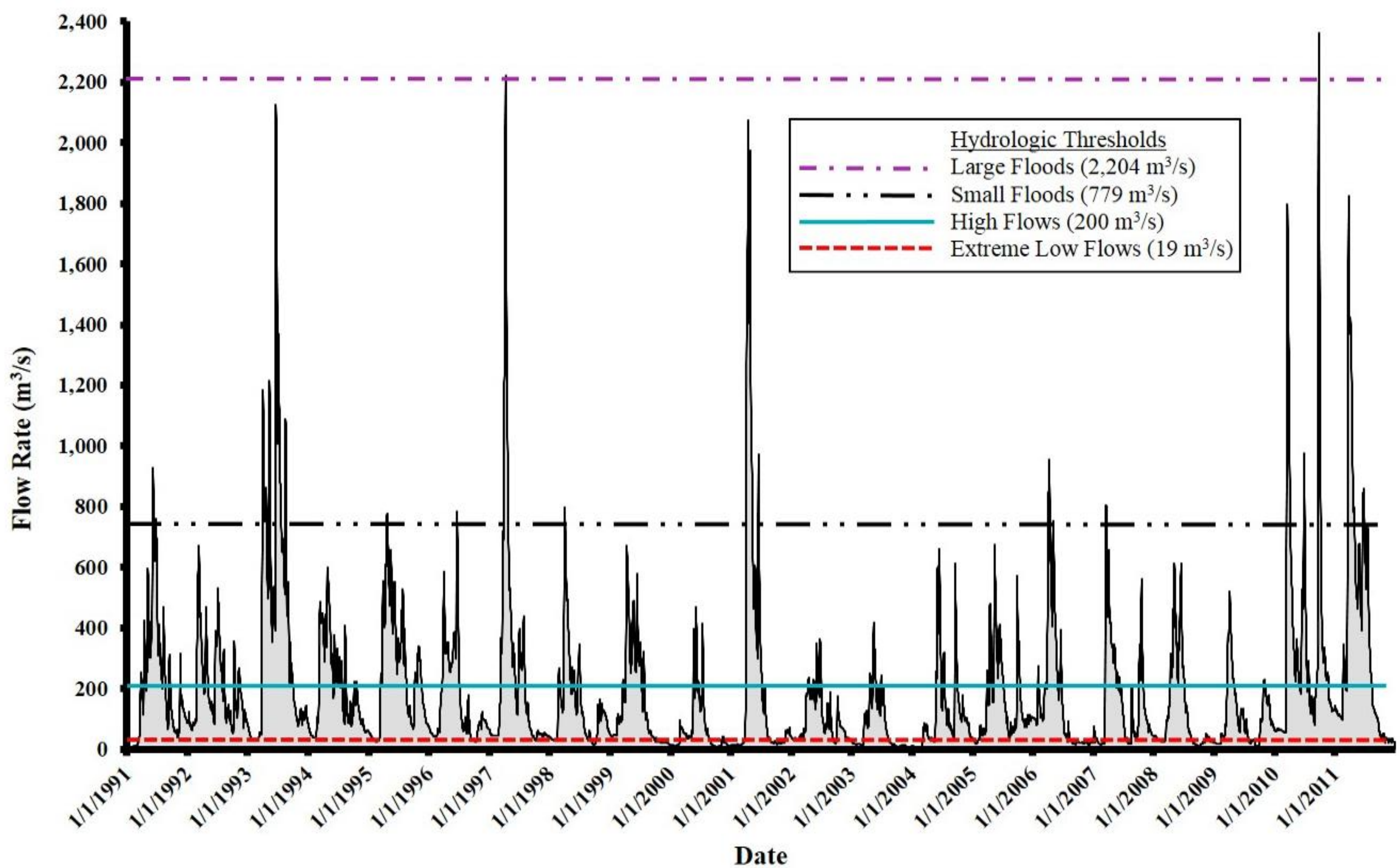

Figure 4.2. Hydrograph for the Minnesota River in Mankato, MN from 1991-2011. Flow rates are in cubic meters per second (m^3/s). The thresholds for extreme low flows (19 m^3/s), high flows (200 m^3/s), small floods (779 m^3/s), and large floods (2,204 m^3/s) are denoted by the horizontal lines.

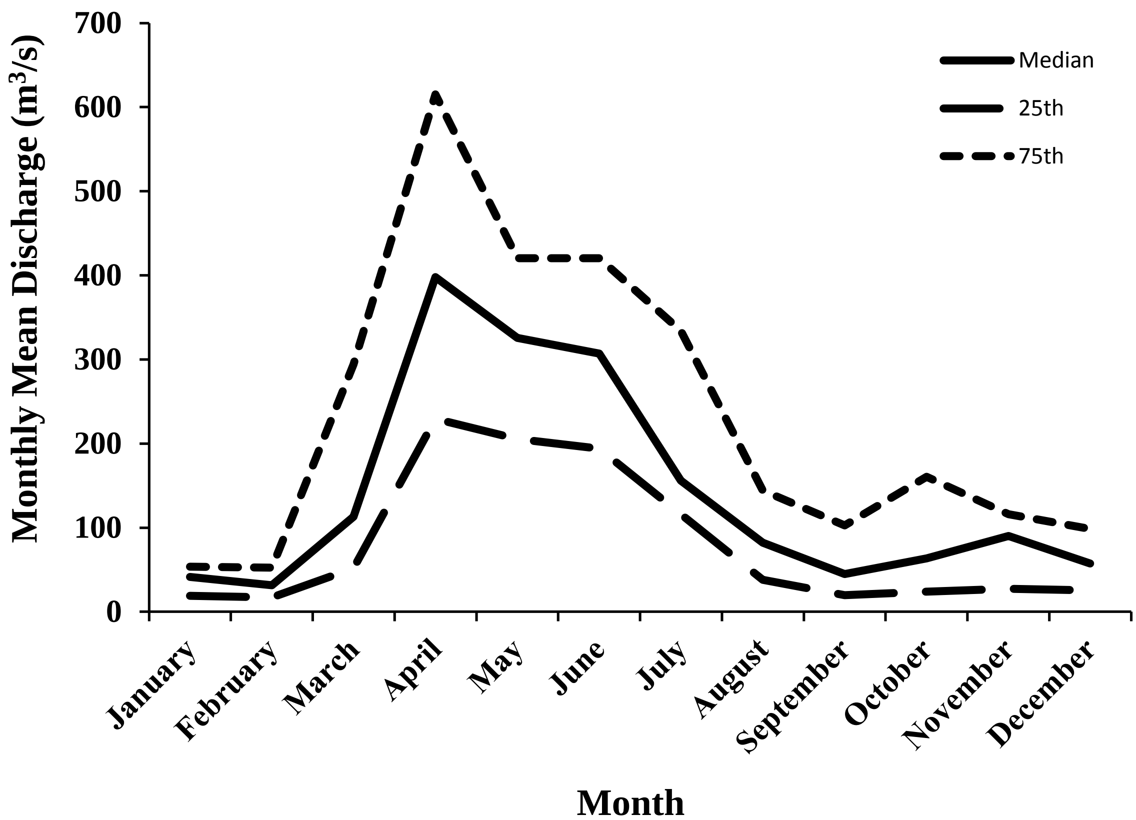

Figure 4.3. Monthly mean flow magnitudes from 1991-2011 for the Minnesota River. Solid line represents median (or 50th percentile). Large dashed line represents 25th percentile. Small dotted line represents 75th percentile.

intermediate flows depicted a similar annual hydrologic pattern to the IHA parameters with lower values in winter followed by increases in spring and early summer. However, median monthly intermediate flows during spring and early summer were lower than IHA parameters because any flows greater than 200 m^3/s were *a-priori* classified as either backwater connection flows, small floods, or large floods in EFC calculations (*i.e.*, intermediate flows stop being intermediate flows after reaching the 200 m^3/s threshold). Backwater connection flow conditions typically occur one to five times per year, often in mid-June. When backwater connection flows occur, the condition persists from 35 to 204 days. Backwater connection flows tend to rise faster than they fall, having a daily rise of 24 m^3/s and a daily fall of 12 m^3/s.

The Minnesota River at Mankato did not exhibit an annually predictable flood pulse, as described by the flood pulse concept, between 1991 and 2011. The main river channel was only connected to its floodplain in 11 of the 21 years examined (*i.e.*, exhibited either a small flood or a large flood; Table 4.1; Figure 4.2). When small or large floods occur, it is almost exclusively only one flood event in a given year. The current baseline range of variation for small floods is that they last for 2 – 44 days, occur between April 1 and June 12, rise rapidly at 17 to 113 m^3/s, and fall much slower at 11 to 24 m^3/s. Large floods last for 2 - 3 days, occur between April 9 and September 27, rise at 66 to 144 m^3/s, and fall at 33 to 36 m^3/s. In 2010, the largest large flood peaked at 2,362 m^3/s and in 2011 the largest small flood peaked at 1,826 m^3/s

Flood Pulse Concept

An annual flood pulse was similarly lacking in the truncated 2001-2011 time period with the active floodplain (> small flood event), only being connected in 2001, 2006, 2007 (briefly-2days), 2010, and 2011 (Table 4.3). The longest time the active floodplain was connected to the main channel was for 51 days in 2011. Instead, a flood-pulse effect might have been more common for backwater connection flows that connected secondary off-channel habitats in all 11 years. The number of backwater connection flow events each year ranged from one (in three of the study years) to six events in 2010. Backwater connection durations ranged from 35 days in 2003 to 204 days in 2010. Backwater connection fall rates also varied from year to year. The fastest fall rate was in 2004 at 31 m^3/s per day and the slowest fall rate was in 2001 and 2008 at 7 m^3/s per day.

Duration of optimum spawning and growing temperatures for the selected Minnesota River fishes were temporally variable (Table 4.4). On average, Flathead Catfish had the greatest number of OSD, while Bigmouth Buffalo and Walleye had the fewest number of OSD. River Carpsucker, Walleye, and Freshwater Drum had the greatest number of OGD, while Bigmouth Buffalo had the fewest number of OGD.

Optimal spawning and growing temperatures were coupled with active floodplain connection only in 2001, 2006, 2010, and 2011 (Table 4.5**)**. Optimal temperatures and floodplain inundation were decoupled in the other seven years. However, optimal spawning and growing temperatures were coupled with backwater connections in all years, with exception of 2009 for Channel Catfish and Flathead Catfish. In general, 2009

Table 4.3 Total number of backwater connections, backwater connection fall rates, backwater connection duration, and active floodplain connection duration from 2001-2011 for the Minnesota River in Mankato, MN.

Parameter	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Backwater Connection Frequency	1	3	1	4	5	3	3	3	1	6	2
Backwater Connection Fall Fate	-7	-10	-12	-31	-18	-16	-8	-7	-10	-19	-11
Backwater Connection Duration	100	44	35	59	109	101	120	87	55	204	172
Active Floodplain Connection Duration	41	0	0	0	0	10	2	0	0	42	51

Table 4.4. Total number of days with either optimal spawning and growing temperatures for each target species from 2001-2011for the Minnesota River in Mankato, MN.

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	Mean (SE)
Optimal Growing Days (OGD)												
Common Carp	40	47	33	15	42	34	55	22	15	46	41	35 (4.0)
Bigmouth Buffalo	13	19	9	1	16	7	8	5	3	12	12	10 (1.7)
River Carpsucker	77	84	88	78	95	102	105	98	84	91	89	90 (2.8)
Shorthead Redhorse	47	56	46	23	49	52	60	31	18	52	45	44 (4.1)
Channel Catfish	54	66	58	41	59	63	77	47	32	73	58	57 (4.0)
Flathead Catfish	40	47	33	15	42	34	55	22	15	46	40	35 (4.0)
Walleye	77	84	88	78	95	102	105	98	84	91	89	90 (2.8)
Freshwater Drum	77	84	88	78	95	102	105	98	84	91	89	90 (2.8)
Optimal Spawning Days (OSD)												
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	Mean (SE)
Common Carp	33	29	32	40	42	40	38	40	27	44	37	37 (1.7)
Bigmouth Buffalo	29	28	32	32	38	38	43	34	26	42	30	34 (1.7)
River Carpsucker	44	42	54	48	49	60	63	55	49	65	43	52 (2.4)
Shorthead Redhorse	35	29	47	47	29	40	31	32	47	37	31	37 (2.2)
Channel Catfish	46	29	39	16	40	51	50	27	18	51	42	39 (3.9)
Flathead Catfish	68	29	74	57	75	86	89	80	65	79	73	75 (2.8)
Walleye	31	29	45	37	29	38	29	29	43	33	28	34 (1.8)
Freshwater Drum	45	29	56	57	52	57	63	58	53	64	44	54 (2.3)

Table 4.5. Total number of days when optimal growing and spawning temperatures were coupled with backwater connection and active floodplain connection flows for eight selected fishes from 2001-2011 for the Minnesota River in Mankato, MN. First value represents number of optimal growing days (OGD) and second value represents number of optimal spawning days (OSD).

Backwater Connection Coupled with Optimal Growing and Spawning Days											
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Common Carp	13,20	13,14	1,13	3,23	13,36	6,28	11,28	6,40	0,3	24,35	36,37
Bigmouth Buffalo	1,29	7,15	0,11	1,20	3,33	1,26	0,29	2,34	0,2	5,34	10,30
River Carpsucker	33,32	15,14	11,12	26,23	44,39	23,25	29,23	29,34	1,2	57,54	59,43
Shorthead Redhorse	16,35	15,12	1,19	8,12	15,24	10,39	12,31	7,31	0,19	29,36	39,31
Channel Catfish	20,16	15,14	3,1	15,6	22,13	13,10	16,10	9,7	0,0	45,28	45,41
Flathead Catfish	13,33	13,12	1,11	3,20	13,39	6,21	11,23	6,29	0,0	24,48	35,59
Walleye	33,31	15,15	11,16	26,7	44,23	23,37	29,27	29,27	1,20	57,33	59,28
Freshwater Drum	33,36	15,15	11,14	26,27	44,41	23,26	29,28	29,38	1,2	57,53	59,44
Active Floodplain Connection Coupled with Optimal Growing and Spawning Days											
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Common Carp	0,13	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,0	4,5	1,9
Bigmouth Buffalo	0,11	0,0	0,0	0,0	0,0	0,2	0,0	0,0	0,0	1,6	0,10
River Carpsucker	7,10	0,0	0,0	0,0	0,0	0,1	0,0	0,0	0,0	6,5	7,7
Shorthead Redhorse	1,17	0,0	0,0	0,0	0,0	0,4	0,0	0,0	0,0	5,5	1,7
Channel Catfish	2,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	6,4	4,1
Flathead Catfish	0,7	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	4,3	1,7
Walleye	7,17	0,0	0,0	0,0	0,0	0,4	0,0	0,0	0,0	6,7	7,12
Freshwater Drum	7,11	0,0	0,0	0,0	0,0	0,2	0,0	0,0	0,0	6,6	7,10

resulted in the fewest days that backwater connection flows were coupled with important spawning and growing temperatures for all species. In 2001, 2010 and 2011, backwater connection and active floodplain connection were coupled the longest with OGD and OSD.

Low Flow Recruitment Concept

Extreme low flow duration varied by year (Table 4.6). The longest extreme low flow duration was in 2003 and lasted 179 days, while the shortest was 0 days in 2002, 2010, and 2011. In 2005, extreme low flow duration was only 9 days. In 2004, 2006, 2007-2009 extreme low flow duration lasted at least 3 weeks (2006) and up to 9 weeks in 2004 (similar to median extreme low flow duration – 7 weeks). Extreme low flows were rarely coupled with appropriate spawning temperatures for the selected Minnesota River fishes, but were coupled more often with OGD (Table 4.6). Optimal spawning temperatures were only coupled with extreme low flow for Channel Catfish, Flathead Catfish, and Walleye. Only in 2007 did coupling of extreme low flow and OSD coincide for an extended period (1 week on average) for Channel Catfish and Flathead Catfish. Extreme low flows were most often coupled with OGD in 2003 and 2006-2009 for most fishes (with the exception of Bigmouth Buffalo; where zero days were coupled for all years). Extreme low flows were only coupled with Common Carp and Flathead Catfish growth temperatures in 2003 and 2007. The most days that optimal growing temperatures and extreme low flows were coupled were for River Carpsucker, Walleye and Freshwater Drum.

Table 4.6. Total optimal growing and spawning days (OGD;OSD) coupled with extreme low flows for each target species from 2001-2011 for the Minnesota River in Mankato, MN.

Extreme Low Flows Coupled with Optimal Growing Days											
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Common Carp	0	0	4	0	0	0	4	0	0	0	0
Bigmouth Buffalo	0	0	0	0	0	0	0	0	0	0	0
River Carpsucker	0	0	16	0	0	10	10	17	18	0	0
Shorthead Redhorse	0	0	9	0	0	1	6	2	0	0	0
Channel Catfish	0	0	10	0	0	2	9	3	1	0	0
Flathead Catfish	0	0	4	0	0	0	4	0	0	0	0
Walleye	0	0	16	0	0	10	10	17	18	0	0
Freshwater Drum	0	0	16	0	0	10	10	17	18	0	0
Extreme Low Flows Coupled with Optimal Spawning Days											
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Common Carp	0	0	0	0	0	0	0	0	0	0	0
Bigmouth Buffalo	0	0	0	0	0	0	0	0	0	0	0
River Carpsucker	0	0	0	0	0	0	0	0	0	0	0
Shorthead Redhorse	0	0	0	0	0	0	0	0	0	0	0
Channel Catfish	0	0	2	0	0	0	6	0	0	0	0
Flathead Catfish	0	0	2	0	0	1	10	0	1	0	0
Walleye	0	0	0	1	0	0	0	0	0	0	0
Freshwater Drum	0	0	0	0	0	0	0	0	0	0	0

Intermediate Flow Concept

Intermediate flow duration varied by year (Appendix A). The median intermediate flow duration was 235 days per year, and was the most dominant condition annually. The longest intermediate flow duration was in 2002 and lasted 321 days, while the shortest was in 2010 and lasted 161 days. Because intermediate flows were the dominant flow condition in the Minnesota River, a greater number of intermediate flow days were coupled with OGD and OSD than other flow conditions for the selected Minnesota River fishes (Table 4.7). Optimal growing temperatures for River Carpsucker, Walleye, and Freshwater Drum are the same. Intermediate flows coupled with OGD are the greatest for the aforementioned species, with longest coupled duration in 2002 and 2006 (69 days). The lowest reported intermediate flow duration coupled with OGD was for Bigmouth Buffalo where conditions only coincided for a week on average. The year where intermediate flow duration and OGD coincided was greatest for all species in 2007, while the lowest was in 2011. On average, intermediate flow duration was coupled with OSD for Flathead Catfish for at least one week, and up to 47 days. In 2011, intermediate flow duration was only coupled with OSD for Channel Catfish (1 day) and Flathead Catfish (14 days). Moreover, in 2001, intermediate flow duration was only coupled with OSD for River Carpsucker, Channel Catfish, Flathead Catfish, and Freshwater Drum. The years where intermediate flow duration and OSD were coupled for the longest duration for all species were 2003 and 2009.

The intermediate flow concept suggests that hydrological variability might help flush riffle habitats to aid spawning and/or enable greater drift of food organisms;

Table 4.7. Total optimal growing and spawning days (OGD;OSD) coupled with intermediate flows for each target species from 2001-2011 for the Minnesota River in Mankato, MN.

Intermediate Flows Coupled with Optimal Growing Days											
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Common Carp	27	34	28	12	29	28	40	16	15	22	5
Bigmouth Buffalo	12	12	9	0	13	6	8	3	3	7	2
River Carpsucker	44	69	61	52	51	69	66	52	65	34	30
Shorthead Redhorse	31	41	36	15	34	41	42	22	18	23	6
Channel Catfish	34	51	45	26	37	48	52	35	31	28	13
Flathead Catfish	27	34	28	12	29	28	40	16	15	22	5
Walleye	44	69	61	52	51	69	66	52	65	34	30
Freshwater Drum	44	69	61	52	51	69	66	52	65	34	30
Intermediate Flows Coupled with Optimal Spawning Days											
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Common Carp	0	15	19	17	6	9	10	0	24	9	0
Bigmouth Buffalo	0	13	21	12	5	12	14	0	24	8	0
River Carpsucker	12	28	42	25	10	35	40	21	47	11	0
Shorthead Redhorse	0	17	28	35	5	1	0	1	28	1	0
Channel Catfish	30	34	36	10	27	41	34	20	18	23	1
Flathead Catfish	35	69	61	37	36	64	56	51	64	31	14
Walleye	0	17	29	29	6	1	2	2	23	0	0
Freshwater Drum	9	26	42	30	11	31	35	20	51	11	0

however, hydrological reversals place physical stress on organisms. As reported in the current hydrology of the Minnesota River section, median number of hydrological reversals was 64 per year. The greatest number of reversals occurred in 2006 and 2008 at 87 and 85, respectively, while the lowest number of reversals occurred in 2007 and 2011 at 51 and 57, respectively

Discussion

Similar to other Midwestern rivers, the Minnesota River was characterized by highly variable flow conditions. Therefore, fish spawning and development may not reflect patterns reported in large tropical floodplain rivers (Moore and Thorp 2008). For instance, only one year (2010) between 2001 and 2011 had flows that exceeded the large flood threshold of 2,204 m^3/s. From 2002 to 2005, and in 2008 and 2009, flow magnitude never exceeded the small flood threshold of 779 m^3/s. Despite not having an annual spring flood pulse, the 2001 to 2011 flows were sufficient to have allowed fishes to enter and exit isolated backwater lakes (Figure 4.4).

Storm-event flow pulses may not overlap with optimal temperatures needed for spawning cues and larval development. In the Minnesota River, several years resulted in negligible rising flows coupled with increasing temperatures. From 2000 to 2002, only 2001 had a substantial spring flood pulse in combination with gradual warming temperature (Figure 4.5). Instances where increased flow and temperature do not align may favor conditions for fishes exhibiting adaptations to spawn during low flow recruitment. In 2000 and 2002, a gradual rise in discharge did occur followed by extended periods of low flow. The years of 2001, 2010, and 2011 yielded the most days where small flood magnitude coupled with optimal spawning conditions for all eight target species, with the exception of 2006 for Channel and Flathead Catfish. Whereas, in most years at least one week occurred where backwater connection and optimal spawning conditions coupled for all eight target species, except Channel and Flathead Catfish in 2009. A recent synthesis of flood pulse literature completed by Junk and Bayley (2008) generated some consensus that

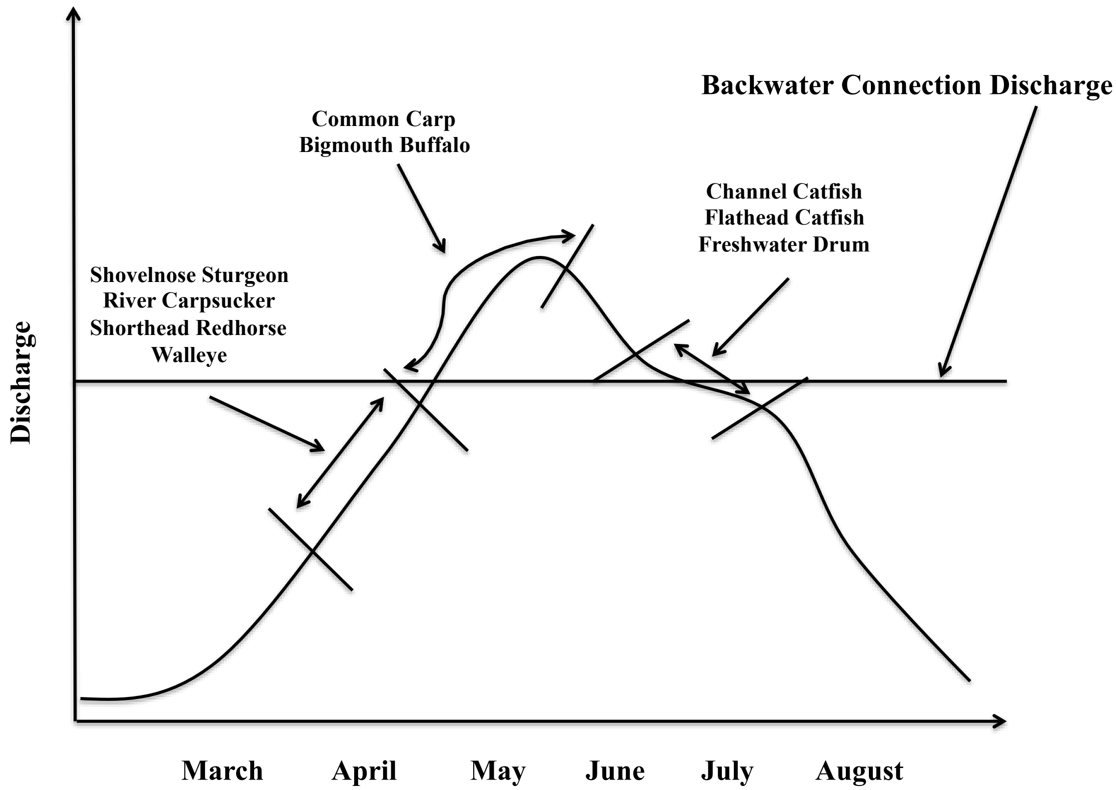

Figure 4.4. Predicted spawning times and discharge stage for target species from March to August for the Minnesota River. Horizontal bar represents hypothetical flow magnitudes allowing connection to backwater habitats.

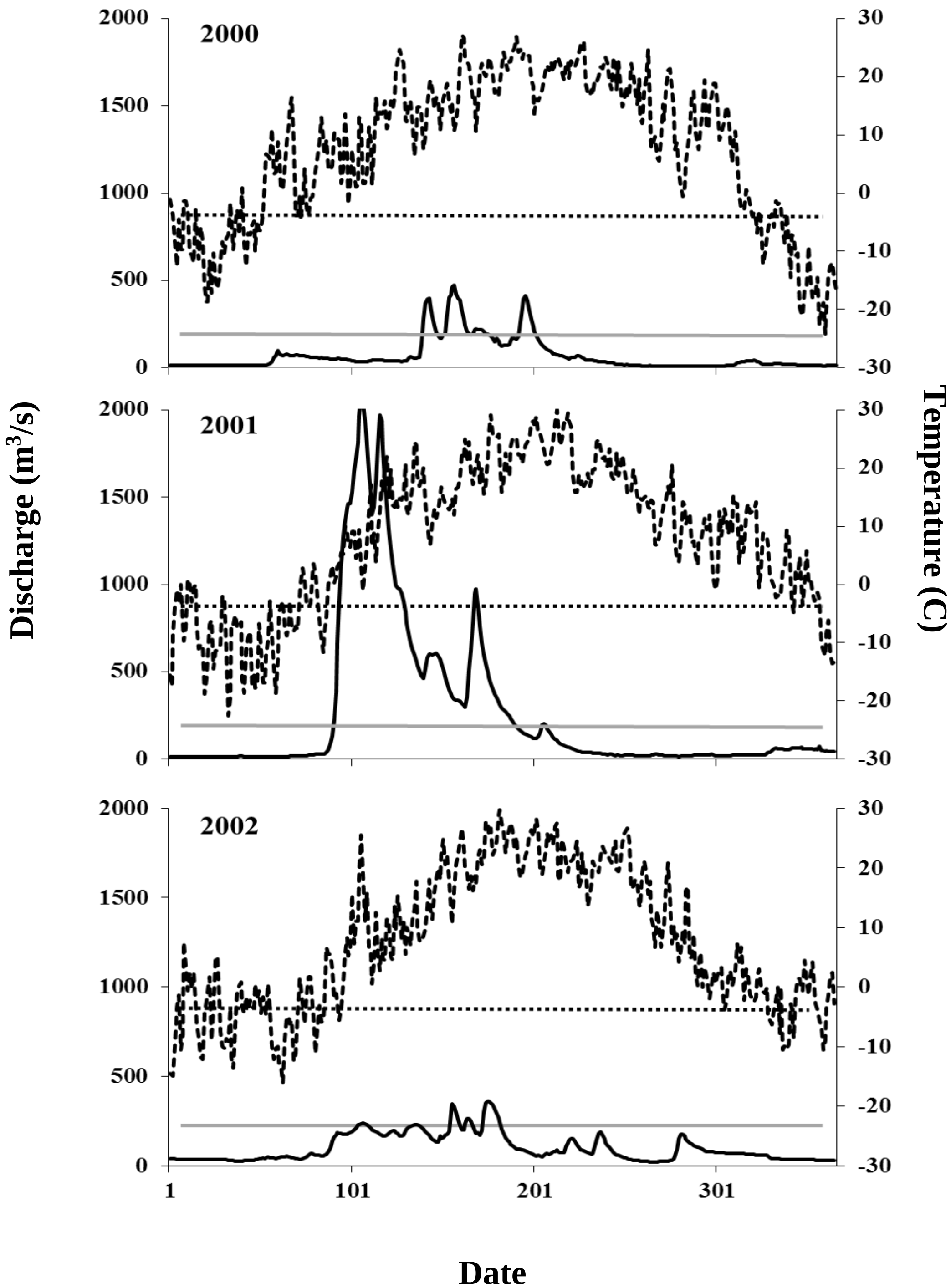

Figure 4.5. Discharge (m^3/s - solid line) and air temperature (Celsius – dotted line) plotted for 2000-2003 from USGS Gauging station for the Minnesota River in Mankato, MN. Horizontal gray bar represents minimal discharge (200 m^3/s) for connection to isolated backwater lakes. Dotted line represents small flood-stage discharge (779 m^3/s).

waterways such as the Minnesota River, may not adhere to tenets of the flood pulse concept originally proposed by Junk et al. (1989). Junk and Bayley (2008) further suggested that there is little interaction between the floodplain and river channel in low to medium order temperate rivers.

Reduced floodplain and river channel interactions are the result of unpredictable heavy regional rainfall and snowmelt and destruction or separation of the floodplain from the river channel (Junk and Bayley 2008). Therefore, elements of the flood pulse concept that depend on concurrent aquatic production during periods of inundation are not significant, but rather floodplains are most productive during dry, terrestrial phases during summer (autochthonous production) and lags in benefits of terrestrial production need to be accounted for (Junk and Bayley 2008).

Humphries et al. (1999) noted that during environmental conditions where flow and temperature do not coincide, temperature often takes a dominant role influencing spawning. During low flow conditions, turbidity is likely reduced and allows increased light penetration that promotes instream primary production. As mentioned earlier, increased primary production may shift the fish community structure from one dominated by insectivores and top predators to one dominated by niche generalists, omnivores, and detritivores (Fajen and Layzer 1993; Rankin et al. 1999). In the Minnesota River, omnivorous species such as Common Carp, River Carpsucker, and Channel Catfish could have improved growth rates in years of increased low flow conditions, such as 2003 and 2007. The Minnesota River extreme low flow and intermediate flow conditions often occur in early spring and then again fall through winter. However, in 2007 and 2009, extreme low flow conditions happened in early to mid-August and may be reflected by stronger recruitment for nest building fishes such as Channel and Flathead Catfish. Aforementioned conditions are common and typically account for over half the environmental flow condition days for the Minnesota River on an annual basis (Table 4.2).

Warm summer temperatures would also increase metabolic rates of fishes, thereby resulting in increased growth and YOY production (Moore and Thorp 2008). It is common that during most years, there was flow exceeding 200 m^3/s allowing connection to backwater habitats. Similar to instream primary production, isolated backwaters could have a significant contribution to larval production resulting from long nutrient retention times from brief connection periods and nutrient pulses from the main channel.

An alternative to flood years and low flow years, could be years of intermediate flow conditions. As suggested by Moore and Thorp (2008), intermediate flow conditions maximized habitat heterogeneity and resulted in peak community complexity for YOY fishes in the Kansas River in 2004. Similar to other Great Plains rivers, the Minnesota is characterized by erratic storm events and subsequent overland flow. Increased flow fluctuations, or storm-based flow regimes, would tend to favor fishes with more generalized feeding strategies and habitat preferences and those that are more tolerable of inter-flood low flows compared with fishes that have specialized feeding and habitat preferences (Poff and Allen 1995; Poff et al. 2010). Similar findings were reported in the Upper Mississippi River basin, where mean trophic position decreased for feeding guilds during low flow periods, favoring species with a more generalized feeding behavior using lower trophic levels (Roach et al. 2009).

Moreover, hydrological reversals and high flows at bankfull could result in YOY fish being washed downstream resulting in increased mortality (Moore and Thorp 2008). If true for the Minnesota River, this suggests that fishes would have recruited poorly in 2006 and 2008. Life history strategies adapted to hydrologic variability may include extended or delayed spawning, multiple spawning periods, and YOY survival that relies on some level of disturbance (Moore and Thorp 2008). In the Minnesota River, the number of hydrological reversals varied from year to year and was further complicated by variation in rise and fall rates. The Minnesota River is a structurally complex riverine ecosystem that has a complexion resulting from a wide range of natural and man-made conditions and disturbances.

CHAPTER V: HYDROLOGY AND TEMPERATURE INFLUENCES ON SELECTED MINNESOTA RIVER FISHES: A TEMPORAL ANALYSIS OF FISH GROWTH AND RECRUITMENT

Introduction

Effective management of any fish population necessitates an understanding of the factors regulating recruitment, growth, and mortality (i.e., the key dynamic rate functions; Ricker 1975; Isely and Grabowski 2009). Growth is an extremely complex physiological process. Like other poikilothermic animals, fishes have indeterminate growth, meaning the organisms continue to add length throughout their life (Van Den Avyle and Hayward 1999). Assessing growth rates in northern latitudes, where annuli are formed during alternate periods of faster and slower growth (or no growth at all), can reflect various environmental or internal influences (Bagenal and Tesch 1978). Regardless of location, growth is an important component in understanding population and community health because an increase in size is the direct result of ingestion, metabolism, maintenance, excretion, and reproduction as functions dictated by habitat quality, prey availability, and presence of stressors (Putman et al. 1995; Devries and Frie 1996; Isely and Grabowski 2009).

Recruitment can be viewed as the addition of new fish to a population from smaller size categories and is often described as the most governing variable of the three dynamic rate functions (Ricker 1975; Quist 2007). Willis and Murphy (1996) described recruitment as the "number of fish hatched or born in any given year that survives to a particular size (*e.g.*, reproductive size, harvestable size, size or age, or a size captured by a particular sampling gear)." Recruitment is often referred to as cohort or year-class strength and is typically assessed from age-frequency data (Guy 1993). Recruitment often varies annually in response to a wide range of abiotic and biotic factors (Maceina and Pereira 2007).

The three dynamic rate functions tend to be regulated more by abiotic factors in lotic systems than in more stable lentic environments, with streamflow being perhaps the most important abiotic driver (Poff et al. 1997). Therefore, annual patterns in hydrology and thermal conditions, representing each of the three riverine concepts quantified in Chapter IV, were used to establish testable hypotheses of how hydro-thermal conditions might influence fish recruitment and growth in the Minnesota River. Then, annual changes in growth and recruitment were estimated for each target species, and if found to be temporally variable, were tested for association with annual changes in hydro-thermal conditions to determine if any of the riverine concepts were applicable to Minnesota River fishes. .

Chapter Objectives

Specific objectives for this chapter were to

1) set up testable hypotheses for each riverine concept by species,
2) describe population dynamics of Minnesota River target fishes (a-c below),
    a) quantify fish collection results by gear type and length ranges,
    b) estimate annual growth variation of target fishes
    c) estimate annual recruitment variation by identifying strong and weak year classes
3) describe if and how three riverine concepts apply to the Minnesota River (a below),
    a) test associations between growth and recruitment variation and annual patterns in hydro-thermal regimes representing each riverine concept or combination of concepts.

Riverine Concepts

Flood Pulse Concept

A major component of the flood pulse concept is that floodplain/backwater inundation is beneficial to riverine fishes, as it allows access to new food resources and habitat (Junk et al. 1989). Thus, the overwhelming bulk of riverine fish biomass is typically derived directly or indirectly from lateral connections to the floodplain (Junk et al. 1989). Also, many river fishes display behavioral responses to flooding, such as cues for spawning (Dutterer et al. 2012) and use of inundated floodplains as spawning sites. Complex floodplain habitats also serve as nursery habitat for young fishes, providing food items and refuge from predation (Junk et al. 1989; Bayley 1991)

Low Flow Recruitment

The low-flow recruitment model places an emphasis on the importance of in-stream production and low discharge periods for spawning and larval recruitment (Moore and Thorp 2008). During summer low flow periods, prey items are condensed and temperatures are greater at that time (Humphries et al. 1999). In addition, during periods of low flow, less energy is expended to maintain position (Allen and Castillo 2007). Therefore, extended periods of extreme low flows may benefit certain riverine fishes by providing optimal foraging conditions leading to improved growth. Moreover, extended periods of extreme low flow may benefit certain riverine fishes that either spawn during these conditions, or depend on low flows for improved YOY survivorship.

Intermediate Flows Concept

Temperate rivers throughout the Midwestern United States have been characterized as "temporally dynamic" due to the stochastic nature of precipitation events that result in low hydrologic predictability (Dodds et al. 2004; Moore and Thorp 2008). However, Junk et al. (1989) and Sparks (1995) suggested rivers in temperate climates often have predictable annual flow characterized by a high spring flood, a moderate fall flood, and a summer low-flow period. Moore and Thorp (2008) observed increased survival of YOY riverine fishes during periods of intermediate flows that they attributed to increased habitat heterogeneity and ample slackwater patches (areas of reduced current velocity) that served as YOY nursery habitat. Intermediate-flow slackwaters have been noted to have richer zooplankton fauna that could support higher density of invertebrates and fishes (Roach et al. 2009).

Hypotheses

The following hypotheses were used to test each riverine concept's influence on growth and recruitment of selected Minnesota River fish species. However, because not all hypotheses could be tested for all species, I replaced the term "fish" in the hypotheses with Common Carp, Bigmouth Buffalo, River Carpsucker, Shorthead Redhorse, Channel Catfish, Flathead Catfish, Walleye, or Freshwater Drum when stating each hypothesis.

Growth

H_0: There was no association between fish growth and any of the selected hydro-thermal variables representative of the flood pulse, low flow recruitment, or intermediate flows concepts

H_{a1}: Lateral connection to backwaters (*i.e.*, number of days flows were between 200-779 m^3/s) and active floodplain habitat for an extended duration (*i.e.*, number of days flows exceeded 779 m^3/s) positively increases "fish" growth as predicted by the flood pulse concept (supported model as described in methods)

H_{a2}: Extended duration (*i.e.*, number of days flows were less 19 m^3/s) of low flow positively increases "fish" growth as predicted by the low flow recruitment concept (supported model as described in methods)

H_{a3}: Extended duration of intermediate flows (*i.e.*, number of days flows were between 19 -200 m^3/s) positively increases "fish" growth as predicted by the intermediate flows concept (supported model as described in methods)

H_{a4}: Variation in flow regime among years has positive impacts on "fish" growth and corresponds to a combination of riverine concepts (supported model as described in methods)

Recruitment

H_0: "Fish" recruitment demonstrated no association with any of the three riverine concepts (no supported model as described in methods)

H_{a1}: Lateral connection to backwaters (*i.e.*, number of days flows were between 200-779 m^3/s) and active floodplain habitat for an extended duration (*i.e.*, number of days flows exceeded 779 m^3/s) positively impacts "fish" recruitment as predicted by the flood pulse concept (supported model as described in methods)

H_{a2}: Extended duration (*i.e.*, number of days flows were less 19 m^3/s) of low flow positively impacts "fish" recruitment as predicted by the low flow recruitment concept (supported model as described in methods)

H_{a3}: Extended duration of intermediate flows (*i.e.*, number of days flows were between 19 -200 m^3/s) positively impact "fish" recruitment as predicted by the intermediate flows concept (supported model as described in methods)

H_{a4}: "Fish" recruitment success depends on variation in flow regime (*i.e.*, differences in spawning habitat and nursery habitat); therefore, positive recruitment corresponds to a combination of riverine concepts (supported model as described in methods)

Fish Collection Methods

Fishes were sampled from April to September of 2012 at randomly chosen sites. Exact sampling locations ultimately depended of ability of a specific gear type to effectively sample that area. Fishes were collected using a variety of active and passive gears including benthic trawling, boat electrofishing, trotlines, commercial harvest, angling, trap nets, hoop nets, and seining. Each gear may have specific biases associated with it. Therefore, combined gear types for a given species were used for growth assessments, but not for recruitment. It was determined that boat electrofishing captured the widest range of lengths and ages and thus was the only gear used for recruitment estimates.

Benthic Trawling

A benthic beam trawl 1.2-m wide by 0.5-m high with four different net styles was used. The net specifications included

- Net style 1: 6.35-mm bar mesh throughout,
- Net style 2: 31.75-mm bar mesh body, 6.35-mm bar mesh bag,
- Net style 3: 6.35-mm bar mesh body, 6.35-mm bar mesh bag with a separator, and
- Net style 4: dual mesh with a 3.18-mm inner mesh and 38-mm outer chafing mesh.

Net styles 1-3 all have throats, trash chains, and rubber rollers.

Operation and deployment procedures were adopted from Sappington et al. (1998), Everett et al. (2003), Herzog et al. (2005, 2009), and Guy et al. (2009). The trawl was attached to two hard points from the trawl frame to the bottom of the bow of the vessel. As suggested by Guy et al. (2009), towrope length varied with depth, using about 2.1 m of towline for every 0.3 m water depth. Trawls were pulled downstream in reverse slightly faster than the current for safety and mechanical reasons (Guy et al. 2009). Trawling was avoided in areas <1.5 m, however, if needed an s-curve pattern was used to reduce disturbance from prop wash. Trawl hauls were about 300 m and lasted about 5 min in an attempt to standardize effort by distance and time sampled. Distance trawled and time was monitored by use of a Garmin GPSmap 765CSx and stopwatch. If the trawl became snagged or if the net turned over, data were not used to calculate relative abundance, however, target species captured were still processed for age and growth (Sappington et al. 1998).

Boat Electrofishing

Boat electrofishing was conducted during daylight hours as described by Reynolds (1996). Collection of fishes was completed along both banks and mid-channel with runs lasting about 20 minutes in an effort to standardize catch by time sampled. Most electrofishing used 60 HZ, 10-15% duty cycle, and a voltage setting around 220-280 as this samples the widest range of fishes of various sizes (Rabeni et al. 2009).

Additional fish data were obtained from the MN DNR during routine Index of Biological Integrity electrofishing sampling (Chapman 2000, 2004). To increase sample size, an additional 20-min electrofishing run was conducted near Le Sueur, Minnesota (RKM 80) using low frequency (~15 Hz), low amperage (< 5 amps) to sample juvenile Flathead Catfish for growth purposes only. All electrofishing consisted of two dippers collecting stunned fishes from the bow of the vessel.

Trotlines

Trotlines were used to increase sample sizes of several nocturnal-feeding fishes, particularly large-sized Ictaluridae. Methods for trotline use were adopted from Hubert (1996), Stauffer et al. (1996), and Arterburn and Berry Jr. (2002). Trotlines were set at locations near the communities of New Ulm (RKM 245), Judson (RKM 204), and Belle Plaine (RKM 90) in Minnesota.

At each location, twenty trotlines were set at a slight angle downstream by fastening the upstream end to the riverbank and anchoring the downstream end. Trotlines were about 20 m in length and had 10 hooks spaced 1.2 m apart. Each hook consisted of a 30 cm drop-line. Ten trotlines consisted of size 8/0 straight-shanked hooks baited with 12 to 20 cm live bullheads to target Flathead Catfish. Ten trotlines consisted of size 4/0 straight-shanked hooks with cut bait to target Channel Catfish. Each trotline was set overnight.

Commercial Harvest

In May of 2012, a small crew assisted commercial fisherman in a backwater near New Ulm. The commercial harvest targeted Bigmouth Buffalo and Common Carp. Length and ageing structures were obtained from commercially-harvested Bigmouth Buffalo, River Carpsucker, Walleye, and Freshwater Drum. The commercial harvest operated under a Special Class “B” fish removal permit using a 396-m seine with 6.35-cm bar mesh. To collect fishes, the seine was stretched across the backwater-main river channel confluence and fishes were corralled to the seine by staking one end to shore and the opposite end fixed to an anchor and buoy. The seine was then pursed and hauled to shore. Fishes were randomly selected from a pen of entrapped fish.

Sport Angling

Sport angling was also used to supplement numbers of Common Carp, Channel Catfish, and Flathead Catfish at two annual weigh-in and release fishing contests along the Minnesota River. The first tournament, held at Franklin (RKM 310) in July 2012 targeted Channel and Flathead Catfish. The second tournament at Belle Plaine in August targeted Common Carp, Channel Catfish, and Flathead Catfish. When applicable, all entered fishes were used. Flathead Catfish caught during the Franklin event were transported for display at the Minnesota State Fair and were not included.

Hoop nets

Hoop nets are a common fish sampling gear used in river channels because they are easy to handle, can be set in a variety of habitats, and are relatively harmless to fish (Holland and Peters 1992; Hubert 1996; Guy et al. 2009). In an effort to increase Ictaluridae numbers in the collective data set, some hoop nets were baited following procedures described by Gerhardt and Hubert (1989), Tillma et al. (1997), and Shroyer (2011). Hoop nets were used early in the sampling season; however, low catch rates resulted in discontinuation of use. The hoop nets that were used had 5-mm bar mesh, were 1.98 m in length and comprised of five hoops about 75 cm in diameter with two throats. The first throat opening was about 44-cm when stretched and the second throat about 30-cm stretched measure.

Hoop nets were placed parallel with the river current in areas of flowing water, with the mouth opening downstream so that water covered the entire net (Hubert 1996), and secured by attaching a rope from the upstream hoop to an anchor or steel rod. Barada (2009) noted that anchors may also be secured to the bank to further reduce net displacement. For areas with little to no current, the mouth was staked or anchored to prevent collapsing (Guy et al. 2009). A buoy was placed on the furthest downstream hoop and a GPS waypoint was recorded to ensure retrieval. Hoop nets were deployed and set for 24-h, similar to methods used by Holland and Peters (1992) and Tillma et al. (1997).

Trap Nets

Trap nets had 5-mm bar mesh and included five steel hoops about 75 cm in diameter with two fykes in the first two hoops. Traps were constructed of a single 96- x 185-cm steel frame, with a 15- x 91-cm opening. The lead lines were 10.5-m long and were equipped with a float line and a weighted line. Trap nets were deployed perpendicular to the riverbank in areas with minimal current. Trap nets were deployed and set for 24 h, similar to methods used by Holland and Peters (1992) and Tillma et al. (1997).

Seining

Three 15-m hauls (lower, mid-point, and upper) were completed along wadeable shorelines. The seine was pulled by hand in a downstream direction parallel to the shore (Sappington et al. 1998; Neebling and Quist 2011). Two people, one at each end of the seine, pulled the seine downstream where they could safely walk faster than the current (Rabeni et al. 2009). Seine dimensions were 4.6-m long x 1.2-m high, 3-mm bar mesh. In areas of fast current, the seine was set as a “cup” downstream from the area to be sampled, and a third person walked downstream through the sample area, driving the fish (Rabeni et al. 2009).

Basic Fish Data Collection Information

To estimate growth and age, the following procedures were used. Procedures for fish identification, age-structure collection, and measurement were primarily adopted from Gutreuter et al. (1995) and Sappington et al. (1998). Total length (TL) was measured to the nearest 1.0 mm for all fishes sampled. Literature-recommended ageing structures from 10 fish per cm length group and were collected for Common Carp, Bigmouth Buffalo, River Carpsucker, Shorthead Redhorse, Channel Catfish, Flathead Catfish, Walleye, or Freshwater Drum (species were always listed in phylogenetic order by family; Table 5.1). Although lethal sampling techniques were avoided when possible, some specimens had to be euthanized for later identification and/or removal of ageing structures. Euthanasia followed protocols in Mathews and Varga (2012). When euthanasia was required, captured fishes were immobilized by submersion in ice water (4°C) for at least 20 minutes leading to death by hypoxia or, at a minimum, a deep state of anesthesia. All euthanized fish were then placed in a bleach solution (sodium hypochlorite 6.15%) at 1 part bleach to 5 parts water for a minimum of 5 minutes to ensure metabolic termination.

Population Dynamics Assessment Methods

Growth

Ageing structures for all species were allowed to air dry and embedded in epoxy resin to prevent fracturing while being cut. Two to four cuts were made using a low-speed diamond saw (Buehler Isomet, Buehler, Inc., Lake Bluff, IL). An Olympus (Unitron z850) dissecting and Leica (DM750) compound microscope were used to project structures for digital image capture. Measurements of annuli spacing were

Table 5.1. Fish species collected for growth and recruitment analyses from the Minnesota River in the summer of 2012.. The age structures collected from each species for age and growth determination, the number of fishes used (*N*), and the references used to justify age structure choices and procurement methods are noted. Definitions for age structure abbreviations are listed in the footnotes

Species	Structure(s)*	*N*	Notes/References
Common Carp	LMPF	170	Sappington et al. (1998), Bratten et al. (1999), and Koch et al. (2008)
Bigmouth Buffalo	SDS	76	Sappington et al. (1998), Bratten et al. (1999), and Koch et al. (2008)
River Carpsucker	SDS	95	Sappington et al. (1998), Bratten et al. (1999), and Koch et al. (2008)
Shorthead Redhorse	LMPF	84	Harbicht (1990) and Koch et al. (2008)
Channel Catfish,	LPS	131	Koch and Quist (2007)
Flathead Catfish	LPS	33	Koch and Quist (2007)
Walleye	SDS	110	Borkhodler and Edwards (2001)
Freshwater Drum	SO	70	Davis-Foust et al. (2009)

*Left Marginal Pectoral Fin (LMPF), Second Dorsal Spine (SDS), Left Pectoral Spines (LPS), Sagittal Otoliths (SO).

obtained using imaging software (Image J; Rasband 2014).

Back calculation of length-at-age was used to assess growth rates for individual fish and was the proportion between fish TL and the radius, or distance from the age structure focus or center to each annuli (Busacker et al. 1990). Because fish were sampled throughout the summer of 2012, the current year of growth was not included in analyses. The Dahl-Lea method was used for all ageing structures because calcified structures are present at the time of hatching (DeVries and Frie 1996; Pierce et al. 2003). The Dahl-Lea method assumes a direct proportional relation, or that the fish hard part forms at the time of hatching (*i.e.,* 1:1 relation between body and fish hard part).

The Dahl-Lea model back-calculates length-at-age according to the equation

$$Li = (Si/Sc)Lc, \text{ where}$$

L_i= *length at ith increment,*

L_c= *length at time of capture,*

S_i= *radius of scale at the ith annuli,*

S_c= *radius of scale at time of capture,*

a= y-intercept (determined by published standards or generated through body length-scale length regressions), and

$(L_c-a)/S_c$= *Slope.*

Growth analyses were restricted to fish less than age 12 (*i.e.,* from the 2001 to the 2011 year classes) for subsequent analyses. Years with only one growth year data point were removed from analyses, as it was determined to be too small of sample size (*i.e.,* only one fish for that given year). The data consisted of back-calculated growth increments from capture age to age 1, but again was restricted to fishes from age 1 to age 12. To assess factors associated with variations in growth among years, Weisberg et al. (2010) developed fixed-effects and mixed-effects, or additive error terms to describe the dependent variable such as fish growth in this case, linear models that can be applied to short-term samples. The mixed-effects models identify age effects, environmental effects, and within-fish effects, such as allowing each fish to have its own growth rate that applies to all increments on that fish compared to others in the sample (Weisberg et al. 2010). Age was treated as a fixed effect, year as a random effect, and a random individual fish effect was used to account for repeated measures of growth increments of individual fish as done for Catostomidae populations in Iowa by (Weisberg et al. 2010; Quist and Spiegel 2011).

Three mixed effects growth models were developed for each species:

1. Growth ~ Age Effect + Individual Fish Effect
    - Implies that variation in growth is only due to fixed age effects (e.g., younger fish grow faster than older fish) and random individual fish effects (e.g., some individuals within a cohort grow faster than others due to genetics or sex (males vs. females)).
2. Growth ~ Age Effect + Individual Fish Effect + Year
    - An additional error term that implies growth variation is also attributed to year-effects (e.g., fish grow faster in some years than in others), but is consistent for all age groups.
3. Growth ~ Age Effect + Individual Fish Effect + Year + Cohort
    - Model three is a slight modification of Weisberg et al. (2010) year*age random effects interaction model, where cohort (age-year) is substituted for the interaction term. The cohort model was

> constructed to account for correlations in growth increments between fish born in the same year (accounts for repeated measures of the same cohort over time; D. Staples, MN DNR Biometrician, Personal Communication). The cohort model 3, indicates that growth varied among years and among fish ages within those years and deflates the growth impacts by accounting for cohort contribution.

Developing three separate growth models allowed me to determine if variation in growth could be attributed to age and individuals only (model 1), to year-effects (model 2), or to cohort contributions to year effects [i.e., growth differed for different age groups in different years (model 3; Equation 1)]. Growth for each fish species was only tested in hydrologic models if the selected growth model contained a growth-year effect. A growth-year effect was defined as differences in growth among years attributed to factors other than age and individual fish effects, (*i.e.*, models 2 or 3 (Weisberg et al. 2010)). Year-effects were quantified as the growth model predicted growth increment each year and were the predicted realizations of the random effects or the predicted residual errors. Therefore, year-effects were modeled as random draws from a normal distribution with a mean of zero or the observed value (Davis-Foust 2012). Thus, growth results were interpreted as deviations (+/-) from a mean of zero, not as positive or negative growth. Davis-Foust (2012) indicted that by using this technique, all components of each growth model contribute to the predicted growth increment for each year and are therefore the difference between the observed and predicted values.

As suggested by Burnham and Anderson (2002) and Davis-Foust (2012), Akaike's information criterion (AIC) was used to compare candidate models. To correct for small sample size and overfitting models, a second-order bias correction (AIC_c) was

Equation 1. Mixed-effects models used to define growth of target species sampled from the Minnesota River, 2012. Included is the model number, model parameters, and model selection implications. Listed below is a definition of each model parameter.

Model	Model Variables	Model Selection Implications
1	$^{Y}cka = {}^{l}a + {}^{f}ck + {}^{e}cka$	No growth-year effect
		• no abiotic factors are influencing growth
		• growth did not differ among years
2	$^{Y}cka = {}^{l}a + {}^{f}ck + {}^{h}c{+}a{-}1 + {}^{e}cka$	Growth-year effect
		• growth differs among years but is the same for all age groups
3	$^{Y}cka = {}^{l}a + {}^{f}ck + {}^{h}c{+}a{-}1 + {}^{(COH)l}a{-}c + {}^{e}cka$	Growth-year effect
		• growth differs among years and among age groups within those years

^{Y}cka *(c =year class; k = fish; a = annular increment; (Predicted growth)*

^{l}a*= the intrinsic growth or annual increment for a fish in the ath year of life (Age effect)*

^{f}ck *=random fish effect (Individual fish effect)assumed distributed Normal*$(0,\sigma_{ID})$

$^{h}c{+}a{-}1$*= random environmental effects assumed distributed Normal*$(0,\sigma_{Y}$

$^{(COH)l}a{-}c$*= random cohort effect assumed distributed Normal*$(0,\sigma_{C})$

^{e}cka *=independent errors assumed distributed Normal*$(0,\sigma$

applied when *n/K* was less than 40 for the model with the largest *K* (Burnham and Anderson 2002). Criterion differences (Δ_i) were deemed meaningful for model selection (*i.e*., strength-of-evidence) of candidate models and were the difference among each model and that of the best approximating model (*i.e.*, larger Δ_i means less plausible of being the best approximate model; Burnham and Anderson 2002). Similar to confidence intervals, criterion differences provide a ranking scheme for other models in comparison to the best model. Generally, models having Δ_i from 0 to 2 are showing similar levels of support (most 'parsimonious'), models having Δ_i from 4 to 7 show considerably less support, and models with Δ_i >10 essentially show no support (Burnham and Anderson 2002). Of competing candidate models, the model with the lowest AIC_c was considered the most parsimonious model. However, if the ΔAIC_c was less than 2 for models 2 and 3, the simpler model, in this case model 2, was selected.

Recruitment

Recruitment can be assessed by identifying strong and weak year-classes indexed from catch-curve regression residuals (Tetzlaff et al. 2011). Assessing recruitment, as described by Maceina (1997), was a useful approach for analyzing year-class strength from the data set presented here, as inferences about past recruitment can be secured from a single sample season, rather than requiring multiple years of relative abundance data. Strong year-classes were represented by positive residuals and weak year classes by negative residual values from a weighted catch curve regression (Maceina and Pereira 2007; Quist and Spiegel 2011).

Fishes sampled using electrofishing were included for recruitment analyses, as the gear captured the greatest length distribution of each species, and this sampling method best met the assumption that age data were secured from a random sample of fish (equal catchability). Similar to growth, only fish age 11 or younger were included for recruitment analyses as these ages corresponded with current hydrological conditions in the Minnesota River outlined in Chapter IV. All age classes were used from the descending limb of weighted catch-curve regressions (meeting the assumption of constant recruitment and mortality). Year-classes with less than two individuals were only included if subsequent year-classes included more than two fish, or subsequent year-classes were not represented in the sample (Isermann et al. 2002). The descending limb represents those age classes that were fully recruited to the sampling gear and weighted catch-curves reduce the influence of older fish, facilitating the inclusion of the more mature age classes that typically have much smaller sample sizes (Miranda and Bettoli 2009). Assessment of recruitment was done by identifying strong and weak year classes using the studentized residuals from the catch-curve regressions (Maceina 1997). Maceina (1997) reported that residuals greater than 0.50 indicate strong year classes, while residuals less than -0.50 indicate weak year classes.

Growth and Recruitment Analyses in Relation to Riverine Concepts

Growth and recruitment variation for each species was examined using single and multiple regression models with an AIC approach for the years 2001 to 2011. Years were replicates in all regression models. Dependent variables were the predicted year-effects obtained from growth models 2 or 3 (growth analyses) and the studentized residuals from catch-curve regressions (recruitment analyses). Independent variables included EFC, IHA, and temperature parameters outlined in chapter 4 (Table 5.2). Independent variables were excluded from statistical models if less than three years of data were available. First, univariate linear regressions were conducted for each riverine concept. Second, univariate regression model plots were examined for positive-slope and negative-slope relationships. Third, all individual positive recruitment parameters were then examined using multiple regression to determine if several parameters were collectively impacting growth and recruitment and provided improved model fit. For example, some fishes may benefit from both active floodplain duration for spawning and extreme low flow duration during early development; however, parameters may be covariable. Therefore, multicollinearity diagnostics were computed using variance inflation factors (VIF). Collinear independent variables were not included in the same models (VIF > 3; Zuur et al. 2009). If variables were found to be collinear, that model was not run; however, these variables may not be collinear with other positive parameters where they could be analyzed. Negative relationships and OGD/OSD were reported and discussed, but not included for multiple regression or hypothesis testing (only positive relationships).

As done with growth, AIC_c was used to compare candidate models. For assessment purposes, supported models (both univariate and multiple regression) were those having a $\Delta AIC_c < 2$ when compared to the most supported model ($\Delta AIC_c = 0$) of the set of candidate models (Burnham and Anderson 2002). To better assess each model, coefficients of determination (R^2) was calculated to gauge model fit and *P*-values were included to determine regression significance (Shoup and Wahl 2009). Regressions were considered biologically significant at α=0.1.

Table 5.2. Regression models used to test hypotheses related to riverine concepts. Growth and recruitment variation were the dependent variables. Independent variables are IHA and EFC parameters obtained from the IHA hydrological modeling program described in Chapter IV.

Growth
No Supported Models (addresses H_{a0})
Flood Pulse Concept (addresses H_{a1})
Backwater Connection Frequency (BWCF)
Backwater Connection Duration (BWCD)
Active Floodplain Connection Duration (AFCD)
Optimal Growing Days (OGD)
Backwater Connection Duration + OGD (BWCDOGD-coupled)
Active Floodplain Connection Duration + OGD (AFCDOGD-coupled)
Low Flow Recruitment Concept (addresses H_{a2})
Extreme Low Flow Duration (ELFD)
Optimal Growing Days (OGD)
Extreme Low Flow Duration + OGD (ELFDOGD-coupled)
Intermediate Flows Concept (addresses H_{a3})
Intermediate Flow Duration (IFD)
Optimal Growing Days (OGD)
Intermediate Flow Duration + OGD (IFDOGD-coupled)
Combined Models and Concepts (addresses $H_{a\,4}$)
Recruitment
No Supported Models (addresses H_0)
Flood Pulse Concept (addresses H_{a1})
Backwater Connection Frequency (BWCF)
Backwater Connection Duration (BWCD)
Backwater Connection Fall rate (BWCFR)
Active Floodplain Connection Duration (AFCD)
Optimal Spawning Days (OSD)
Backwater Connection Duration + OSD (BWCDOSD-coupled)
Active Floodplain Connection Duration + OSD (AFCDOSD-coupled)
Low Flow Recruitment Concept (addresses H_{a2})
Extreme Low Flow Duration (ELFD)
Optimal Spawning Days (OSD)
Extreme Low Flow Duration + OGD (ELFDOSD-coupled)
Intermediate Flows Concept (addresses H_{a3})
Intermediate Flow Duration (IFD)
Optimal Spawning Days (OSD)
Intermediate Flow Duration + OSD (IFDOSD-coupled)
Hydrological Reversals (HR)
Combined Models and Concepts (addresses $H_{a\,4}$)

Support for each riverine concept was determined by AIC_c results and *P*-values ($\Delta AIC_c \leq 2$ and/or *P*-value ≤ 0.1). In order to accept or reject a hypothesis there must have been at least one positively supported model (Table 5.2) for a given riverine concept or combined concepts. If no regression models were supported for a given riverine concept then H_0 was accepted. If there was support for a regression model for a given riverine concept, that riverine concept was determined to be important for that species and the associated hypothesis was rejected (H_{a1}, H_{a2}, *and* H_{a3}). Lastly, to address *Ha4*, multiple regression models of all positive relationships were conducted and if there was support for a model that incorporated parameters from two riverine concepts *Ha4* was rejected. If there was only model support for combined parameters from the same riverine concept *Ha4* was not be rejected, as it only pertained to an already addressed hypothesis. All statistical analyses were performed using the R environment version 3.1.2 (R Development Core Team 2014).

Results

Fish Collection, Growth and Recruitment

A total of 2,183 individuals from the eight target fish species were captured in 2012 (Table 5.3). Of the total fish sampled and used in this study, 43% were collected by trawling, 42% with electrofishing, 4% with trap nets, 3% with trot lines, 3 % by sport angling, 2% by commercial harvest, 2% by seining, and 1% with hoopnets. Electrofishing sampled more individuals (*N*=909) than any other gear for Bigmouth Buffalo, Common Carp, Freshwater Drum, River Carpsucker, Shorthead Redhorse, and Walleye. The greatest numbers of Channel Catfish, however, were captured with trawling whereas, trot lines were the most productive gear for capturing Flathead Catfish. Channel Catfish dominated trawl catches, numerically comprising over 90% of all fishes sampled with this gear.

Of the 2,183 fish captured, 1,142 were Channel Catfish (52%), followed by 269 Freshwater Drum (12%) and 261 Common Carp (12%). The other five species totaled 511 individuals in combination, of which River Carpsucker and Shorthead Redhorse each represented 6%, Bigmouth Buffalo was 5%, and Flathead Catfish and Walleye combined make up the remaining 7%.

Total length ranges varied among the target species. For example, Channel Catfish ranged from 15- to 806-mm TL, while Bigmouth Buffalo ranged from 283- to 690-mm TL (Table 5.3; Appendix B). Electrofishing captured the greatest range of lengths for all species except Common Carp.

Table 5.3.Fishes sampled from the Minnesota River, 2012. Species are listed in phylogenetic order by family. Top value is the number of individuals for each gear type, and total number sampled for each species. Values in parentheses denote percentage of total for each gear type. Bottom value is the length range for each gear type and species (TL mm).

	Electrofishing	Low Frequency Electrofishing	Commercial Harvest	Trot Line	Sport Angling
Common Carp	237 (91)	-	-	-	14 (5)
	220-810	-	-	-	535-753
Bigmouth Buffalo	54 (55)	-	43 (43)	-	-
	283-682	-	381-690	-	-
River Carpsucker	117 (91)	-	7 (5)	-	-
	53-556	-	410-483	-	-
Shorthead Redhorse	133 (99)	-	-	-	-
	83-441	-	-	-	-
Channel Catfish	131 (11)	-	-	38 (3)	35 (3)
	42-723	-	-	270-761	203-806
Flathead Catfish	16 (21)	6 (8)	-	36 (49)	11(15)
	187-1230	161-242	-	489-1100	332-1000
Walleye	68 (91)	-	3 (4)	1 (1)	-
	145-687	-	544-656	710	-
Freshwater Drum	153 (57)	-	1 (<1)	-	-
	76-535	-	362	-	-

Table 5.3.Continued.

Species	Trap Net	Hoop Net	Trawl	Seine	Total
Common Carp	10 (4)	-	-	-	261
	41-667	-	-	-	41-810
Bigmouth Buffalo	-	1 (1)	1 (1)	-	99
	-	608	483	-	283-690
River Carpsucker	3 (2)	-	2 (2)	-	129
	400-480	-	485-496	-	53-556
Shorthead Redhorse	-	-	-	1 (<1)	134
	-	-	-	458	83-458
Channel Catfish	36 (3)	4 (<1)	858 (75)	40 (4)	1142
	28-600	61-160	15-482	26-72	15-806
Flathead Catfish	3 (4)	-	2 (3)	-	74
	272-730	-	611-735	-	161-1230
Walleye	-	2 (3)	1 (1)	-	75
	-	140-279	562	-	140-710
Freshwater Drum	32 (12)	2 (<1)	79 (30)	2 (<1)	269
	26-456	226-274	27-462	60-80	26-535

Trap nets captured the greatest length range for Common Carp, 41- to 667-mm TL. Gear selectivity was apparent as different gears sampled different portions of the overall species length range. For instance, electrofishing captured Channel Catfish ranging from 42-723mm, with numbers declining around 500-mm TL. Trot lines captured Channel Catfish ranging from 270-761mm with higher numbers starting around 500-mm TL. Similar results were noted for Flathead Catfish where electrofishing (standard and low-frequency) captured fish 161 mm to about 400 mm (with exception of three large individuals). Trot lines captured fish ranging from 489-1100mm. Trawl sampled all but Common Carp and Shorthead Redhorse, but at low abundance (>5 individuals, with the exception of Channel Catfish (*N*=858) and Freshwater Drum (*N*=79).Trawl catch for Channel Catfish was comprised of small individuals (over 95% of total catch was individuals less than 100 mm), while trawling sampled Freshwater Drum ranging from 27-462mm.

Following model selection steps, growth was found to vary among years for six of the eight species; Common Carp, Bigmouth Buffalo, Shorthead Redhorse, Channel Catfish, Flathead Catfish, and Freshwater Drum (Table 5.4). However, growth did not differ among age groups (*i.e.*, cohorts) within years for two of these species; Shorthead Redhorse and Flathead Catfish. This suggests that any growth effect (*e.g.*, a growth increase) in a particular year was the same for all age groups of Shorthead Redhorse and Flathead Catfish. Conversely, growth was not influenced by abiotic changes from year to year for two species; River Carpsucker and Walleye.

Table 5.4 Mixed-effects growth models for target species sampled from the Minnesota River, 2012. Species are listed in phylogenetic order by family. Included is sample size (*n*), number of parameters (K), Akaike's Information Criterion (AIC_c), and the difference between each model and the model with the minimum AIC_c (Δ AICc). Models in bold denote the most supported model. Highlighted model denotes simplest model to be used in further analyses.

Species	Model	*n*	K	AICc	Δ AICc
Common Carp	**GROWTH = AGE + Individual Fish + Year + Cohort**	170	**13**	**5968.97**	**0.00**
	GROWTH = AGE + Individual Fish + Year		12	5988.01	19.03
	GROWTH = AGE + Individual Fish		11	6106.29	137.32
Bigmouth Buffalo	**GROWTH = AGE + Individual Fish + Year**	**76**	**13**	**3845.41**	**0.00**
	GROWTH = AGE + Individual Fish		12	3846.79	1.38
	GROWTH = AGE + Individual Fish + Year + Cohort		14	3847.55	2.14
River Carpsucker	**GROWTH = AGE + Individual Fish**	95	**13**	**6955.26**	**0.00**
	GROWTH = AGE + Individual Fish + Year		14	6956.98	1.72
	GROWTH = AGE + Individual Fish + Year + Cohort		15	6959.05	3.79
Shorthead Redhorse	**GROWTH = AGE + Individual Fish + Year + Cohort**	84	**10**	**2533.90**	**0.00**
	GROWTH = AGE + Individual Fish + Year		11	2534.59	0.70
	GROWTH = AGE + Individual Fish		9	2539.76	5.86
Channel Catfish	**GROWTH = AGE + Individual Fish + Year + Cohort**	131	**15**	**4859.38**	**0.00**
	GROWTH = AGE + Individual Fish + Year		14	4863.45	4.07
	GROWTH = AGE + Individual Fish		13	4947.40	88.02
Flathead Catfish	**GROWTH = AGE + Individual Fish + Year + Cohort**	33	**14**	**1523.97**	**0.00**
	GROWTH = AGE + Individual Fish + Year		13	1524.01	0.03
	GROWTH = AGE + Individual Fish		12	1598.71	74.73
Walleye	**GROWTH = AGE + Individual Fish**	70	**11**	**1682.86**	**0.00**
	GROWTH = AGE + Individual Fish + Year		12	1685.17	2.31
	GROWTH = AGE + Individual Fish + Year + Cohort		13	1687.50	4.65
Freshwater Drum	**GROWTH = AGE + Individual Fish + Year + Cohort**	110	**14**	**3530.38**	**0.00**
	GROWTH = AGE + Individual Fish + Year		15	3547.31	16.93
	GROWTH = AGE + Individual Fish		13	3604.62	74.25

Annual changes in growth were variable among the six fish species (Table 5.5 and Figure 5.1). Flathead Catfish growth was most variable where predicted year effects (growth in mm) ranged from -33.10 mm to 19.68 mm. Channel Catfish and Bigmouth Buffalo were the next most variable species. Freshwater Drum growth was least variable where predicted year effects ranged from -0.10 mm to 3.19 mm. In general, years with greatest growth were 2010 and 2011, while 2008 and 2009 had slowest growth (negative year-effect for all species).

Growth rates of Minnesota River fishes in the current study were compared to other riverine populations in the upper Midwest and south (Appendix C). In the Minnesota River, River Carpsucker were longer lived than reported in other populations and grew faster than the mean for all age groups with the exception of age 2 and 11. The only population of River Carpsucker from age 1 to 3 to grow faster than the Minnesota River is the Missouri in Nebraska. By age 4 River Carpsucker reach quality lengths (289 mm) in the Minnesota River. Minnesota River Shorthead Redhorse grew slower than those reported in Iowa and Illinois, but reach quality length (250mm) by age 3. Channel Catfish growth was similar to several populations from Iowa, Kansas, and other Minnesota studies. In the Minnesota River, Channel Catfish reach quality length (410 mm) by age 6 and typically reach a maximum age of 16-18. Flathead Catfish in the Minnesota River grew faster than the average when comparing several studies from the south and upper Midwest (including a previous Minnesota River study). Quality length for Flathead Catfish is 510mm and was reached by age 6 in the Minnesota River. Walleye growth for age 1 and 2 was slower than the upper Midwest average, but

Table 5.5. Growth-year effects obtained from mixed-effect growth models for target species sampled from the Minnesota River, 2012. Included is growth year-effect (Year-Effect=+/- increment in mm – top value) and standard error of the predictor (SE – bottom value).

Species	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Common Carp	-	-	0.04	0.22	-0.51	0.63	-2.84	-1.34	-2.12	4.64	1.27
	-	-	3.39	3.28	3.11	3.02	2.77	2.70	2.55	2.36	2.36
Bigmouth Buffalo	-	0.28	6.57	-1.09	2.82	-4.14	-3.13	-3.84	-0.02	4.06	-1.50
	-	4.20	3.99	3.70	3.38	2.88	2.51	2.32	2.25	2.21	2.22
Shorthead Redhorse	-	-	-	-	-0.34	1.81	0.00	-0.61	-3.32	-3.63	6.10
	-	-	-	-	3.66	2.94	2.33	1.89	1.06	0.85	0.85
Channel Catfish	4.26	4.40	1.96	-3.10	3.28	-0.46	-6.14	-3.97	-12.93	5.15	7.55
	3.71	2.99	2.71	2.66	2.31	2.05	1.86	1.80	1.68	1.46	1.42
Flathead Catfish	-	-1.11	-13.69	12.07	14.83	15.89	-8.08	-19.78	-33.10	13.29	19.68
	-	10.87	10.87	8.20	6.85	6.13	5.37	5.08	4.84	4.51	4.21
Freshwaer Drum	-	-0.10	0.03	-1.55	0.89	0.10	0.95	-0.98	-2.54	0.02	3.19
	-	2.10	1.98	1.91	1.63	1.53	1.53	1.46	1.46	1.32	1.31

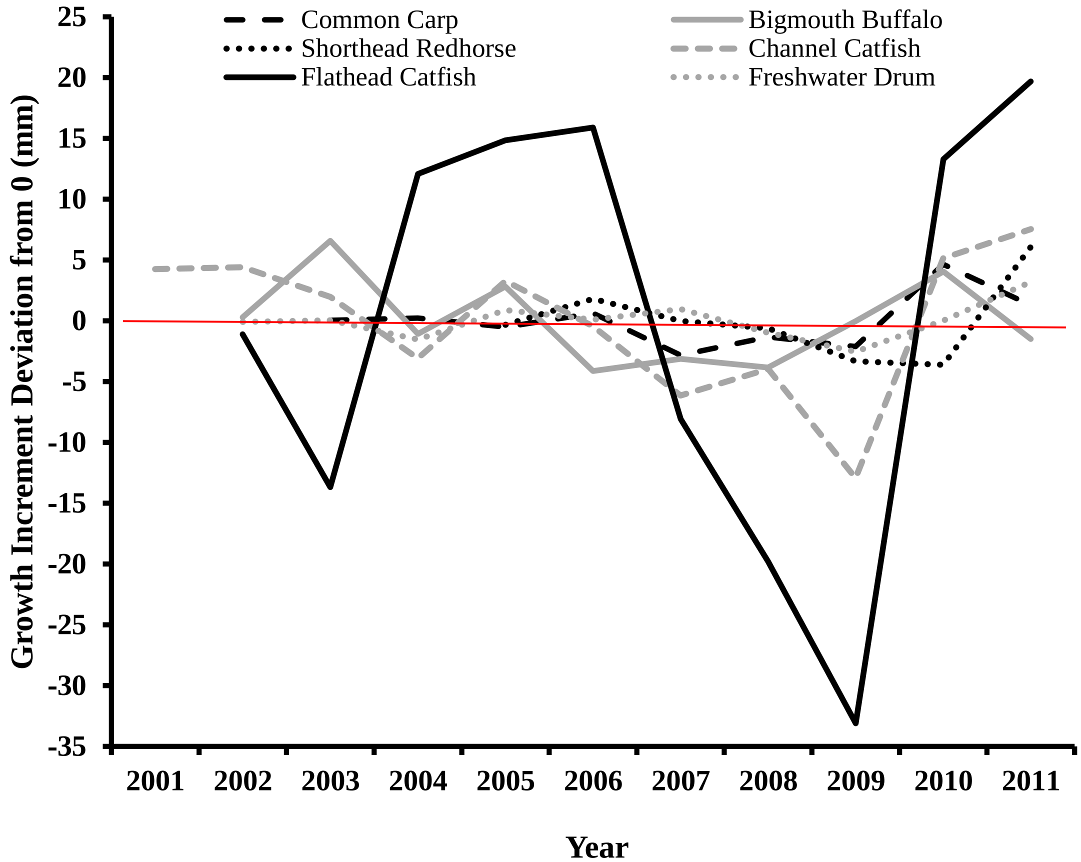

Figure 5.1. Growth-year effects obtained from mixed-effect growth models for target species sampled from the Minnesota River, 2012. Growth increments are deviations from 0 (mm). Years of higher growth are positive and years of lower growth are negative (denoted by red line at 0 mm).

exceeded the average from age 3 to 9. In the Minnesota River, Walleye reach quality length (380mm) by age 3. Minnesota River Freshwater Drum grew faster than the Midwest average for age 1 and 2 but was slower than the average up to age 7. Quality length for Freshwater Drum is 300mm and like catfishes of the Minnesota River is reached by age 6.

Recruitment analysis was restricted to Common Carp, Bigmouth Buffalo, Shorthead Redhorse, Channel Catfish, and Freshwater Drum. Only 16 Flathead Catfish were captured using standard electrofishing, thus sample size was insufficient to estimate recruitment. River Carpsucker age structure data revealed that a majority of the sample were older than age-11 and the descending limb of the catch curve only allowed one year in this study period (age-11 or 2001 year-class), thus they were excluded from further recruitment analyses.

Age distribution used in catch-curve regressions varied by species (Figure 5.2 and Table 5.6). Age 1 (2011 year-class) fish were excluded for all species except Walleye, as they were the only species that were susceptible to this gear at age 1. Common Carp, Channel Catfish, and Freshwater Drum were recruited at age 2 (2010 year-class), while Shorthead Redhorse was recruited to the gear at age 3 (2009 year-class) and Bigmouth Buffalo did not fully recruit to the gear until age 5 (2007 year-class).

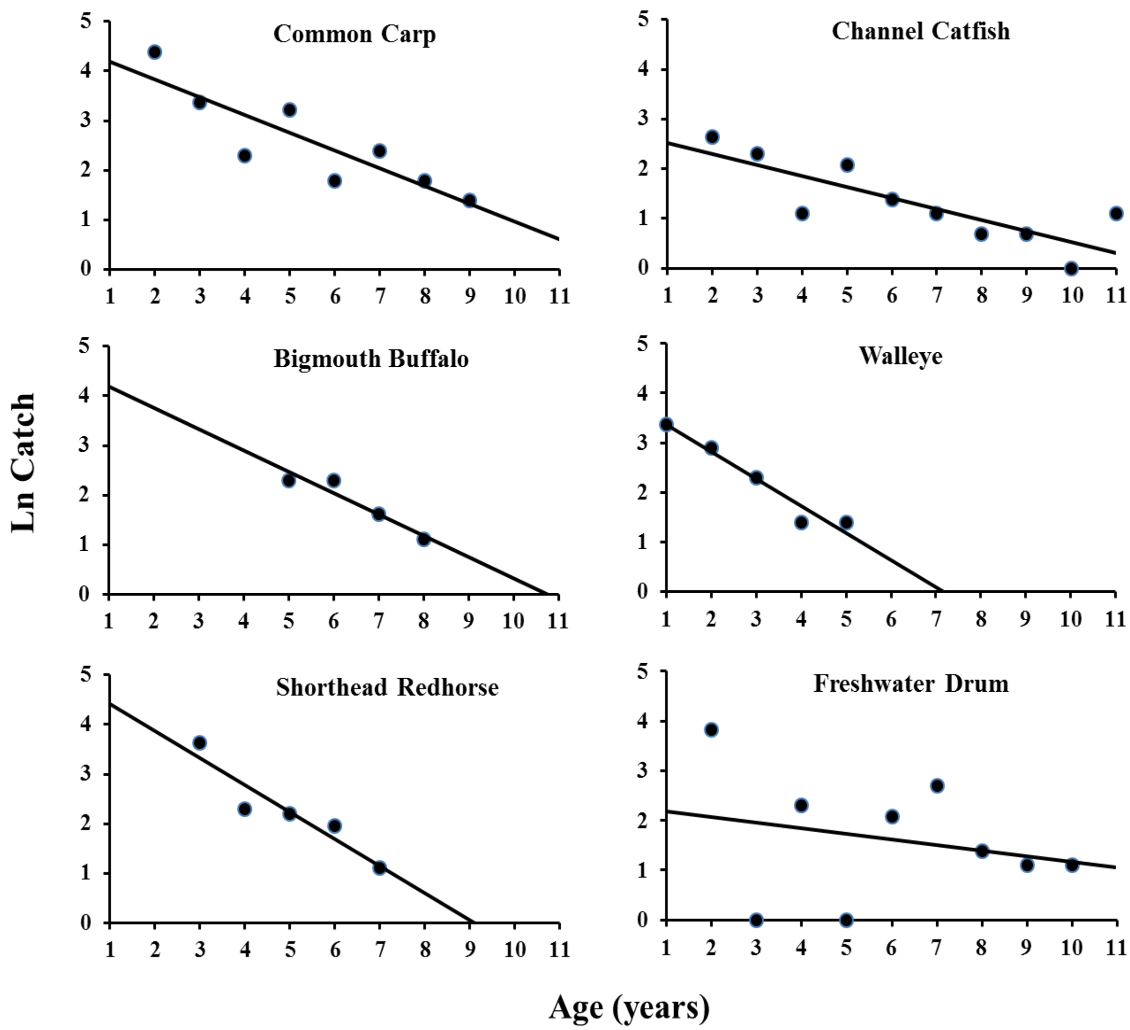

Figure 5.2. Weighted catch curve regression for selected target fish sampled from the Minnesota River, MN, 2012 using electrofishing. Solid dots represent ages used in catch curves.

Table 5.6 Catch at age data for target species sampled from the Minnesota River, 2012. Included is the age-class, sample size (n), the natural, and student residuals (Residual) obtained from weighted catch-curve regression (year-class strength indicators).

Species	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Common Carp											
Age	-	-	9	8	7	6	5	4	3	2	-
n	-	-	3	5	10	5	24	9	28	79	-
Residual	-	-	0.24	0.30	0.71	-1.08	0.91	-1.77	-0.35	1.47	-
Bigmouth Buffalo											
Age	-	-	-	8	7	6	5	-	-	-	-
n	-	-	-	2	4	9	9	-	-	-	-
Residual	-	-	-	-0.70	-0.12	1.38	-1.39	-	-	-	-
Shorthead Redhorse											
Age	-	-	-	-	7	6	5	4	3	-	-
n	-	-	-	-	2	6	8	9	37	-	-
Residual	-	-	-	-	0.01	0.77	-0.08	-1.62	1.52	-	-
Channel Catfish											
Age	11	10	9	8	7	6	5	4	3	2	-
n	2	0	1	1	2	3	7	2	9	13	-
Residual	1.20	-0.56	0.16	-0.38	-0.07	0.00	1.17	-2.36	0.47	0.88	-
Walleye											
Age	-	-	-	-	-	-	5	4	3	2	1
n	-	-	-	-	-	-	3	3	9	17	28
Residual	-	-	-	-	-	-	1.29	-1.70	0.26	0.46	-0.20
Freshwaer Drum											
Age	-	10	9	8	7	6	5	4	3	2	-
n	-	2	2	3	14	7	0	9	0	45	-
Residual	-	-0.01	-0.10	0.02	0.91	0.36	-1.37	0.38	-1.82	1.84	-

Recruitment indicators were variable among years (Figure 5.3). In 2001 and 2010, all residuals were positive suggesting the potential for strong year classes for Common Carp (1.47-2010), Channel Catfish (1.20-2001, 0.88-2010), Walleye (0.46-2010), and Freshwater Drum (1.84-2010). Of these positive residuals, all were greater than 0.50 except 2010 for Walleye. Other strong year classes were in 2005 (0.71) and 2007 (0.91) for Common Carp, 2006 for Bigmouth Buffalo (1.38), 2006 and 2009 for Shorthead Redhorse (0.77,1.52), 2007 for Channel Catfish (1.17), 2007 for Walleye (1.29), and 2005 for Freshwater Drum (0.91). Years of weak year classes were noted in 2006 (-1.08) and 2008 (-1.77) for Common Carp, 2004 (-0.70) and 2007 (-1.39) for Bigmouth Buffalo, 2008 (-1.62) for Shorthead Redhorse, 2002 (-0.52) and 2008 (-2.36) for Channel Catfish, 2008 (-1.70) for Walleye, and 2007 (-1.37) and 2009 (-1.82) for Freshwater Drum. In 2008, recruitment was observed to be poor for all species except Freshwater Drum. Recruitment was most erratic for Freshwater Drum where age 3 and age 5 (2009 and 2007 year-classes) were completely absent from the sample. Data were insufficient for Bigmouth Buffalo and Walleye so no further analyses were tested.

Growth and Recruitment in Relation Riverine Concepts

Flood Pulse Concept – All growth and recruitment models are in Appendix C and D. Only supported models ($\Delta AIC_c<2.00$ and/or P-value<0.10) are reported here. Growth models representing the flood pulse concept received the most support (18/25 supported models; Table 5.7). Species that had growth associated with the flood pulse were Common Carp, Channel and Flathead Catfish, and Freshwater Drum, therefore I

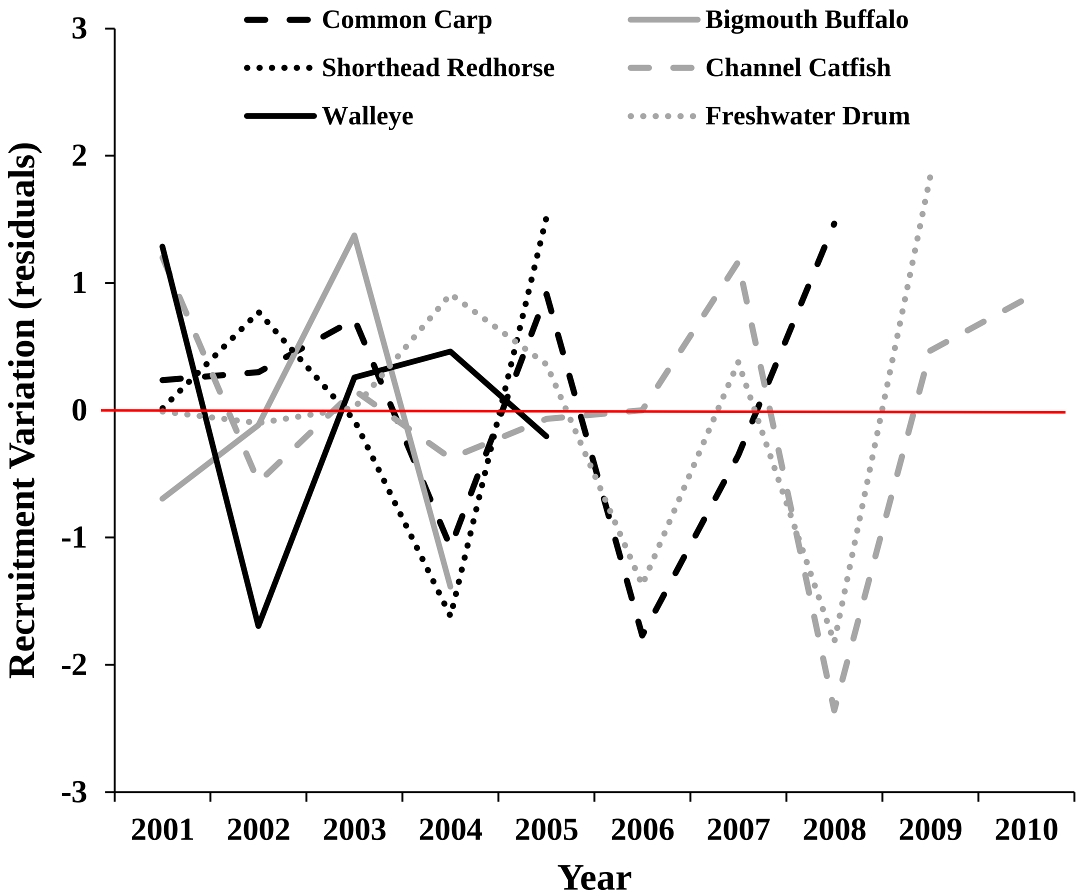

Figure 5.3. Residuals from weighted catch-curve regression for fish species sampled from the Minnesota River, 2012. Positive residuals indicate strong year-class strength, and negative residuals indicate years of weak year-class strength (denoted by red line at 0).

Table 5.7.Supported growth models for target species sampled from the Minnesota River, 2012 (ΔAIC_c<2.00 and/or P-value<0.10). Species listed by riverine concept as the relationship of the model. Species are listed in phylogenetic order by family. Relationships denotes slope of regression line. Relationship results synthesized in summary column.

Riverine Concept	Species	Supported Models	Relationship	Summary
Flood Pulse Concept	Common Carp	AFCD	+	• Active floodplain connection duration important for all species • Backwater connection duration important for Common Carp, Flathead Catfish, and Freshwater Drum • Backwater connection duration coupled with optimal growing temps and backwater connection duration coupled with optimal growing temps + backwater connection frequency important for Channel Catfish, Flathead Catfish, and Freshwater Drum • Backwater connection parameters are more prevalent for Flathead Catfish and Freshwater Drum
		AFCD+BWCF	+	
		BWCD	+	
	Channel Catfish	BWCDOGD	+	
		AFCD	+	
		BWCDOGD+BWCF	+	
		AFCDOGD	+	
	Flathead Catfish	BWCDOGD	+	
		BWCDOGD+BWCF	+	
		BWCF	+	
		BWCF+AFCD	+	
		BWCD	+	
		AFCD	+	
	Freshwater Drum	BWCDOGD+BWCF	+	
		BWCDOGD	+	
		AFCD	+	
		BWCD	+	
		BWCDOGD+AFCD	+	
Low Flow Recruitment Concept	Bigmouth Buffalo	ELFD	+	• Extreme low flow duration was positively associated with Bigmouth Buffalo growth, but optimal growing days was the supported model for Channel Catfish • Extreme low flow duration negatively impacted growth of Flathead Catfish and when coupled with optimal growing days for Freshwater Drum
	Channel Catfish	OGD	+	
	Flathead Catfish	ELFD	-	
	Freshwater Drum	ELFDOGD	-	
Intermediate Flows Concept	Common Carp	IFD	-	• Extended duration of intermediate flows when coupled with optimal growing days was important for Bigmouth Buffalo • Intermediate flow duration negatively impacted Common Carp, and when coupled with optimal growing days for Freshwater Drum
	Bigmouth Buffalo	IFDOGD	+	
	Freshwater Drum	IFDOGD	-	

accept H_{a1} for these species and reject for all others (Table 5.8). Models associated with active floodplain connection comprised 8 of 18 flood pulse models, whereas models with backwater connection comprised 13 of 18 models. Of all supported flood pulse models active floodplain connection duration was significant in 4 of 18 flood pulse models (Common Carp ΔAIC_c=0.00, *P*-value=0.02, R^2=0.48, Channel Catfish ΔAIC_c=2.02, *P*-value=0.05, R^2=0.30, Flathead Catfish ΔAIC_c=1.25, *P*-value=0.10, R^2=0.21, and Freshwater Drum ΔAIC_c=1.93, *P*-value=0.06, R^2=0.30). Additionally, several models were top-ranked for certain fish species, such as active floodplain connection duration for Common Carp, backwater connection duration coupled with optimal growing days for Channel Catfish (*P*-value=0.02, R^2=0.42), Flathead Catfish (*P*-value=0.06, R^2=0.30), Freshwater Drum (*P*-value=0.03, R^2=0.42), and backwater connection duration coupled with optimal growing days + backwater connection frequency for Freshwater Drum (*P*-value=0.02, R^2=0.60). Additionally, several models were top-ranked for certain fish species, such as active floodplain connection duration for Common Carp, backwater connection duration coupled with optimal growing days for Channel Catfish (*P*-value=0.02, R^2=0.42), Flathead Catfish (*P*-value=0.06, R^2=0.30), Freshwater Drum (*P*-value=0.03, R^2=0.42), and backwater connection duration coupled with optimal growing days + backwater connection frequency for Freshwater Drum (*P*-value=0.02, R^2=0.60).

Most fish recruitment models were associated with the flood pulse (7/12 models or 58 percent – not including combined concept models; Table 5.9). The flood pulse was associated with recruitment of Channel and Freshwater Drum, therefore I accepted H_{a1} for these species and rejected for all others (Table 5.8). Five of the Seven of the flood

Table 5.8. Hypothesis testing results for selected fishes sampled from the Minnesota River, 2012. Criteria to accept or reject hypothesis based on model support ($\Delta AIC_c<2.00$ and/or *P*-value<0.10 – only for positive relationships). H_0 denotes no relationship to riverine concepts, H_{a1} denotes positive relationship to flood pulse concept, H_{a2} denotes positive relationship to low flow recruitment concept, H_{a3} denotes positive relationship to intermediate flows concept, and *Ha4* denotes positive relationship to combined riverine concepts.

Species	H_0 *Null*	H_{a1} *Flood Pulse*	H_{a2} *Low Flow Recruitment*	H_{a3} *Intermediate Flows*	H_{a4} *Combined Concepts*
Growth					
Common Carp	Reject	Accept	Reject	Reject	Reject
Bigmouth Buffalo	Reject	Reject	Accept	Accept	Reject
Shorthead Redhorse	Accept	Reject	Reject	Reject	Reject
Channel Catfish	Reject	Accept	Reject	Reject	Reject
Flathead Catfish	Reject	Accept	Reject	Reject	Reject
Freshwater Drum	Reject	Accept	Reject	Reject	Reject
Recruitment					
Common Carp	Accept	Reject	Reject	Reject	Reject
Shorthead Redhorse	Accept	Reject	Reject	Reject	Reject
Channel Catfish	Reject	Accept	Reject	Reject	Reject
Freshwater Drum	Accept	Accept	Reject	Reject	Accept

Table 5.9. Supported recruitment models for target species sampled from the Minnesota River, 2012 (ΔAIC_c<2.00 and/or *P*-value<0.10). Species listed by riverine concept as the relationship of the model. Relationships denote slope of regression line. Relationship results synthesized in summary column.

Riverine Concept	Species	Supported Models	Relationship	Summary
Flood Pulse Concept	Channel Catfish	AFCD	+	• Active floodplain connection duration important for both species • Numerous backwater parameters important for Freshwater Drum and when combined with active floodplain connection duration
	Freshwater Drum	BWCDOSD	+	
		BWCF	+	
		AFCD	+	
		BWCDOSD+AFCD	+	
		BWCF+AFCD	+	
		BWCF+BWCD	+	
Low Flow Recrtuitment Concept				
Intermediate Flows Concept	Common Carp	HR	-	• Hydrological reversals negatively impact Common Carp and Channel Catfish recruitment • Extended duration of intermediate flows combined with optimal spawing temperature reduces Freshwater Drum recruitment
	Channel Catfish	HR	-	
	Freshwater Drum	IFDOSD	-	
Combined Concepts	Freshwater Drum	BWCF+HR	+	• Backwater connection duration and when coupled with optimal spawning days important for Freshwater Drum • Number of hydrological reversals when combined with backwater parameter important for Freshwater Drum recruitment
		BWCDOSD+HR	+	

pulse associated with backwater connection parameters, while active floodplain connection duration associated models only comprised two of seven flood pulse models. Backwater connection duration coupled with optimal spawning days was the only top-ranked model (Freshwater Drum - *P*- value=0.01, R^2=0.60). Two of four active floodplain connection models were comprised of duration only, while the other two models included a backwater connection parameter. Of backwater connection models, three models were backwater connection were associated with frequency. Remaining backwater models included duration coupled with optimal spawning days, and duration only. In every supported model, flood pulse models were positively related to growth and recruitment.

Low Flow Recruitment Concept -- Growth models representing the low-flow recruitment concept were supported less than flood pulse models (3/25 supported models; Table 5.7). For Channel Catfish, optimal growing days was supported (ΔAIC_c=0.53, *P*-value=0.11, R^2=0.18) for the low flow models, but was counted as a low flow model or reflected in hypothesis testing as no flow value was associated. Species that had supported low flow associations related to growth was limited to Bigmouth Buffalo, therefore I accept H_{a2} for this species and reject for all others (Table 5.8). Duration of low flow was associated with growth of Bigmouth Buffalo and Flathead Catfish, whereas for Freshwater Drum extreme low flow duration coupled with optimal growing days (ΔAIC_c=1.86, *P*-value=0.18, R^2=0.12) were supported but were negative relationships. Low flow models related to recruitment variation received no support for any of the four species tested, therefore I rejected H_{a3} for all.

Intermediate Flows Concept -- Growth models representing the intermediate flows concept were only supported for 3 of 25 models– not including combined concept models; Table 5.7). Of the three models, intermediate flow duration coupled with optimal growing days was the only positive relationship for Bigmouth Buffalo (ΔAIC_c=2.00, *P*-value=0.22, R^2=0.07). Therefore, I accept H_{a3} for Bigmouth Buffalo and reject for all other species (Table 5.8). For Common Carp and Freshwater Drum, the intermediate flow duration (ΔAIC_c=1.41, *P*-value=0.12, R^2=0.22) and intermediate flow duration coupled with optimal growing days (ΔAIC_c=1.83, *P*-value=0.17, R^2=0.12) models were supported, respectively, but were negative relationships suggesting some other flow condition is favored.

Intermediate flow models related to recruitment variation received support for 3 of 12 models (not including combined concept models; Table 5.9), but were all negative relationships, therefore I reject H_{a3} for all included species (Table 5.8). Of the negative relationships for recruitment, intermediate flow duration coupled with optimal spawning days was noted for Freshwater Drum and was a top-ranking model (*P*-value=0.003, R^2=0.71). Hydrological reversals was the top-ranked model for Common Carp (*P*-value=0.01, R^2=0.67) and also supported for Channel Catfish (ΔAIC_c=1.63, *P*-value=0.16, R^2=0.14).

Combined Riverine Concepts -- Multiple regression models where more than one riverine concept applied to growth and/or recruitment was only supported for Freshwater Drum recruitment (2 of 12 models, Tables 5.7 and 5.9) and I therefore accepted H_{a4} for Freshwater Drum and rejected for all other species (Table 5.8). In all cases, a flood pulse variable (backwater connection) was included in the combined concept models. Other riverine concept parameters included an intermediate flow parameter (hydrological reversals). Models supported for Freshwater Drum were backwater connection frequency and hydrological reversals (ΔAIC_c=0.74, *P*-value=0.02, R^2=0.62) and backwater connection frequency coupled with optimal spawning days and hydrological reversals (ΔAIC_c=1.55, *P*-value=0.03, R^2=0.58). In both models, the significance level is lower when looking at just the flood pulse parameter, suggesting backwater connection parameters are driving the models.

Discussion

In the present study, several growth patterns were observed for target fishes sampled from the Minnesota River. In 2008 and 2009 growth was below average (baseline of 0 mm) for all six target species that had a growth-year effect, while in 2010 and 2011 growth was above average for all species except Shorthead Redhorse in 2010 and Bigmouth Buffalo in 2011. Below average growth in 2008 and 2009 may be attributed to the amount of optimal growing days, where these two years were in the top three for lowest amount of optimal growing days as a whole for all species (with the exception of 2004 that had the lowest amount; Chapter IV results). The number of optimal growing days in 2010 and 2011 were not the highest among all years, and alone cannot explain the above average growth in these years.

There also were differences in growth among species (Figure 5.4). When looking at the raw output from the linear mixed-effects models, Flathead Catfish by far had the most annual variation in growth when compared to other species. Of all target species, Flathead Catfish grew the largest, so growth results may be a function of growth potential for each species. Another way of looking at the data is normalizing the raw output results and displaying them as a proportion of their standard length category. It was apparent, that Flathead Catfish had the most annual variation in growth. Channel Catfish and Freshwater Drum also showed considerable annual growth variation. Lastly, the observed annual growth variation among species may appear to be minimal (*e.g.,* is below average

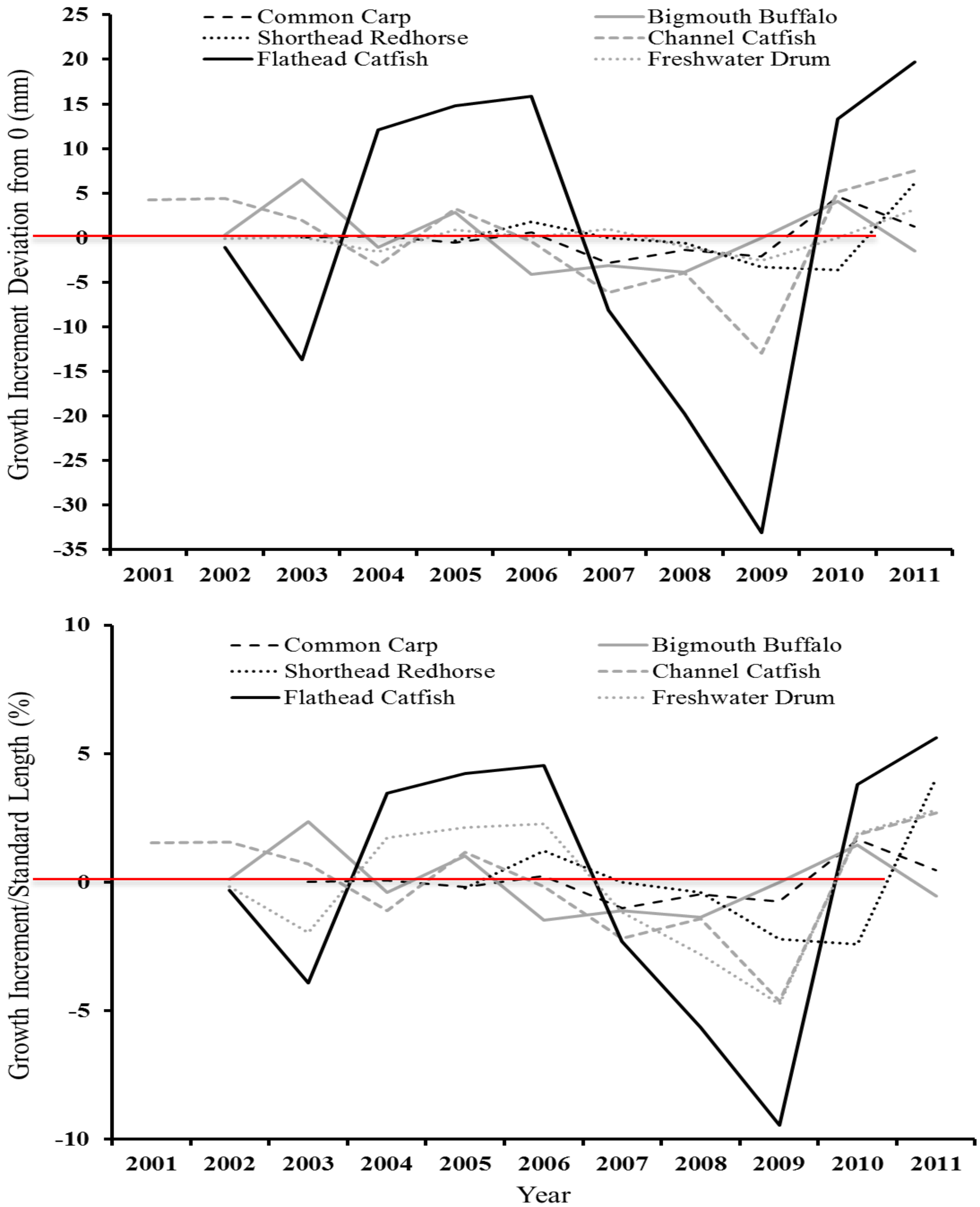

Figure 5.4. Plots of growth-year effects for selected fishes sampled from the Minnesota River, 2012. No year-effect was noted for River Carpsucker and Walleye. Top plot denotes growth increments as deviations from 0 mm. Bottom plot denotes growth increments as a proportion of each species standard length (%). Years of higher growth are positive and years of lower growth are negative (denoted by red line at 0).

growth of -33 mm for Flathead Catfish). To put below average growth of -33 mm into a biomass perspective, if the entire population of Flathead Catfish all had below average growth for a given year, that would result in a substantial decrease in overall Flathead Catfish biomass (little to no growth in a given year).

Similar to fish growth, recruitment variation can provide several insights in understanding the dynamics of fish populations (Quist and Spiegel 2011). Using the Maceina (1997) technique, 2010 resulted in strong recruitment for Common Carp, Channel Catfish, and Freshwater Drum, while 2008 resulted in weak recruitment for Common Carp, Shorthead Redhorse, Channel Catfish, and Walleye. Also, 2007 resulted in strong recruitment for Common Carp, Channel Catfish, and Walleye, while weak recruitment was noted for Bigmouth Buffalo and Freshwater Drum.

Large rivers are complex natural systems with numerous simultaneously interacting physical, chemical, and biological components that dictate community dynamics. Numerous concepts have been introduced to help define the ecological function of large rivers. Although conceptual approaches have furthered the understanding of large riverine processes, their relevance to temperate rivers has been questioned (Johnson et al. 1995). Our results provide empirical evidence demonstrating that these concepts are relevant to at least one temperate river in the upper Midwestern United States.

The Flood Pulse Concept

In the present study, positive growth in relation to flood pulse parameters (*i.e.*, active floodplain connection and/or backwater connection) was supported for Common

Carp, Channel Catfish, Flathead Catfish, and Freshwater Drum and specific flow thresholds were delineated when possible. Specifically, all previously mentioned species had both an active floodplain and backwater connection relationship; however, backwater connection parameters were more prominent for Flathead Catfish and Freshwater Drum. My results are consistent with other flood pulse studies in the upper Midwest, such as Gutreuter et al. (1999) that found growth of several fishes of the Upper Mississippi River was correlated with duration of floodplain inundation. Fishes such as Common Carp and Channel Catfish are classified as omnivores and showed a growth benefit from high flow magnitude. Growth of omnivores has been positively correlated with rate of water level increases (Bayley 1988; Gutreuter et al. 1999).

In the present study, Flathead Catfish and Freshwater Drum showed positive growth in relation to flood pulse parameters, with backwater connection flow being more prominent (5 of 6 models for Flathead Catfish and 4 of 5 models for Freshwater Drum – including combined flow parameters). Positive growth in relation to flooding has been previously reported for Flathead Catfish and Freshwater Drum. Jones and Noltie (2007) found increased growth in Flathead Catfish following the 1993 Mississippi flood and recent work on the Wabash River showed that Freshwater Drum growth was positively related to high magnitude flow events (Jacquemin et al. 2014).

Jones and Noltie (2007) suggested the improved Flathead Catfish growth after flooding could be the result of 1) increased turbidity during floods that would favor olfactory predators, 2) receding flood waters that concentrate flood-augmented prey items into a smaller water volume in the main channel, thereby increasing prey densities, and 3) deposition of woody debris that replenished Flathead Catfish habitat and increased production substrates for invertebrates and prey fishes. Results reported by Jones and Noltie (2007) likely indicate connection to the active floodplain was important for Flathead Catfish, whereas in the present study, backwater connections where of importance, but both support aspects of the flood pulse concept.

Of the supported flood pulse models in relation to growth, 9 models exclusively consisted of backwater parameters, 5 models were solely active floodplain models, and 3 were of some combination of backwater and active floodplain components. The model that included backwater connection duration coupled with optimal growing days was top ranked for Channel Catfish, Flathead Catfish, and Freshwater Drum; whereas, active floodplain connection duration only was the top-ranked model for Common Carp, but was noted for Channel and Flathead Catfish as well as Freshwater Drum. Similar results for Channel Catfish growth was also reported in the Kanas River, Kansas following floodplain inundation (Quist and Guy 1998). Arterburn (2001) reported faster growth rates of Channel Catfish in the James and Big Sioux rivers, South Dakota during high water years. Interestingly, both Common Carp and Channel Catfish are classified as omnivores and similar flow conditions might be expected to favor both species. This might suggest differences in diet and that a broad guild classification might not truly reflect what these fishes consume. Whether or not these fishes directly or indirectly benefitted from floodplain/backwater access was beyond the scope of this project, but does stress the importance of these unique habitats for these species.

In the Minnesota River, Channel Catfish and Freshwater Drum exhibited a positive flood-recruitment effect. Whereas Channel Catfish recruitment variation was related to flood pulse parameters only, Freshwater Drum appeared to be regulated by a combination of riverine concept models. Several studies have documented the impact of hydrology on recruitment success of river fishes (e.g., Quist and Guy 1998, Quist and Spiegel 2011, and Dutterer et al. 2012). Quist and Guy (1998) noted improved Channel Catfish recruitment during flood years in the Kansas River. In Iowa rivers, neither hydrology nor temperature were strongly related to recruitment success of several catostomids (Quist and Spiegel 2011).

Low Flow Recruitment Concept

The low-flow recruitment concept did not appear to be strongly applicable to the Minnesota River for the fishes examined in this study. No species exhibited a recruitment benefit from low flows as predicted by Humphries et al. (20xx). In terms of growth, the only species that benefited from extended low flows, was Bigmouth Buffalo. Because Bigmouth Buffalo are predominantly zooplanktivores, this might suggest that low flows allowed greater zooplankton production in the mainstem Minnesota River. For Flathead Catfish and Freshwater Drum, a negative relationship was noted for extended periods of low flow, possibly suggesting resource limitation or density dependence. King (2004) reported that during periods of low flow in the Broken River in Victoria, Australia, sufficient densities of epibenthic meiofauna were present in the main river channel. However, in tropical floodplain rivers, resource limitation can negatively impact species that feed on algae and invertebrates during protracted periods of low flow (Winemiller 2004).

Intermediate Flows Concept

Recently, there has been a growing body of research that suggests periods of intermediate flow may benefit riverine fish growth and recruitment (Moore and Thorp 2008). For ease of conceptualization, intermediate flows are those that are between extreme low flows, but also below backwater connection magnitude. During intermediate flow periods, a multitude of instream habitat is present (*esp.* slackwater patches) that offer refuge for developing fishes. Moreover, these intermediate flow periods are important for transporting nutrients, energy, and wastes (Roach et al. 2009), while increasing available riffle habitat that is important spawning habitat for many riverine fishes (Aadland et al. 1991).

When exploring the applicability of the intermediate flows concept to growth of Minnesota River fishes, the only species showing support for this concept was Bigmouth Buffalo, and only when coupled with optimal growing days. During periods of intermediate flows in the Minnesota River, I suspect that pool habitat is increased and conditions are near optimum for Bigmouth Buffalo. Mulla (1998) noted that during periods of stable intermediate flow, a burst of instream primary production can occur in the Minnesota River, particularly during late summer. Moreover, very little flow was observed in slackwater pools during the summer, and was also noted to be the primary habitat of main channel Bigmouth Buffalo. Interestingly, Common Carp and Freshwater Drum were also observed in these same habitats, but showed a negative relationship to intermediate flows, suggesting that their differential food habits may be important factors.

No single intermediate flow parameter was positively related to recruitment success for any of the Minnesota River fishes evaluated. There were, however, some noteworthy combined parameters that are discussed below. Hydrological reversals were negatively related to Common Carp and Channel Catfish recruitment. Hydrological reversals are abrupt changes in discharge (either positive or negative) and may disrupt spawning habitat of Common Carp (*e.g.*, dewatering submerged eggs). Recruitment success in the Murray-Darling Basin in Australia was noted to be from long-term flow regulation, where Common Carp seek refuge from high flows (Driver et al. 2005). Similar to the Murray-Darling example, the data here support Common Carp recruitment being negatively impacted by hydrological reversals that would be analogous to a reduction in stable flows. Furthermore, Channel Catfish are nest builders and highly variable flows can negatively affect spawning success and recruitment of Channel Catfish (Sakaris 2013). Sakaris (2006) reported that successful hatching of age-0 Channel Catfish typically occurred during stable low flow periods in the Tallapoosa River, Alabama. Although no recruitment relationships were observed in the Minnesota River during extended periods of low flow, it may be that erratic hydrology is more important in terms of recruitment success for Channel Catfish.

Combined Riverine Concepts

In the current study, Freshwater Drum recruitment success was supported by a wide-array of single-flow conditions (as discussed above) and a combination of flow parameters as well. The most notable findings were combination models where backwater inundation was coupled with hydrological reversals. The benefits of this combination may be that during spawning months, hydrological reversals may act as a spawning cue for Freshwater Drum and backwaters or other inundated areas of reduced current serves as nursery habitat during larval stages. Moreover, high flows may also be beneficial as drifting eggs develop and facilitate the drift component of their life history. Interestingly, it has been reported that in the Kansas River, Kansas, no recruitment trends were observed for Freshwater Drum in relation to high or low flows, indicating flow patterns may not influence recruitment of Freshwater Drum (Gerken 2015). As reported earlier, hydrological reversals alone were not a supported model, whereas backwater connection parameters were suggesting high flows are more important for Freshwater Drum recruitment in the Minnesota River.

Concluding Remarks

No supported models were noted for Common Carp and Bigmouth Buffalo recruitment in relation to backwater parameters. However, the observation of spawning Common Carp and Bigmouth Buffalo in a backwater in 2012 raises logical questions about the results presented here. Fisher (1999) noted substantial spawning and use as nursery habitat by both Bigmouth Buffalo and Common Carp in upper Missouri River backwaters. Nickel (2014) also noted presence of YOY Common Carp but not *Ictiobus* spp. in a backwater of the Minnesota River; however, catch rates were lower than anticipated. A valid criticism of theses analyses is that fishes were documented using backwaters for spawning (and to some extent use for nursery habitat), but I do not have sufficient data to describe the extent of backwater use and must limit my discussion to growth and recruitment that was positively related to a specific flow threshold.

In the Minnesota River, numerous relationships were noted for growth and recruitment in regards to various riverine concepts; however, some species showed no response to flow. No riverine parameter explained any of the variation in growth or recruitment for Shorthead Redhorse, but it is expected that flow regime does impact this species at all or specific parts of its life cycle but to a lesser extent than other riverine species examined. Lastly, River Carpsucker was not included in the recruitment analyses as sample size was insufficient within the examined time frame. It should be noted that the most prominent year class was the 2001 year class. 2001 was noted to be a high water year and may suggest flooding may be beneficial to River Carpsucker as found by Quist and Spiegel (2011) in Iowa rivers.

CHAPTER VI: MANANGEMENT IMPLICATIONS AND FUTURE RESEARCH NEEDS

This study provided a review of several large river ecology concepts and a broad overview of the Minnesota River basin. Moreover, this study helped establish a baseline for the current hydrology of the Minnesota River. Lastly, this study provided insight as to how large riverine concepts apply to the Minnesota River and influence the growth and recruitment of selected fishes. Primary research findings from this study are summarized below.

1. Like other Midwestern rivers, the Minnesota River has a highly variable flow regime largely driven by precipitation events.
2. Indicators of Hydrologic Alteration are a useful tool to establish flow thresholds that define riverine concepts.
3. Electrofishing was most effective at capturing the widest length ranges of fishes and based on results of this study target species become recruited to electrofishing at the following ages:
    - Common Carp – Age-2 (~270mm)
    - Bigmouth Buffalo – Age-5 (~480mm)
    - River Carpsucker – Age-11 (~475mm)
    - Shorthead Redhorse – Age-3 (~255mm)
    - Channel Catfish – Age-2 (~165mm)
    - Flathead Catfish – Age-2 (~275mm)
    - Walleye – Age-1 (~160mm)
    - Freshwater Drum – Age-2 (~200mm)
4. Of competing large river concepts, the flood pulse concept was most applicable to selected fishes of the Minnesota River

5. Both the active floodplain and backwaters are of ecological importance for selected Minnesota River fishes.
6. Active floodplain connection was beneficial for numerous Minnesota River fishes, in particular Common Carp growth and two a lesser extent Channel and Flathead Catfish, and Freshwater Drum where the backwater connection was more beneficial. Floodplain connections were positively related to recruitment for Channel Catfish and Freshwater Drum, with backwater connections being more important for Freshwater Drum recruitment.
7. Extreme low flow conditions were only beneficial for Bigmouth Buffalo growth.
8. Intermediate flows were the dominant flow condition annually in the Minnesota River, followed by backwater connection flows, extreme low flows, and lastly active floodplain flows, but were only favored for Bigmouth Buffalo growth.

Specifically, this study can be used to compare to future research and to establish important baseline population data for several common fishes of the Minnesota River. The study area encompassed in this project is considered ‘Reach 2’ as outlined in the current Minnesota River Management Plan and supporting information can help supplement any data gaps that may be missing for this stretch of river. Based on findings of this research the following are suggested management implications and recommendations:

1. Backwater and active floodplain connections were important to many fishes in this study, therefore, maintaining and restoring these connections should be a high priority for Minnesota River managers.
2. To some extent, every riverine concept or flow threshold was beneficial for at least one species, suggesting that a natural flow regime (*i.e.*, with variation) should be maintained through continued efforts of Best Management Practices, riparian corridor protection, wetland restoration, and set aside programs such as CRP and CREP.
3. Specific focus should be placed on Channel Catfish, Flathead Catfish, and Walleye recruitment in future studies to assess specific spawning conditions and locations as well as nursery habitat use as these are primary game fishes of the Minnesota River.

4. Future studies could also focus on telemetry, diets, and stable isotopes to determine seasonal habitat use and foraging of Minnesota River fishes.

5. Sampling efforts indicated that benthic trawling was effective at capturing small Channel Catfish. Annual trawling could be implemented as a standard gear to determine YOY abundance and coupled with electrofishing and/or trot lines as an index for year-class strength could be developed.

6. Although not included in this thesis report, data show that trawling was the most effective gear for capturing Shovelnose Sturgeon; however, it is recommended other gears such as electrofishing, trammel nets, and drifting gill nets also be included in Shovelnose Sturgeon assessments.

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APPENDICES

APPENDIX A: IHA Data

Summary table of Indicators of Hydrologic Alteration (IHA) parameters and associated percentiles from 1991-2011 for the Minnesota River at Mankato, Minnesota. The values represent the Coefficient of Dispersion (C.D.) for each parameter and year. The shaded rows denote IHA parameters that had significant C.D. values and were therefore used in the assessments described in this thesis.

Appendix A.

IHA Parameter	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
January	7.9	85.0	46.7	52.4	45.3	55.2	46.7	33.1	45.3	14.2	13.3	34.6
February	9.5	87.8	28.9	39.6	27.5	43.0	43.9	29.0	83.4	13.6	13.9	31.4
March	32.3	450.2	49.3	430.4	215.5	181.2	342.6	162.3	113.0	64.9	20.3	51.8
April	211.7	247.1	783.0	397.9	594.7	342.6	1222.0	502.6	454.5	41.2	1557.0	184.2
May	373.8	155.2	529.5	393.6	515.4	276.9	379.4	222.6	354.0	59.5	603.1	188.0
June	707.9	136.1	533.8	307.2	383.7	380.9	193.8	167.1	304.4	216.3	416.3	261.2
July	348.3	362.5	883.5	252.3	354.0	108.2	320.0	123.7	246.4	152.9	162.5	80.4
August	226.8	157.4	623.0	130.5	237.6	79.6	128.0	42.8	95.7	45.9	39.1	101.1
September	150.1	103.4	277.8	100.7	97.3	32.4	50.7	21.4	43.0	11.5	21.6	27.3
October	63.7	135.9	138.8	182.6	237.6	33.7	47.0	51.8	26.7	8.8	19.9	84.4
November	71.2	191.1	98.8	99.1	247.8	93.0	49.6	124.9	22.8	21.7	22.9	62.7
December	117.5	109.9	112.7	60.9	87.8	79.3	45.6	90.1	20.5	13.0	56.6	34.0
1 Day Minimum	7.6	50.4	28.9	37.9	26.3	25.0	28.6	14.3	14.7	8.0	11.6	19.5
3 Day Minimum	7.6	51.3	28.9	37.9	26.3	25.3	29.1	14.9	14.7	8.0	11.6	20.5
7 Day Minimum	7.6	53.4	28.9	37.9	26.3	25.5	29.5	15.2	14.8	8.3	11.9	22.1
30 Day Minimum	7.8	77.4	28.9	40.5	28.2	28.6	37.8	20.0	19.6	8.9	13.3	30.0
90 Day Minium	34.7	140.8	69.6	115.6	90.6	58.8	46.1	42.5	23.2	16.0	18.4	42.2
1 Day Maximum	928.8	671.1	2127.0	600.3	778.7	784.4	2223.0	798.5	671.1	470.1	2073.0	362.5
3 Day Maximum	912.7	664.5	2043.0	595.6	775.9	771.2	2181.0	790.0	664.5	452.1	2027.0	357.7
7 Day Maximum	863.7	640.4	1907.0	580.1	759.3	720.9	2025.0	748.4	644.4	422.7	1909.0	341.0
30 Day Maximum	722.9	486.4	1325.0	477.1	626.7	466.9	1339.0	554.3	463.1	292.3	1582.0	263.9
90 Day Maximum	491.7	319.0	865.4	397.3	519.0	381.5	724.0	326.3	392.9	199.1	912.5	214.6
Zero Days	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Base Flow	0.0	0.3	0.1	0.2	0.1	0.2	0.1	0.1	0.1	0.1	0.0	0.2
Date Minimum	25.0	279.0	31.0	41.0	49.0	288.0	285.0	269.0	360.0	284.0	56.0	268.0
Date Maximum	161.0	71.0	173.0	120.0	115.0	173.0	100.0	94.0	104.0	157.0	107.0	176.0
Low Pulse Number	1.0	0.0	1.0	1.0	1.0	1.0	2.0	3.0	2.0	6.0	1.0	5.0
Low Pulse Low	1.0	-	49.0	9.0	44.0	34.0	8.0	35.0	79.0	7.5	102.0	24.0
Backwater Connection Frequency	6.0	7.0	3.0	7.0	3.0	1.0	2.0	6.0	3.0	3.0	1.0	3.0
High Pulse Low	7.0	5.0	5.0	8.0	49.0	100.0	61.0	1.5	30.0	7.0	95.0	5.0
Rise Rate	7.6	12.2	14.6	11.3	14.2	5.7	4.2	4.8	2.8	1.4	1.0	4.0
Fall Rate	-8.5	-5.9	-11.8	-8.5	-5.7	-2.8	-7.1	-3.7	-3.1	-1.1	-2.8	-2.5
Reversals	44.0	54.0	58.0	60.0	48.0	52.0	66.0	64.0	77.0	77.0	74.0	60.0

Appendix A Continued.

IHA Parameter	2003	2004	2005	2006	2007	2008	2009	2010	2011	Median	25%	75%	C.D.
January	19.3	7.8	23.3	100.2	33.7	41.3	18.5	63.7	121.2	41.3	18.9	53.8	0.8
February	17.1	6.3	41.8	132.7	17.2	26.5	41.9	61.3	108.5	31.4	17.2	52.6	1.1
March	51.8	66.0	61.7	199.4	436.1	49.8	85.8	875.0	245.5	113.0	51.8	294.1	2.1
April	109.0	36.8	262.4	635.7	414.8	253.9	359.6	553.6	1120.0	397.9	229.4	615.2	1.0
May	252.0	35.4	325.6	441.7	281.5	399.3	157.2	269.6	574.8	325.6	205.3	420.5	0.7
June	156.5	502.6	320.0	210.8	194.5	378.0	116.2	424.8	587.6	307.2	194.2	420.5	0.7
July	146.1	156.0	153.2	49.6	38.2	135.4	55.8	291.7	577.7	156.0	116.0	334.1	1.4
August	27.3	82.1	53.5	28.3	20.2	37.1	26.3	122.6	189.7	82.1	38.1	144.0	1.3
September	12.4	174.9	75.3	18.4	45.0	13.2	10.9	227.5	101.9	45.0	19.9	102.6	1.8
October	8.9	126.3	214.9	21.5	300.2	18.8	98.8	402.1	40.8	63.7	24.1	160.7	2.1
November	11.3	103.8	90.2	22.0	107.6	36.5	173.3	242.1	31.9	90.2	27.4	116.2	1.0
December	8.5	51.3	104.5	21.1	57.5	25.5	92.9	128.8	25.8	57.5	25.6	98.7	1.3
1 Day Minimum	6.3	5.4	16.4	12.3	13.9	8.0	8.4	54.1	19.9	14.7	8.2	27.5	1.3
3 Day Minimum	6.6	5.4	16.6	12.8	13.9	8.1	8.5	54.3	21.5	14.9	8.3	27.6	1.3
7 Day Minimum	7.3	5.5	17.0	14.1	14.3	8.4	8.7	55.6	23.6	15.2	8.5	27.6	1.3
30 Day Minimum	8.4	6.0	24.1	18.7	17.3	11.1	13.5	59.1	26.4	20.0	12.2	29.5	0.9
90 Day Minium	9.6	24.0	51.5	21.0	57.3	19.6	30.6	278.6	32.6	42.2	22.1	64.2	1.0
1 Day Maximum	419.1	662.6	673.9	954.3	804.2	611.6	521.0	2362.0	1826.0	778.7	606.0	1390.0	1.0
3 Day Maximum	398.3	654.1	657.0	941.1	787.2	602.2	517.3	2267.0	1801.0	771.2	598.9	1371.0	1.0
7 Day Maximum	371.0	630.3	609.6	898.5	743.1	568.0	495.5	2032.0	1699.0	720.9	574.0	1299.0	1.0
30 Day Maximum	260.6	474.1	406.6	670.9	579.7	427.6	390.9	1139.0	1378.0	486.4	417.1	931.1	1.1
90 Day Maximum	203.6	257.0	335.7	467.3	384.1	360.5	229.1	589.8	862.5	384.1	288.0	554.4	0.7
Zero Days	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Base Flow	0.1	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.7
Date Minimum	284.0	31.0	24.0	338.0	49.0	280.0	267.0	67.0	326.0	338.0	282.0	36.0	0.3
Date Maximum	136.0	167.0	136.0	101.0	80.0	127.0	96.0	271.0	86.0	120.0	98.0	164.0	0.2
Low Pulse Number	1.0	4.0	2.0	2.0	3.0	4.0	2.0	0.0	4.0	2.0	1.0	3.5	1.3
Low Pulse Low	211.0	13.0	22.5	76.0	34.0	61.5	35.5	-	5.5	34.0	9.0	61.5	1.5
Backwater Connection Frequency	1.0	4.0	5.0	3.0	3.0	3.0	1.0	6.0	2.0	3.0	2.0	5.5	1.2
High Pulse Low	14.0	9.5	18.0	6.0	12.0	32.0	31.0	24.5	76.0	14.0	6.5	40.5	2.4
Rise Rate	1.1	3.7	4.1	2.3	3.9	1.8	4.4	5.7	4.1	4.1	2.6	6.7	1.0
Fall Rate	-1.1	-4.0	-5.9	-3.0	-4.8	-1.6	-2.8	-10.9	-5.1	-4.0	-6.5	-2.8	-0.9
Reversals	72.0	74.0	62.0	87.0	51.0	85.0	74.0	65.0	57.0	64.0	55.5	74.0	0.3

Appendix A Continued.

EFC Parameter	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
January Low Flow	-	85.0	46.7	52.4	45.3	55.2	46.7	33.1	45.3	-	-	34.6
February Low Flow	-	87.1	28.9	39.6	27.5	43.0	43.9	28.6	83.4	56.6	-	31.4
March Low Flow	36.5	-	48.7	96.3	33.7	77.9	127.4	136.3	108.5	64.9	27.1	51.8
April Low Flow	146.4	190.9	-	-	-	-	-	-	157.7	41.2	-	178.4
May Low Flow	-	150.4	-	-	-	-	-	191.6	-	52.4	-	171.3
June Low Flow	-	101.4	-	185.3	-	-	139.9	129.1	-	184.9	-	184.2
July Low Flow	-	-	-	163.1	-	99.3	-	118.9	170.8	128.4	146.5	80.4
August Low Flow	154.6	136.9	-	114.3	137.8	79.6	123.0	42.8	95.7	45.9	39.1	101.1
September Low Flow	125.7	103.4	-	100.7	97.3	32.4	50.7	31.6	43.0	21.0	21.8	27.3
October Low Flow	63.7	116.7	133.8	164.5	124.9	33.7	47.0	87.2	26.7		22.3	84.4
November Low Flow	57.9	181.5	98.8	99.1	167.1	93.0	49.6	124.9	22.8	27.7	23.0	62.7
December Low Flow	117.5	109.9	112.7	60.9	87.8	79.3	45.6	90.1	22.8	20.5	56.6	34.0
Intermediate Flow Duration	142.0	230.0	174.0	208.0	162.0	257.0	232.0	262.0	242.0	190.0	183.0	321.0
Extreme Low Peak	-	-	-	-	-	-	-	16.6	18.7	11.1	19.0	-
Extreme Low Duration	69.0	-	-	-	-	-	-	16.0	13.0	141.0	82.0	-
Extreme Low Timing	-	-	-	-	-	-	-	273.5	353.0	359.0	291.5	-
Extreme Low Frequency	-	-	-	-	-	-	-	2.0	1.0	3.0	4.0	-
Backwater Connection Flow Peak	314.3	413.4	-	376.6	339.8	-	438.9	268.7	322.8	406.3	201.6	292.9
Backwater Connection Duration	154.0	136.0	191.0	157.0	203.0	109.0	133.0	87.0	110.0	35.0	100.0	44.0
Backwater Connetion Timing	224.0	254.0	109.0	226.0	308.0	174.0	211.0	143.5	104.0	163.0	207.0	147.0
Backwater Connection Frequency	5.0	6.0	7.0	5.0	1.0	2.0	1.0	4.0	3.0	4.0	1.0	4.0
Backwater Connection Rise Rate	54.4	42.5	-	7.7	5.5	-	7.3	30.1	34.5	56.8	3.7	32.1
Backwater Connection Fall Rate	-20.8	-17.0	-	-11.8	-7.7	-	-31.0	-13.8	-12.4	-36.2	-6.8	-10.3
Small Flood Peak	928.8	-	-		778.7	784.4	-	798.5	-	-	2073.0	-
Small Flood Duration	7.0	-	65.0	-	-	2.0	26.0	2.0	-	-	41.0	-
Small Flood Timing	161.0	-	173.0	-	-	173.0	-	94.0	-	-	107.0	-
Small Flood Frequency	1.0	-	1.0	-	-	1.0	-	1.0	-	-	1.0	-
Small Flood Rise Rate	17.9	-	22.8	-	-	6.2	-	90.9	-	-	121.3	-
Small Flood Fall Rate	-12.6	-	-18.4	-	-	-39.0	-	-15.9	-	-	-22.3	-
Large Flood Peak	-	-	-	-	-	-	2223.0	-	-	-	-	-
Large Flood Duration	-	-	-	-	-	-	2.0	-	-	-	-	-
Large Flood Timing	-	-	-	-	-	-	100.0	-	-		-	-
Large Flood Frequency	-	-	-	-	-	-	1.0	-	-	-	-	-
Large Flood Rise Rate	-	-	-	-	-	-	66.4	-	-	-	-	-
Large Flood Fall Rate	-	-	-	-	-	-	-32.7	-	-	-	-	-
Active Floodplain Connection Duration	7.0	-	65.0	-	-	2.0	28.0	-	-	-	41.0	-

Appendix A Continued.

EFC Parameter	2003	2004	2005	2006	2007	2008	2009	2010	2011	Median	25%	75%	C.D.
January Low Flow	22.7	-	32.9	100.2	33.7	41.3	21.1	63.7	121.2	45.3	33.4	59.5	0.6
February Low Flow	-	-	41.8	115.5	20.1	26.5	45.3	61.3	104.5	43.0	28.7	72.4	1.0
March Low Flow	110.9	70.2	59.9	119.5	20.8	49.8	77.9	56.9	195.4	67.5	49.0	110.3	0.9
April Low Flow	95.7	36.8	169.1	-	-	142.3	-	-	-	146.4	68.5	173.7	0.7
May Low Flow	156.3	31.4	163.0	-	-	-	144.4	-	-	153.3	75.4	169.2	0.6
June Low Flow	145.3	159.6		173.6	181.2	-	116.2	194.3	-	166.6	131.8	184.7	0.3
July Low Flow	142.3	139.3	127.9	49.6	38.2	129.7	55.8	194.0	-	128.4	80.4	146.5	0.5
August Low Flow	27.9	82.1	53.5	28.3	86.7	38.2	26.4	122.6	140.2	84.4	40.0	122.9	1.0
September Low Flow	-	41.1	70.2	21.3	45.0	20.3	28.2	174.4	101.9	43.0	27.3	100.7	1.7
October Low Flow	-	123.2	137.1	21.5	100.8	23.5	95.7	-	40.8	85.8	32.0	123.6	1.1
November Low Flow	-	103.8	90.2	22.1	106.2	36.5	165.9	164.5	31.9	91.6	33.0	120.2	1.0
December Low Flow	-	51.3	104.5	22.0	57.5	25.5	92.9	128.8	25.8	59.2	27.9	101.6	1.2
Intermediate Flow Duration	151.0	243.0	247.0	237.0	210.0	235.0	258.0	161.0	193.0	230.0	183.0	243.0	0.2
Extreme Low Peak	16.7	5.4	16.4	18.1	18.0	18.2	16.3	-	-	16.7	16.3	18.2	0.1
Extreme Low Duration	179.0	64.0	9.0	27.0	35.0	44.0	52.0	-	-	48.0	18.8	78.8	0.8
Extreme Low Timing	40.0	31.0	24.0	307.0	216.0	280.0	224.0	-	-	307.0	273.5	24.0	0.3
Extreme Low Frequency	2.0	1.0	1.0	5.0	5.0	3.0	3.0	-	-	1.0	0.0	3.0	3.0
Backwater Connection Flow Peak	243.0	465.8	525.3	275.2	211.8	611.6	230.8	291.7	345.5	322.8	268.7	413.4	0.4
Backwater Connection Duration	35.0	59.0	109.0	101.0	120.0	87.0	55.0	204.0	172.0	109.0	87.0	154.0	0.4
Backwater Connetion Timing	165.0	193.0	122.0	73.0	170.0	127.0	301.0	208.0	55.0	170.0	127.0	224.0	0.3
Backwater Connection Frequency	5.0	4.0	4.0	3.0	5.0	1.0	3.0	1.0	1.0	3.0	1.0	4.5	1.2
Backwater Connection Rise Rate	17.7	28.3	63.8	22.2	15.0	17.9	16.3	24.4	40.8	24.4	15.0	40.8	1.1
Backwater Connection Fall Rate	-11.8	-31.3	-18.5	-16.1	-8.5	-6.8	-10.1	-18.7	-10.6	-12.4	-18.7	-10.1	-0.7
Small Flood Peak	-	-	-	954.3	804.2	-	-	1388.0	1826.0	941.5	795.0	1888.0	1.2
Small Flood Duration	-	-	-	10.0	2.0	-	-	39.0	51.0	18.0	2.0	43.5	0.9
Small Flood Timing	-	-	-	101.0	80.0	-	-	132.0	86.0	111.0	92.0	164.0	0.2
Small Flood Frequency	-	-	-	1.0	1.0	-	-	2.0	1.0	0.0	0.0	1.0	0.0
Small Flood Rise Rate	-	-	-	31.5	110.2	-	-	104.0	136.1	61.2	17.1	113.0	1.6
Small Flood Fall Rate	-	-	-	-14.0	-8.3	-	-	-30.6	-11.5	-15.0	-24.4	-10.7	-0.9
Large Flood Peak	-	-	-	-	-	-	-	2362.0	-	2292.0	2223.0	2362.0	0.1
Large Flood Duration	-	-	-	-	-	-	-	3.0	-	2.5	-	-	0.2
Large Flood Timing	-	-	-	-	-	-	-	271.0	-	185.5	100.0	271.0	0.5
Large Flood Frequency	-	-	-	-	-	-	-	1.0	-	0.0	0.0	0.0	0.0
Large Flood Rise Rate	-	-	-	-	-	-	-	144.2	-	105.3	66.4	144.2	0.7
Large Flood Fall Rate	-	-	-	-	-	-	-	-36.4	-	-34.6	-36.4	-32.7	-0.1
Active Floodplain Connection Duration	-	-	-	10.0	2.0	-	-	42.0	51.0	28.0	7.0	42.0	NA

APPENDIX B: Length-Frequency Histograms

Length frequency for selected species of fish sampled from the Minnesota River in 2012. Gear specifications are detailed in the Methods, vary by species, and are noted in each table. The species common name is listed above each table.

Common Carp

Total Length (mm)	Electrofishing	Sport Angling	Trap Net	All Gears Combined
0-50			3	3
51-100			1	1
101-125				
125-150				
151-175				
176-200				
201-225	1			1
226-250	1			1
251-275	3			3
276-300	7			7
301-325	32			32
326-350	32			32
351-375	16			16
376-400	18			18
401-425	14			14
426-450	13			13
451-475	13			13
476-500	10			10
501-525	14			14
526-550	12	2	1	15
551-575	16	2	1	19
576-600	9		1	10
601-625	10	2	1	13
626-650	5	1		6
651-675	3	1	2	6
676-700	3	2		5
701-725	2	3		5
726-750	1			1
751-775		1		1
776-800	1			1
801-825	1			1
826-850				
851-875				
876-900				
901-925				
926-950				
951-975				
976-1000				
1001-1025				
1026-1050				
1051-1075				
1076-1100				
1101-1125				
1126-1150				
1151-1175				
1176-1200				
1201-1225				
1226-1250				
Total	237	14	10	261
Minimum Length	220	535	41	41
Mean Length	441	643	383	450
Maximum Length	810	753	667	810

Appendix B Continued.

Bigmouth Buffalo

Total Length (mm)	Electrofishing	Commercial Harvest	Hoop Net	Trawl	All Gears Combined
0-50					
51-100					
101-125					
125-150					
151-175					
176-200					
201-225					
226-250					
251-275					
276-300	2				2
301-325					
326-350	1				1
351-375	1				1
376-400	1	2			3
401-425	3	1			4
426-450	4	6			10
451-475	2	8			10
476-500	8	4		1	13
501-525	9	3			12
526-550	6	7			13
551-575	8	2			10
576-600	3	5			8
601-625	3	2	1		6
626-650	2				2
651-675		2			2
676-700	1	1			2
701-725					
726-750					
751-775					
776-800					
801-825					
826-850					
851-875					
876-900					
901-925					
926-950					
951-975					
976-1000					
1001-1025					
1026-1050					
1051-1075					
1076-1100					
1101-1125					
1126-1150					
1151-1175					
1176-1200					
1201-1225					
1226-1250					
Total	54	43	1	1	99
Minimum Length	283	381	608	483	283
Mean Length	506	514	608	483	510
Maximum Length	682	690	608	483	690

Appendix B Continued.

River Carpsucker

Total Length (mm)	Electrofishing	Commercial Harvest	Trap Net	Trawl	All Gears Combined
0-50					
51-100	1				1
101-125					
125-150	3				3
151-175					
176-200					
201-225	1				1
226-250	1				1
251-275					
276-300	1				1
301-325	4				4
326-350	2				2
351-375	6				6
376-400	9				9
401-425	16	2	1		19
426-450	22	3			25
451-475	24	1	1		26
476-500	13	1	1	2	17
501-525	7				7
526-550	5				5
551-575	2				2
576-600					
601-625					
626-650					
651-675					
676-700					
701-725					
726-750					
751-775					
776-800					
801-825					
826-850					
851-875					
876-900					
901-925					
926-950					
951-975					
976-1000					
1001-1025					
1026-1050					
1051-1075					
1076-1100					
1101-1125					
1126-1150					
1151-1175					
1176-1200					
1201-1225					
1226-1250					
Total	117	7	3	2	129
Minimum Length	53	410	400	485	53
Mean Length	427	441	445	491	430
Maximum Length	556	483	480	496	556

Appendix B Continued.

Shorthead Redhorse

Total Length (mm)	Electrofishing	Seine	All Gears Combined
0-50			
51-100	2		2
101-125	2		2
125-150	1		1
151-175	8		8
176-200	10		10
201-225	5		5
226-250	8		8
251-275	14		14
276-300	19		19
301-325	15		15
326-350	15		15
351-375	9		9
376-400	11		11
401-425	10		10
426-450	4		4
451-475		1	1
476-500			
501-525			
526-550			
551-575			
576-600			
601-625			
626-650			
651-675			
676-700			
701-725			
726-750			
751-775			
776-800			
801-825			
826-850			
851-875			
876-900			
901-925			
926-950			
951-975			
976-1000			
1001-1025			
1026-1050			
1051-1075			
1076-1100			
1101-1125			
1126-1150			
1151-1175			
1176-1200			
1201-1225			
1226-1250			
Total	133	1	134
Minimum Length	83	458	83
Mean Length	293	458	294
Maximum Length	441	458	458

Appendix B Continued.

Channel Catfish

Total Length (mm)	Electrofishing	Trot Line	Sport Angling	Trap Net	Trawl	Seine	Hoop Net	All Gears Combined
0-50	6			18	795	32		851
51-100	32			13	27	8	2	82
101-125	1				5			6
125-150	3				8		1	12
151-175	7			1	8		1	17
176-200	9			2	10			21
201-225	12		3		2			17
226-250	8							8
251-275	9	1			1			11
276-300	3			1	1			5
301-325	3	2	1					6
326-350	5	2	1					8
351-375	5	1						6
376-400	3	1						4
401-425	4	2	2					8
426-450	4	1	2					7
451-475	5	2						7
476-500	2	4			1			7
501-525	3	2	1					6
526-550	2	4						6
551-575	2	2	1					5
576-600		1		1				2
601-625		3						3
626-650		3	2					5
651-675	2	2	4					8
676-700		2	4					6
701-725	1	1	3					5
726-750		1	7					8
751-775		1	2					3
776-800			1					1
801-825			1					1
826-850								
851-875								
876-900								
901-925								
926-950								
951-975								
976-1000								
1001-1025								
1026-1050								
1051-1075								
1076-1100								
1101-1125								
1126-1150								
1151-1175								
1176-1200								
1201-1225								
1226-1250								
Total	131	38	35	36	858	40	4	1142
Minimum Length	42	270	203	28	15	26	61	15
Mean Length	240	525	603	83	31	45	104	92
Maximum Length	723	761	806	600	482	72	160	806

Appendix B Continued.

Flathead Catfish

Total Length (mm)	Low Frequency Electrofishing	Electrofishing	Trot Line	Sport Angling	Trap Net	Trawl	All Gears Combined
0-50							
51-100							
101-125							
125-150							
151-175	5						5
176-200		2					2
201-225							
226-250		1					1
251-275	1	2			1		4
276-300		4					4
301-325		3					3
326-350		1		1			2
351-375							
376-400							
401-425							
426-450				1			1
451-475							
476-500			1				1
501-525			1	1			2
526-550			1		1		2
551-575							
576-600			3	2			5
601-625			3			1	4
626-650				1			1
651-675			2				2
676-700			3				3
701-725			1				1
726-750			3	2	1	1	7
751-775			1	1			2
776-800			3				3
801-825			2				2
826-850			1	1			2
851-875			1				1
876-900			2				2
901-925		1	1				2
926-950		1					1
951-975							
976-1000				1			1
1001-1025			2				2
1026-1050			3				3
1051-1075			1				1
1076-1100			1				1
1101-1125							
1126-1150							
1151-1175							
1176-1200							
1201-1225							
1226-1250		1					1
Total	6	16	36	11	3	2	74
Minimum Length	161	187	489	332	272	611	161
Mean Length	182	417	776	653	513	673	618
Maximum Length	264	1230	1100	1000	730	735	1230

Appendix B Continued.

Walleye

Total Length (mm)	Electrofishing	Commercial Harvest	Hoop Net	Trawl	Trot Line	All Gears Combined
0-50						
51-100						
101-125						
125-150	4		1			5
151-175	6					6
176-200	9					9
201-225	5					5
226-250	5					5
251-275	3					3
276-300	2		1			3
301-325	6					6
326-350	9					9
351-375	4					4
376-400						
401-425	3					3
426-450	2					2
451-475						
476-500	2					2
501-525						
526-550	1	1				2
551-575	2			1		3
576-600	2					2
601-625	1	1				2
626-650						
651-675	1	1				2
676-700	1					1
701-725					1	1
726-750						
751-775						
776-800						
801-825						
826-850						
851-875						
876-900						
901-925						
926-950						
951-975						
976-1000						
1001-1025						
1026-1050						
1051-1075						
1076-1100						
1101-1125						
1126-1150						
1151-1175						
1176-1200						
1201-1225						
1226-1250						
Total	68	3	2	1	1	75
Minimum Length	145	544	140	562	710	140
Mean Length	312	602	210	562	710	329
Maximum Length	687	656	279	562	710	710

Appendix B Continued.

Freshwater Drum

Total Length (mm)	Electrofishing	Commercial Harvest	Hoop Net	Trawl	Trap Net	Seine	All Gears
0-50				21	4		25
51-100	6			23	1	2	32
101-125	28			17	1		46
125-150	12			3	3		18
151-175	3			2			5
176-200	1						1
201-225	11			1	1		13
226-250	27		1	2	3		33
251-275	14		1	3	1		19
276-300	12						12
301-325	12			1	3		16
326-350	6			3	7		16
351-375	9	1			1		11
376-400	4			1	3		8
401-425	5			1			6
426-450	1				3		4
451-475	1			1	1		3
476-500							
501-525							
526-550	1						1
551-575							
576-600							
601-625							
626-650							
651-675							
676-700							
701-725							
726-750							
751-775							
776-800							
801-825							
826-850							
851-875							
876-900							
901-925							
926-950							
951-975							
976-1000							
1001-1025							
1026-1050							
1051-1075							
1076-1100							
1101-1125							
1126-1150							
1151-1175							
1176-1200							
1201-1225							
1226-1250							
Total	153	1	2	79	32	2	269
Minimum Length	76	362	226	27	26	60	26
Mean Length	235	362	250	118	266	70	204
Maximum Length	535	362	274	462	456	80	535

APPENDIX C: Fish Growth Comparisons from Selected Riverine Populations

Average length at age (mm) for selected fish species from selected populations.

Appendix C.

Location	River Carpsucker									Reference
	Total length (mm) at age									
	1	2	3	4	5	6	7	8	9	
Des Moines River, Iowa	74	152	203	254	284	312	333	381	414	Bucholz (1957)
Boone River, Iowa	67	141	216	287	328	361	384	408		Quist and Spiegel (2011)
North Raccoon River, Iowa	74	142	205	261	309	353	398	426	446	Quist and Spiegel (2011)
Shell Rock River, Iowa	74	171	227	272	303	334	356	383		Quist and Spiegel (2011)
Minnesota River, Minnesota*	81	160	232	294	340	376	403	424	443	
Missouri River, Nebraska	100	209	243	275	307	332	424			Morris (1965)
Mean	78.2	162.6	221.1	273.8	311.9	344.7	382.9	404.4	434.2	
SE	4.7	10.4	6.4	6.2	8.0	9.4	13.6	9.7	10.1	

* = present study, [a] Time of Capture, [b] estimated from figure

Appendix C. Continued.

Location	River Carpsucker Total length (mm) at age									Reference
	10	11	12	13	14	15	16	17	18	
Des Moines River, Iowa										Bucholz (1957)
Boone River, Iowa										Quist and Spiegel (2011)
North Raccoon River, Iowa	454	507								Quist and Spiegel (2011)
Shell Rock River, Iowa										Quist and Spiegel (2011)
Minnesota River, Minnesota*	460	474	493	508	514	538	541	556		
Missouri River, Nebraska										Morris (1965)
Mean	457.0	490.7	492.7	507.5	513.5	538.3	540.6	556.0		
SE	3.0	16.3								

* = present study, [a] Time of Capture, [b] estimated from figure

Appendix C. Continued.

	Shorthead Redhorse									
Location	Total length (mm) at age									Reference
	1	2	3	4	5	6	7	8	9	
Boone River, Iowa	83	185	263	306	355	395	421			Quist and Spiegel (2011)
North Raccoon River, Iowa	96	202	258	298	341	360				Quist and Spiegel (2011)
Shell Rock River, Iowa	77	177	231	272	317	341	346	348		Quist and Spiegel (2011)
Wapsipinicon River, Iowa	79	178	254	297	343	376	402	438	460	Quist and Spiegel (2011)
Kankakee River, Illinois	93	207	295	343	368	390	396	402		Sule and Skelly (1985)
Minnesota River, Minnesota*	80	165	256	314	362	397	434			
Mean	84.6	185.6	259.6	305.0	347.6	376.4	399.9	396.0	460.0	
SE	3.2	6.6	8.4	9.5	7.5	9.1	15.1	26.2		

* = present study, [a] Time of Capture, [b] estimated from figure

Appendix C. Continued.

Location	Channel Catfish Total length (mm) at age									Reference
	1	2	3	4	5	6	7	8	9	
Cedar River, Iowa		180	251	307	437	483	523	538		Schoumacher and Ackerman (1965)
Wapsinpinicon River, Iowa		170	203	279	297	371	411	445	500	Schoumacher and Ackerman (1965)
Iowa River, Iowa	170	203	282	310	394					Schoumacher and Ackerman (1965)
Kansas River, Kansas (Fort Riley)	59	148	220	295	398	444				Quist and Guy (1998)
Kansas River, Kansas (Lawrence)	95	181	254	332	407	478	528	587		Quist and Guy (1998)
Minnesota River, Minnesota*	74	165	238	296	350	411	461	505	550	
Minnesota River, Minnesota	101	169	230	280	335	379	425	470	515	Chapman (2000)
Minnesota River, Minnesota	129	207	267	332	388	440	481	518	550	Staufer et al. (1995)
Minnesota River, Minnesota	59	125	196	258	319	373	442	507	531	Chapman (2004)
Red River, Minnesota [a]		173	237	283	330	355	407	434	453	Martini and Stewig (2002)
Mean	98.2	172.2	237.9	297.4	365.5	414.8	460.0	500.5	516.6	
SE	15.3	7.6	8.5	7.5	14.3	16.1	16.8	17.8	15.1	

* = present study, [a] Time of Capture, [b] estimated from figure

Appendix C. Continued.

Location	Channel Catfish Total length (mm) at age									Reference
	10	11	12	13	14	15	16	17	18	
Cedar River, Iowa										Schoumacher and Ackerman (1965)
Wapsinpinicon River, Iowa	554	612	709							Schoumacher and Ackerman (1965)
Iowa River, Iowa										Schoumacher and Ackerman (1965)
Kansas River, Kansas (Fort Riley)										Quist and Guy (1998)
Kansas River, Kansas (Lawrence)										Quist and Guy (1998)
Minnesota River, Minnesota*	596	648	678	708	710	766				
Minnesota River, Minnesota	563	588	616	631	674	710	763	784	799	Chapman (2000)
Minnesota River, Minnesota	587	589	614	646	659	634	685			Staufer et al. (1995)
Minnesota River, Minnesota	501	533	565	600	616	669	687	789		Chapman (2004)
Red River, Minnesota [a]	509	531	573	619	618	656	656	697	729	Martini and Stewig (2002)
Mean	551.7	583.4	625.9	640.6	655.3	687.0	697.8	756.6	764.0	
SE	16.1	18.6	23.3	18.5	17.9	23.2	22.8	29.9	35.0	

* = present study, [a] Time of Capture, [b] estimated from figure

Appendix C. Continued.

Location	Flathead Catfish Total length (mm) at age									Reference
	1	2	3	4	5	6	7	8	9	
Tennesee River, Alabama	93	157	199	239	318	384	367	451	387	Adopted from Kwak et al. (2006)
Alabama River, Alabama	110	189	265	433	534	544	560			Adopted from Kwak et al. (2006)
Tallapoosa River, Alabama	147	208	261	307	351	398	427	484	510	Adopted from Kwak et al. (2006)
Des Moines River, Iowa	142	269	393	469	550	600	674	714		Adopted from Kwak et al. (2006)
Mississippi River, Iowa-Illinois	165	267	305	394	432	508	596	635	699	Adopted from Kwak et al. (2006)
Mississippi River, Illinois-Missouri	191	304	406	457	482	559	660	787	851	Adopted from Kwak et al. (2006)
Big Blue River, Kansas	142	262	366	483	630		701	772		Adopted from Kwak et al. (2006)
Kansas River, Kansas	210	254	400	622	648	819	851	1022	1118	Adopted from Kwak et al. (2006)
Minnesota River, Minnesota*	104	213	314	416	498	567	637	693	738	
Minneosta River, Minnesota	96	195	319	436	520	584	649	703	752	Adopted from Kwak et al. (2006)
Missouri River, Missouri	119	188	251	310	368	419	490	526	597	Adopted from Kwak et al. (2006)
Missouri River, Nebraska	75	188	321	411	487	541	536			Adopted from Kwak et al. (2006)
Verdigris River, Oklahoma	91	155	206	274	320	373	419	523	584	Adopted from Kwak et al. (2006)
Rio Grande River, Texas	61	124	232	350	485	590	673	757	914	Adopted from Kwak et al. (2006)
Mean	124.7	212.4	302.7	400.1	473.1	529.7	588.6	672.3	715.0	
SE	11.6	13.9	18.7	26.5	28.1	33.4	35.1	46.5	66.9	

* = present study, [a] Time of Capture, [b] estimated from figure

Appendix C. Continued.

Location	Flathead Catfish Total length (mm) at age									Reference
	10	11	12	13	14	15	16	17	18	
Tennesee River, Alabama										Adopted from Kwak et al. (2006)
Alabama River, Alabama										Adopted from Kwak et al. (2006)
Tallapoosa River, Alabama	513	535	540	565	589	589	598	619	650	Adopted from Kwak et al. (2006)
Des Moines River, Iowa										Adopted from Kwak et al. (2006)
Mississippi River, Iowa-Illinois	826	864		902	953	953				Adopted from Kwak et al. (2006)
Mississippi River, Illinois-Missouri			914			1041				Adopted from Kwak et al. (2006)
Big Blue River, Kansas										Adopted from Kwak et al. (2006)
Kansas River, Kansas	889									Adopted from Kwak et al. (2006)
Minnesota River, Minnesota*	775	840	875	884	941	990	1018	1039		
Minneosta River, Minnesota	798	932	875	924	947	970	1016	1045	1060	Adopted from Kwak et al. (2006)
Missouri River, Missouri	645	673	688							Adopted from Kwak et al. (2006)
Missouri River, Nebraska										Adopted from Kwak et al. (2006)
Verdigris River, Oklahoma	615									Adopted from Kwak et al. (2006)
Rio Grande River, Texas										Adopted from Kwak et al. (2006)
Mean	723.0	768.8	778.4	818.7	857.6	908.5	877.2	901.0	855.0	
SE	50.8	72.3	71.4	85.0	89.6	81.2	139.6	141.0	205.0	

* = present study, [a] Time of Capture, [b] estimated from figure

Appendix C. Continued.

Location	Flathead Catfish Total length (mm) at age									Reference
	19	20	21	22	23	24	25	26	27	
Tennesee River, Alabama										Adopted from Kwak et al. (2006)
Alabama River, Alabama										Adopted from Kwak et al. (2006)
Tallapoosa River, Alabama	673	764	858	880	900	822	947	953	968	Adopted from Kwak et al. (2006)
Des Moines River, Iowa										Adopted from Kwak et al. (2006)
Mississippi River, Iowa-Illinois										Adopted from Kwak et al. (2006)
Mississippi River, Illinois-Missouri										Adopted from Kwak et al. (2006)
Big Blue River, Kansas										Adopted from Kwak et al. (2006)
Kansas River, Kansas										Adopted from Kwak et al. (2006)
Minnesota River, Minnesota*										
Minneosta River, Minnesota	1054									Adopted from Kwak et al. (2006)
Missouri River, Missouri										Adopted from Kwak et al. (2006)
Missouri River, Nebraska										Adopted from Kwak et al. (2006)
Verdigris River, Oklahoma										Adopted from Kwak et al. (2006)
Rio Grande River, Texas										Adopted from Kwak et al. (2006)
Mean	863.5	764.0	858.0	880.0	900.0	822.0	947.0	953.0	968.0	
SE	190.5									

* = present study, [a] Time of Capture, [b] estimated from figure

Appendix C. Continued.

Location	Walleye Total length (mm) at age									Reference
	1	2	3	4	5	6	7	8	9	
Des Moines River, Iowa	213	292	366	422	475	516	551	572	574	Schmulback (1959)
Wapsipinian River, Iowa	221	356	445	536	592					Adopted from Fisher (1996)
Cedar River, Iowa	206	305	391	483	569	627	653			Adopted from Fisher (1996)
Raccoon River, Iowa	218	330	399	500	566	605	658	709		Adopted from Fisher (1996)
Shellrock River, Iowa	226	373	439	505	579					Adopted from Fisher (1996)
Minnesota River, Minnesota*	163	291	399	491	546	592	623	658	699	
Minnesota River, Minnesota	173	300	406	433	504	573	600			Chapman (2000)
Minnesota River, Minnesota	195	301	386	449	501	554	609	652	676	Staufer et al. (1995)
Minnesota River, Minnesota	189	307	380	501	551	585	622	657	676	Chapman (2004)
Current River, Missouri	203	316	394	439	480	526	612	648	706	Adopted from Fisher (1996)
Beaver Creek Montana	76	127	185	246	309	361	405	489	540	Adopted from Fisher (1996)
Big Sioux River, South Dakota	197	346	460	529	581	624	675			Adopted from Fisher (1996)
Wisconsin River, Wisconsin	188	274	356	454	520	547	579	633	657	Adopted from Fisher (1996)
Red Cedar River, Wisconsin	162	262	323	371	421	457	485	511	570	Adopted from Fisher (1996)
Wolf River, Wisconsin	111	244	325	376	413	442	486	672		Adopted from Fisher (1996)
Mean	182.7	294.8	376.9	448.9	507.1	539.1	581.4	620.0	637.1	
SE	10.77	14.91	17.00	19.40	20.24	21.81	22.02	22.80	23.07	

* = present study, [a] Time of Capture, [b] estimated from figure

Appendix C. Continued.

Location	Walleye Total length (mm) at age									Reference
	10	11	12	13	14	15	16	17	18	
Des Moines River, Iowa										Schmulback (1959)
Wapsipinian River, Iowa										Adopted from Fisher (1996)
Cedar River, Iowa										Adopted from Fisher (1996)
Raccoon River, Iowa										Adopted from Fisher (1996)
Shellrock River, Iowa										Adopted from Fisher (1996)
Minnesota River, Minnesota*										
Minnesota River, Minnesota										Chapman (2000)
Minnesota River, Minnesota	749									Staufer et al. (1995)
Minnesota River, Minnesota	685	667	672	690	693	697				Chapman (2004)
Current River, Missouri	752	759								Adopted from Fisher (1996)
Beaver Creek Montana	575	605								Adopted from Fisher (1996)
Big Sioux River, South Dakota										Adopted from Fisher (1996)
Wisconsin River, Wisconsin	673	665	690	720						Adopted from Fisher (1996)
Red Cedar River, Wisconsin	628	662	718							Adopted from Fisher (1996)
Wolf River, Wisconsin										Adopted from Fisher (1996)
Mean	677.0	671.5	693.3	705.0	693.0	697.0				
SE	28.10	24.73	13.38	15.00						

* = present study, [a] Time of Capture, [b] estimated from figure

Appendix C. Continued.

Location	Freshwater Drum Total length (mm) at age									Reference
	1	2	3	4	5	6	7	8	9	
Illinois River, Illinois [b]	105	160	207	250	265	268	295	300	315	Smith et al. (2007)
Wabash River, Illinois [b]	70	198	250	260	275	305	315	350	370	Jacquemin et al. (2014)
Minnesota River, Minnesota*	120	203	223	260	281	312	341	340	369	
Grand River, Oklahoma	86	180	241	312						Adopted from Houser (1960)
Illinois River, Oklahoma	91	175	267	351	406	465	500			Adopted from Houser (1960)
Salt Creek, Oklahoma	99	206	315	325	406	457				Adopted from Houser (1960)
Verdigris River, Oklahoma	104	188	254	323	409	455	523			Adopted from Houser (1960)
Mean	100.2	190.4	260.0	314.1	340.4	422.1	454.9	329.9	351.3	
SE	6.0	6.2	13.1	15.0	30.0	37.2	48.4	15.2	18.2	

* = present study, [a] Time of Capture, [b] estimated from figure

Appendix C. Continued.

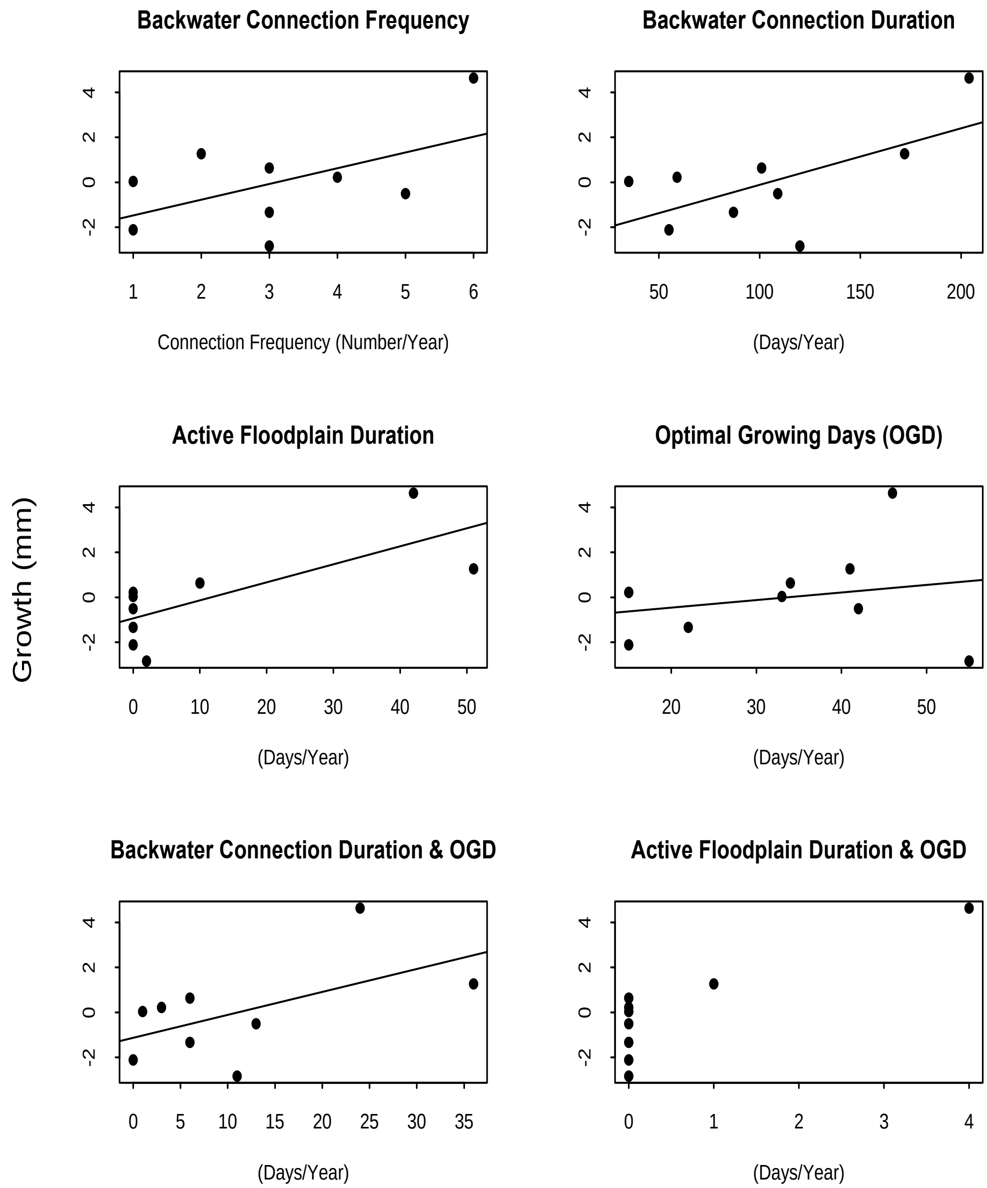
Freshwater Drum										
Location	Total length (mm) at age									Reference
	10	11	12	13	14	15	16	17	18	
Illinois River, Illinois [b]	320	330	345	370	380	393	399	412	430	Smith et al. (2007)
Wabash River, Illinois [b]	390	395	405	425	435	440	445	455	450	Jacquemin et al. (2014)
Minnesota River, Minnesota*	386	431	418	435	457	470	486	504	518	
Grand River, Oklahoma										Adopted from Houser (1960)
Illinois River, Oklahoma										Adopted from Houser (1960)
Salt Creek, Oklahoma										Adopted from Houser (1960)
Verdigris River, Oklahoma										Adopted from Houser (1960)
Mean	365.4	385.2	389.3	409.9	424.0	434.3	443.2	456.9	466.0	
SE	22.7	29.5	22.4	20.2	22.9	22.4	25.0	26.5	26.7	

* = present study, [a] Time of Capture, [b] estimated from figure

APPENDIX D: Fish Growth – Flow/Temperature Regression Plots

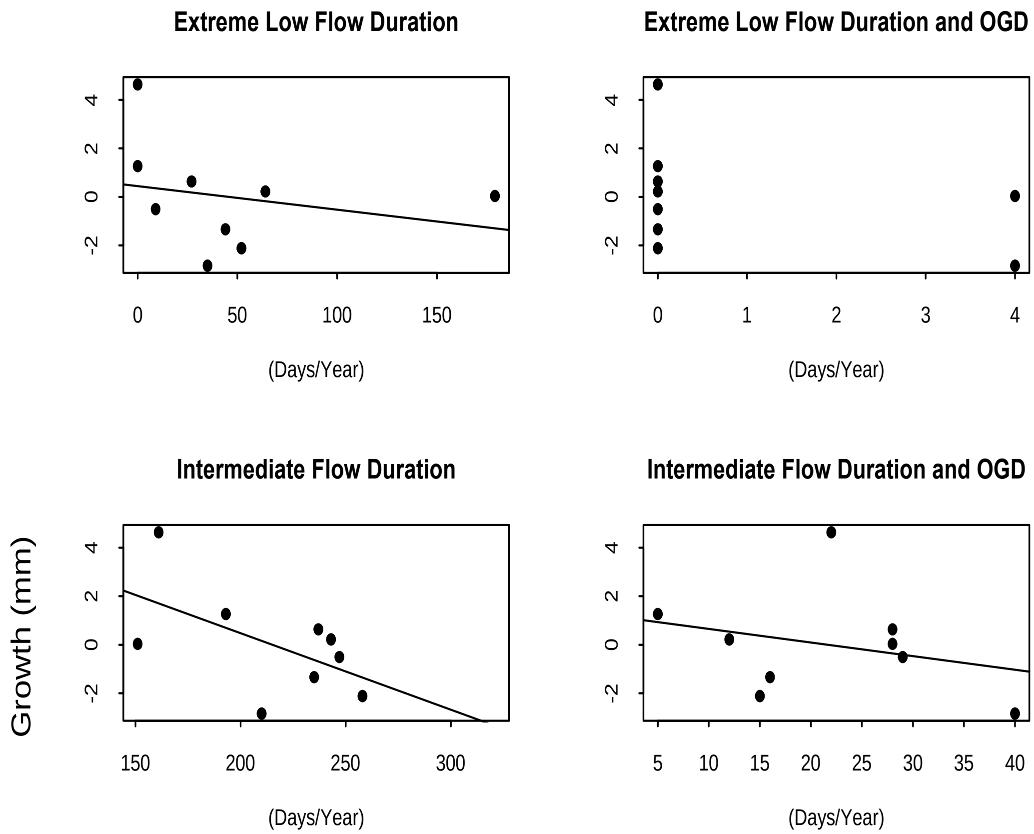
Linear regression plots showing relationships between growth and various flow and temperature parameters of selected fish species collected in the Minnesota River in 2012. The species is noted at the top of each group of plots. Plots with no regression line denote insufficient sample size to perform analyses.

Common Carp


Backwater Connection Frequency
Connection Frequency (Number/Year)
Backwater Connection Duration
(Days/Year)
Active Floodplain Duration
(Days/Year)
Optimal Growing Days (OGD)
(Days/Year)
Backwater Connection Duration & OGD
(Days/Year)
Active Floodplain Duration & OGD
(Days/Year)
Growth (mm)

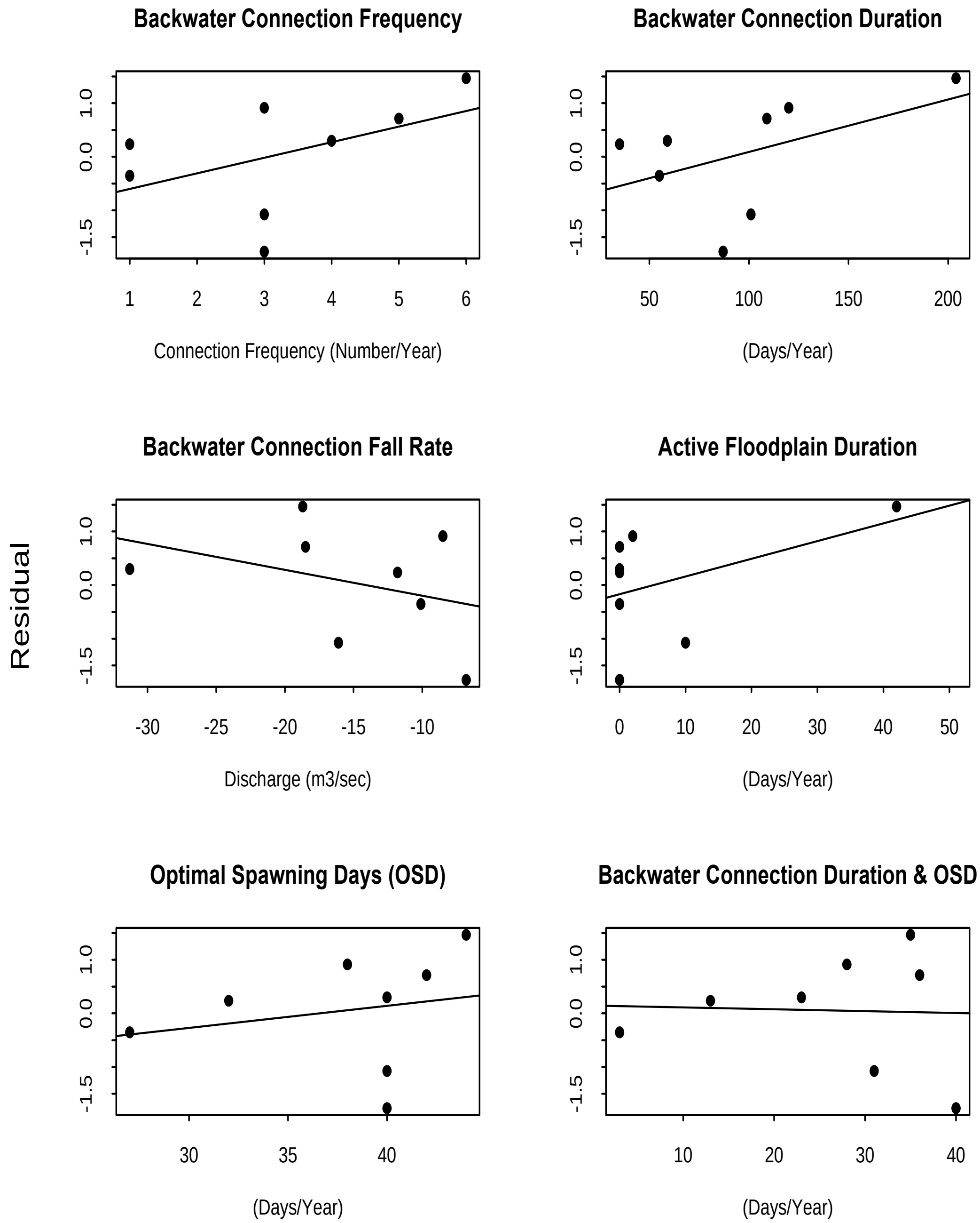
Appendix D. Continued.

Common Carp



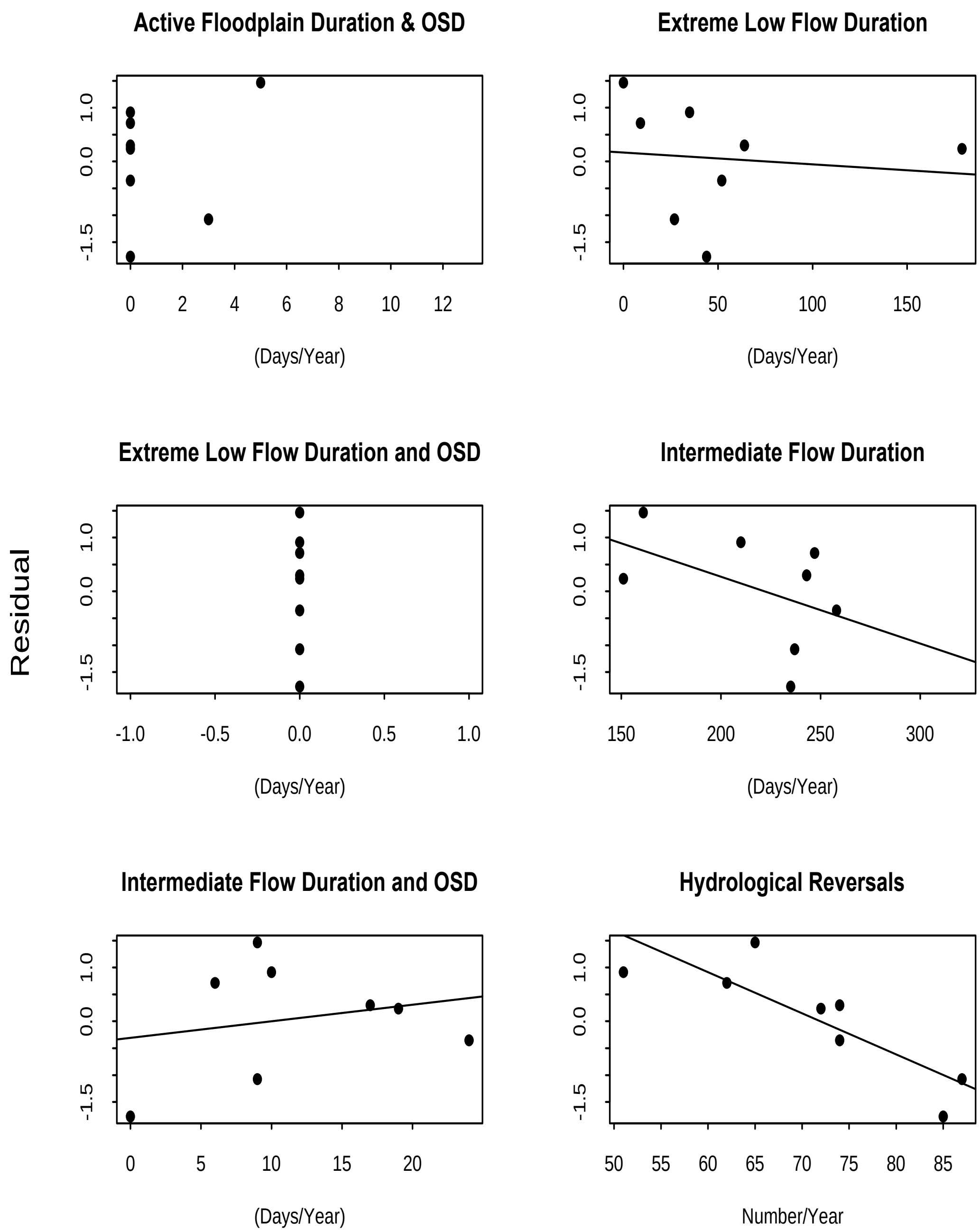
Appendix D. Continued.

Common Carp



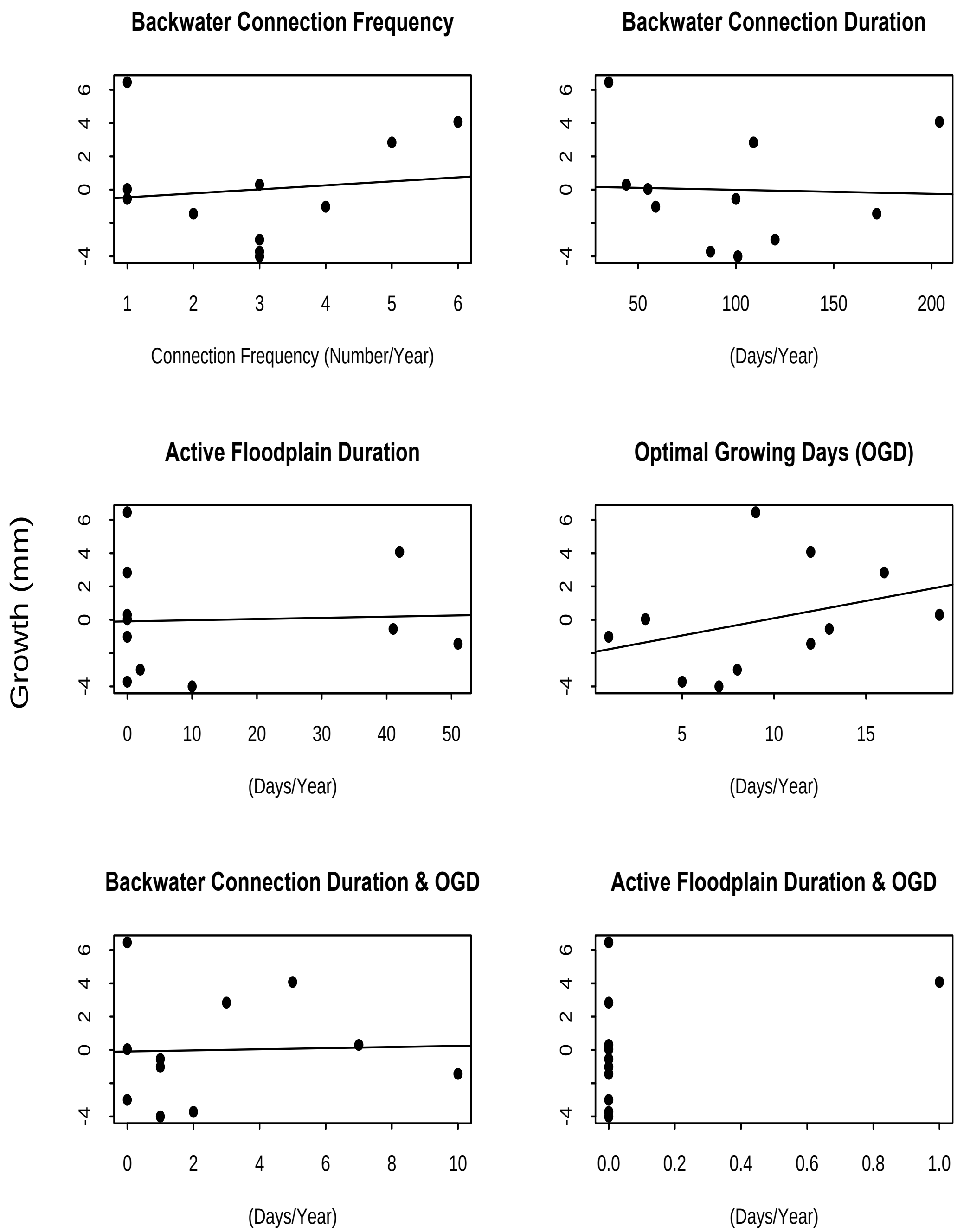
Appendix D. Continued.

Common Carp



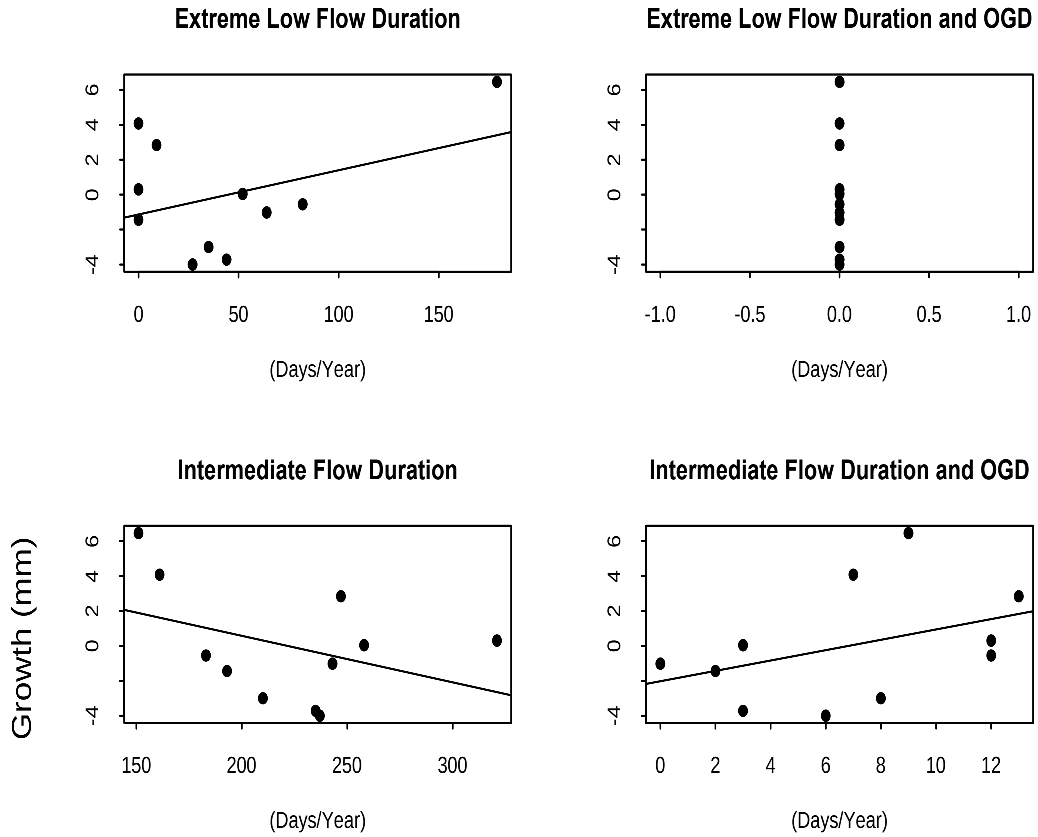
Appendix D. Continued.

Bigmouth Buffalo



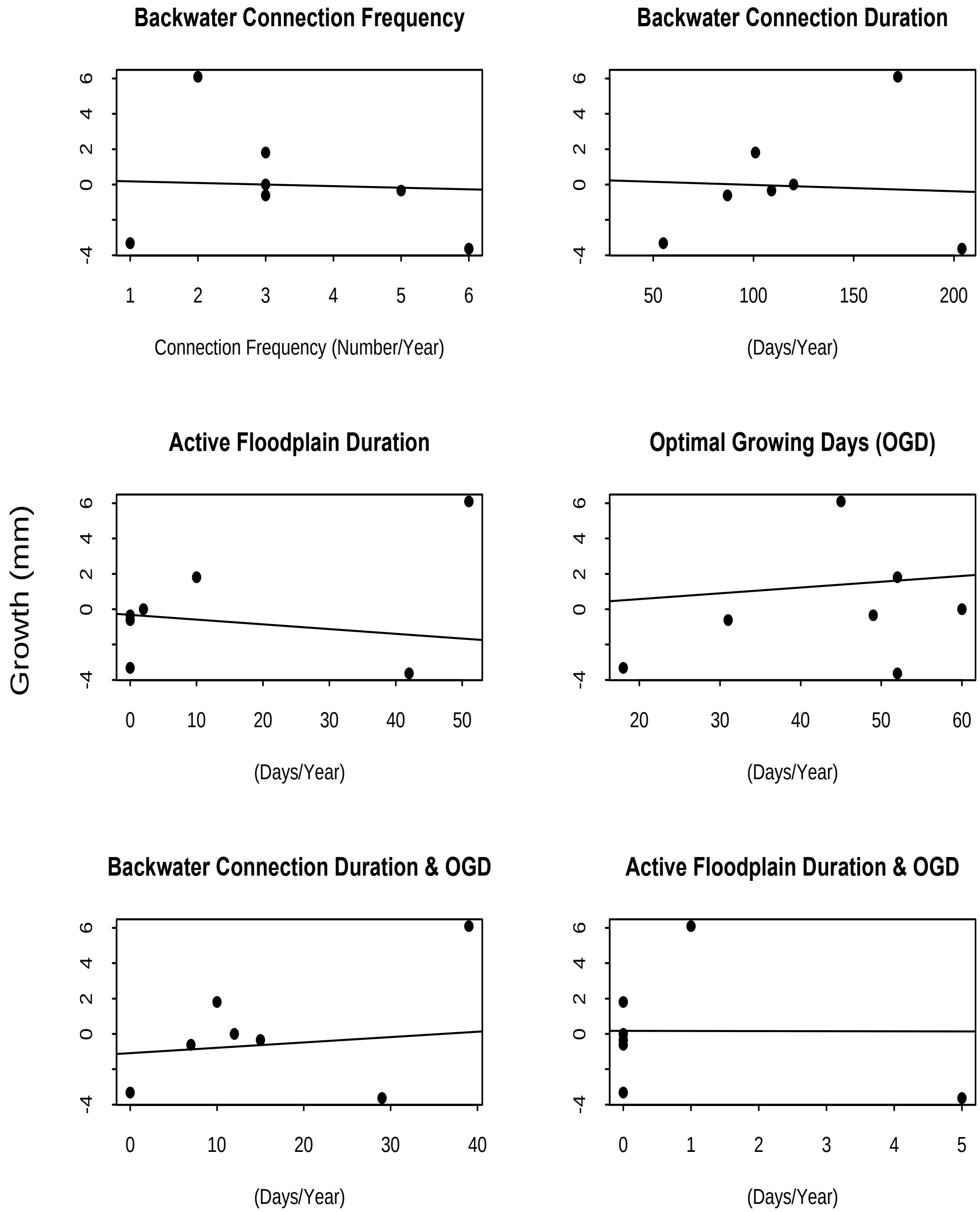
Appendix D. Continued.

Bigmouth Buffalo



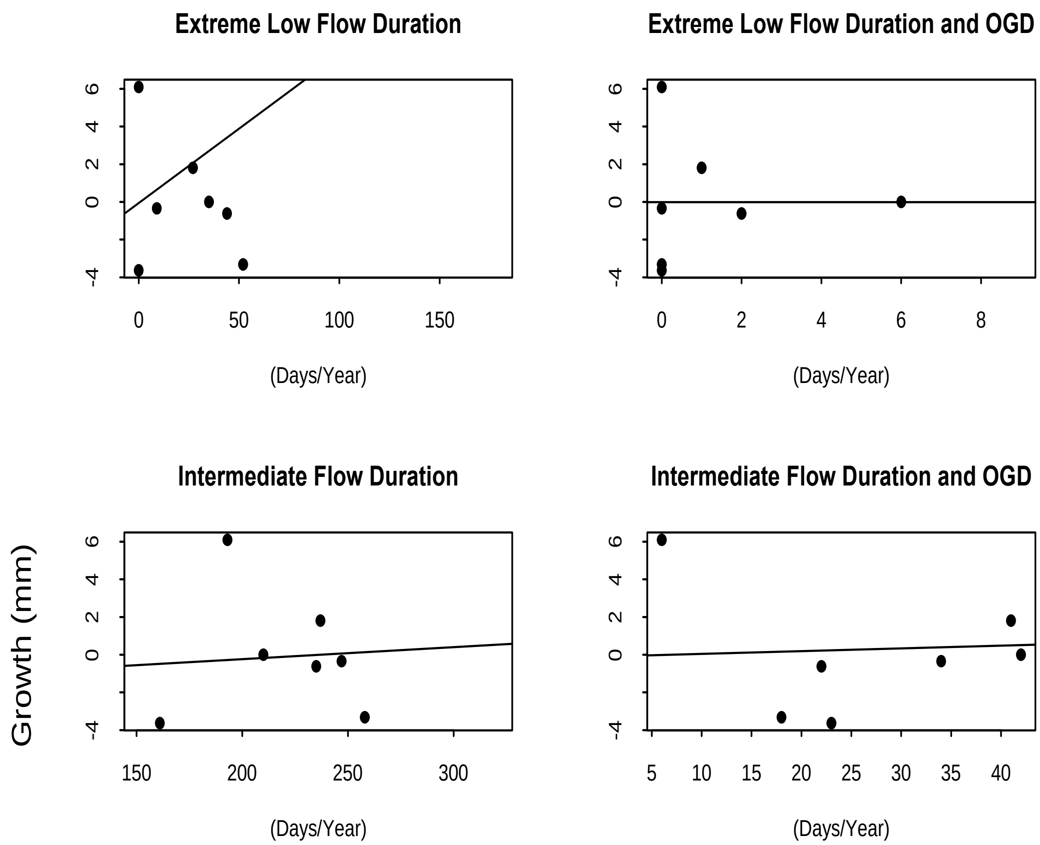
Appendix D. Continued.

Shorthead Redhorse



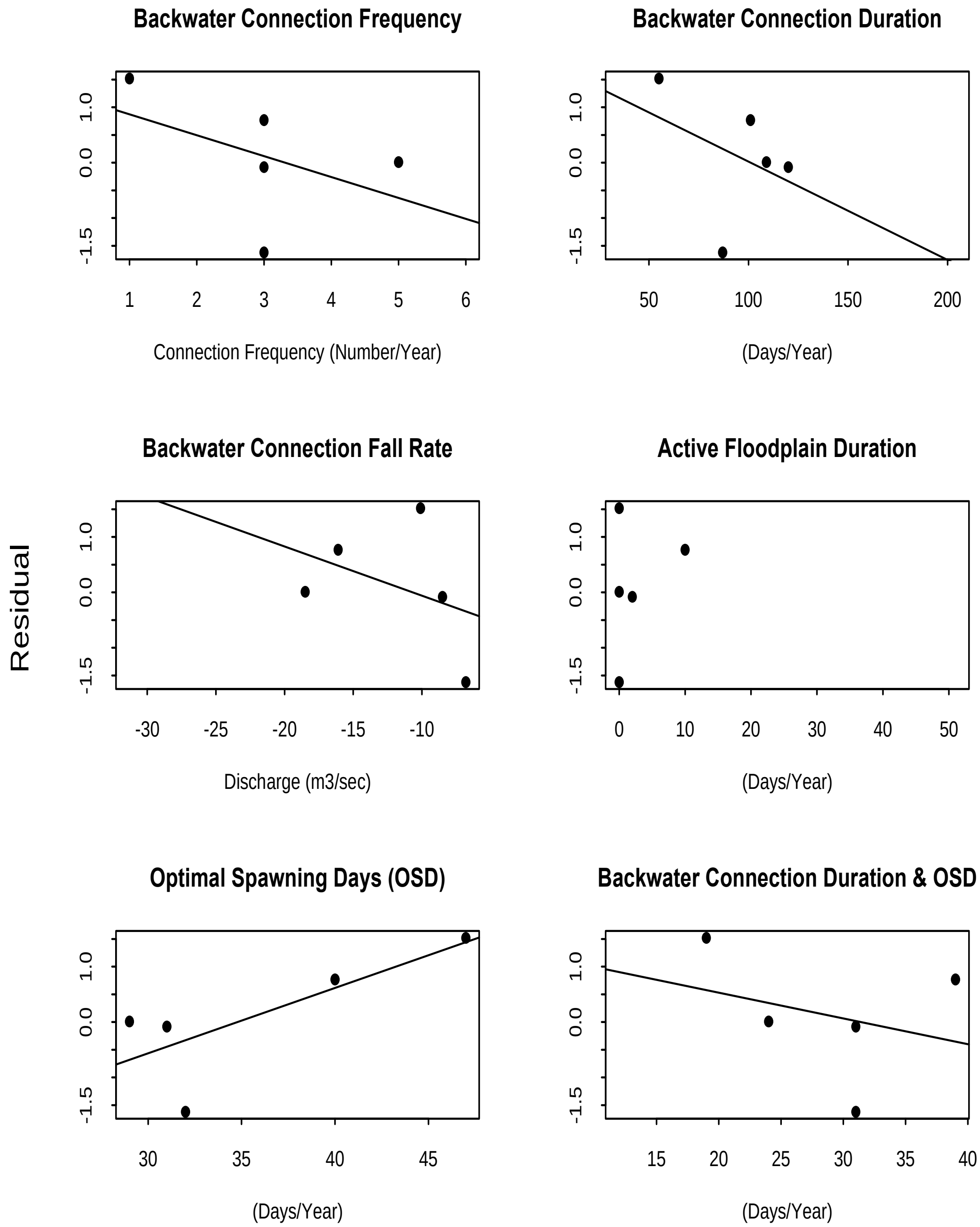
Appendix D. Continued.

Shorthead Redhorse



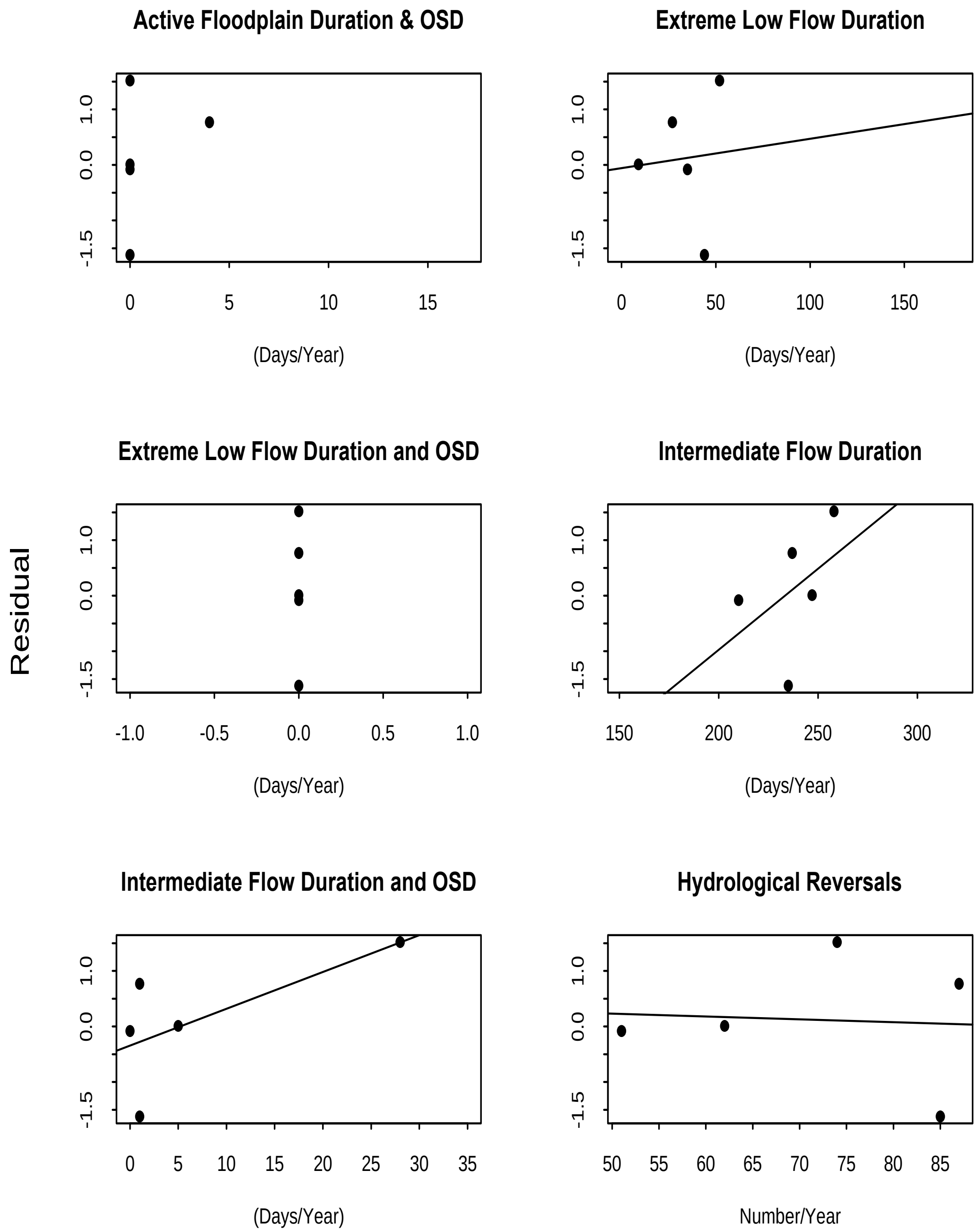
Appendix D. Continued.

Shorthead Redhorse



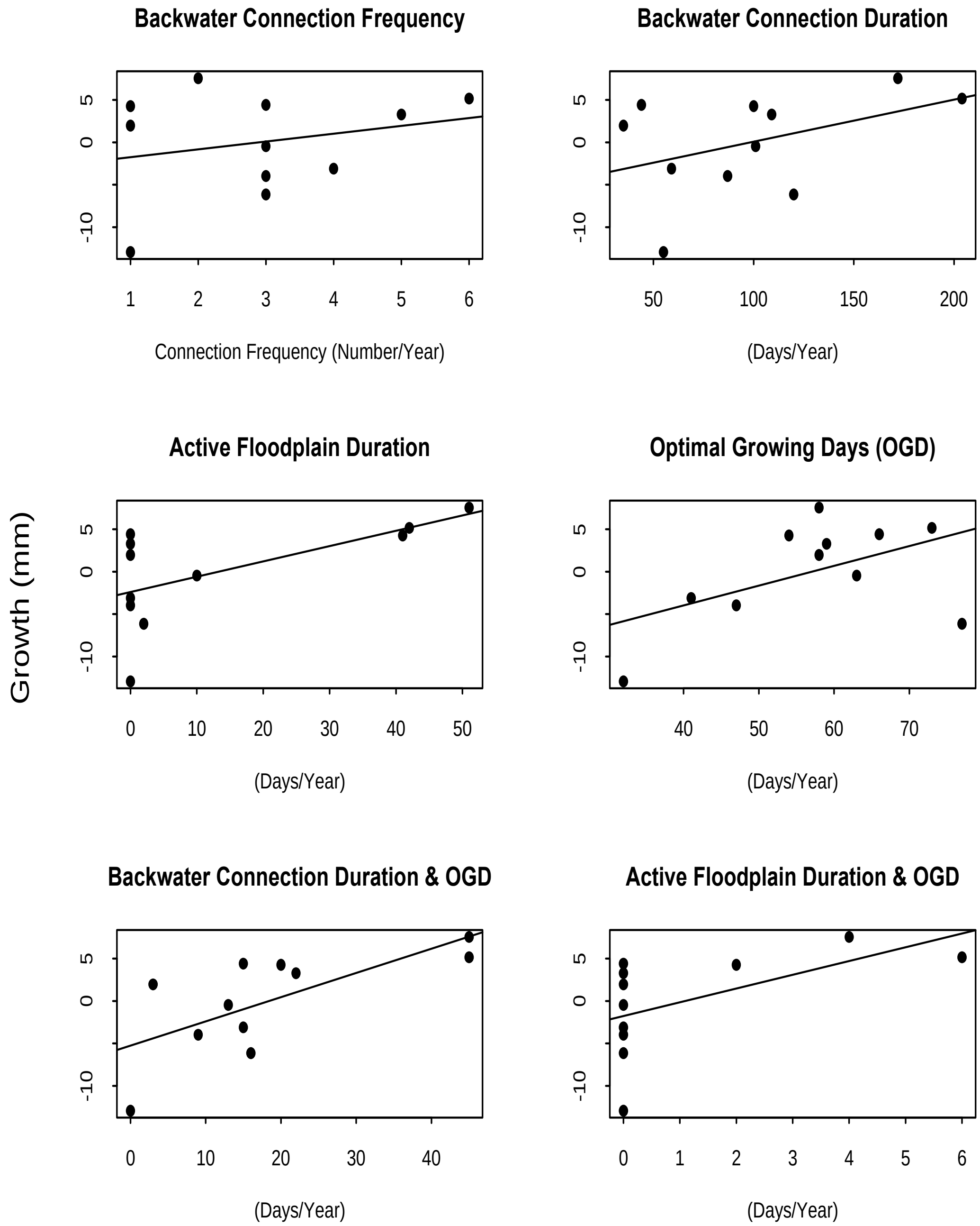
Appendix D. Continued.

Shorthead Redhorse



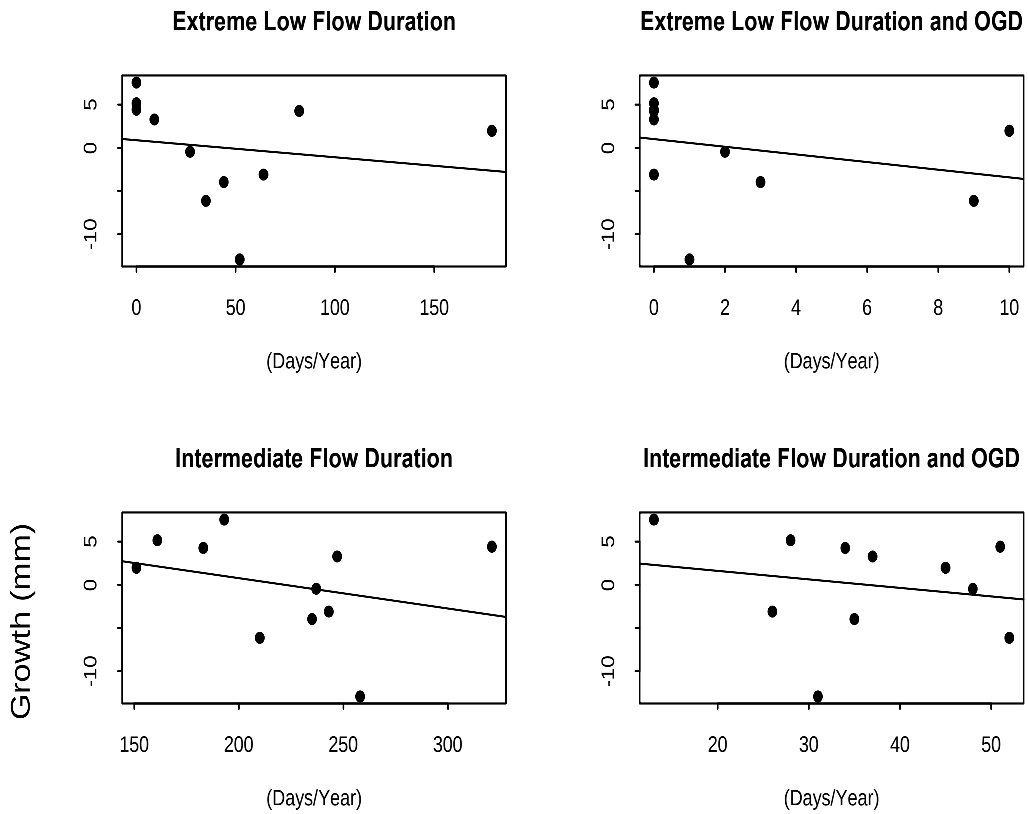
Appendix D. Continued.

Channel Catfish



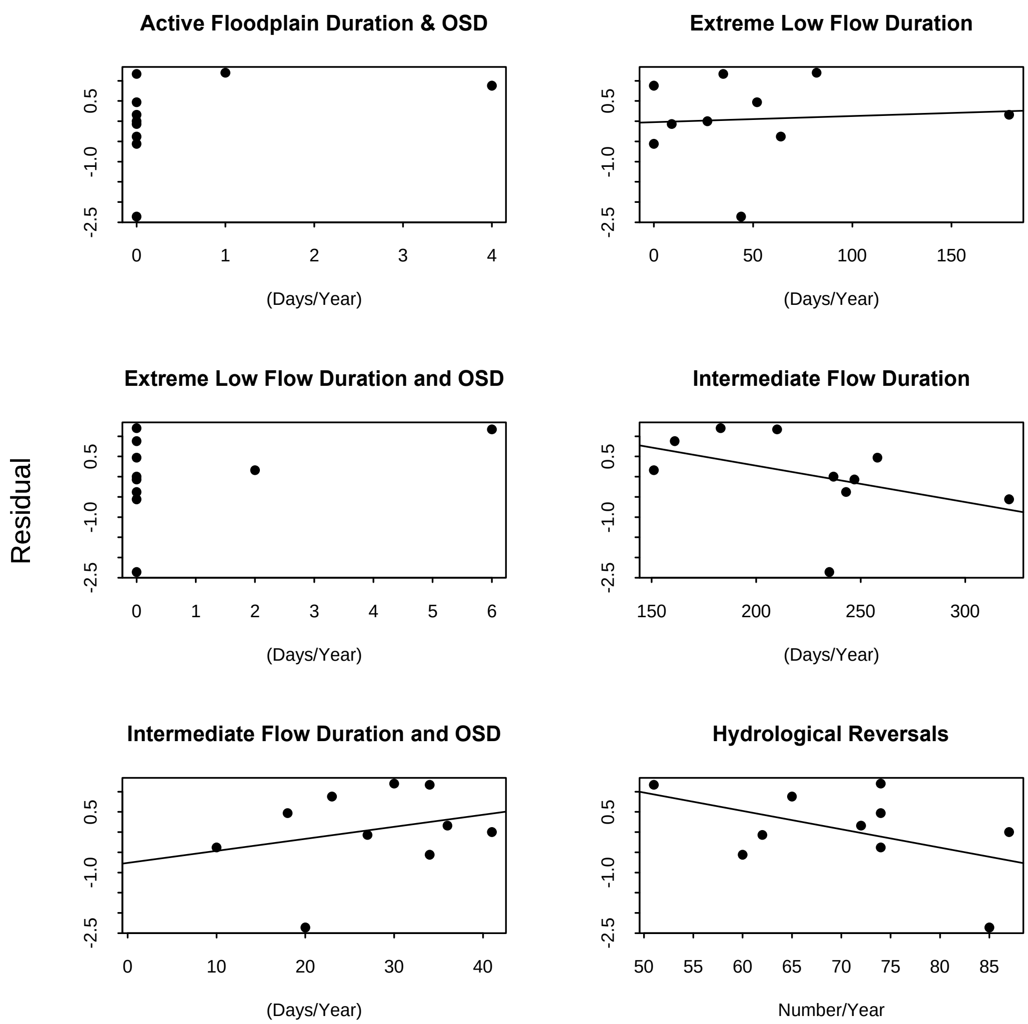
Appendix D. Continued.

Channel Catfish



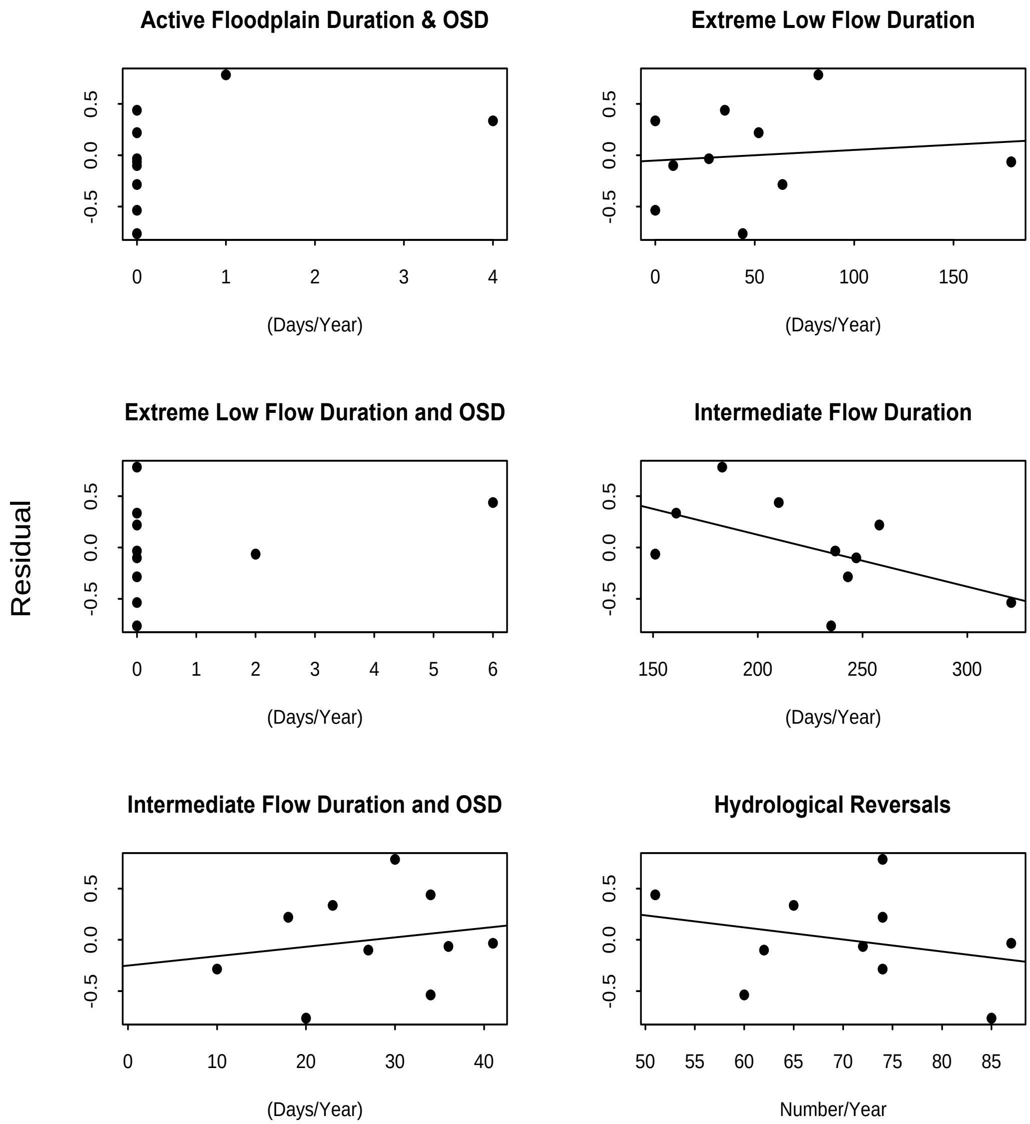
Appendix D. Continued.

Channel Catfish



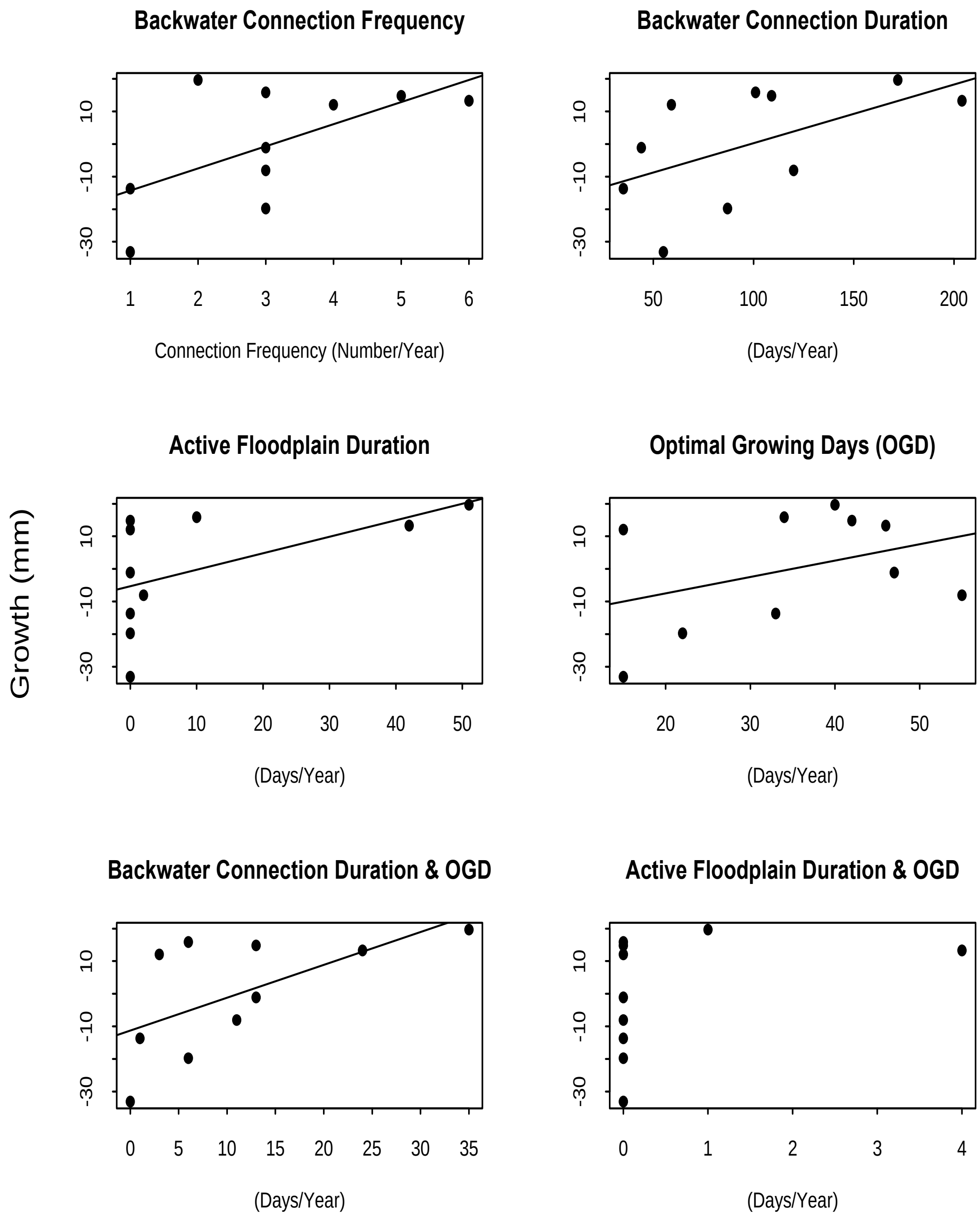
Appendix D. Continued.

Channel Catfish



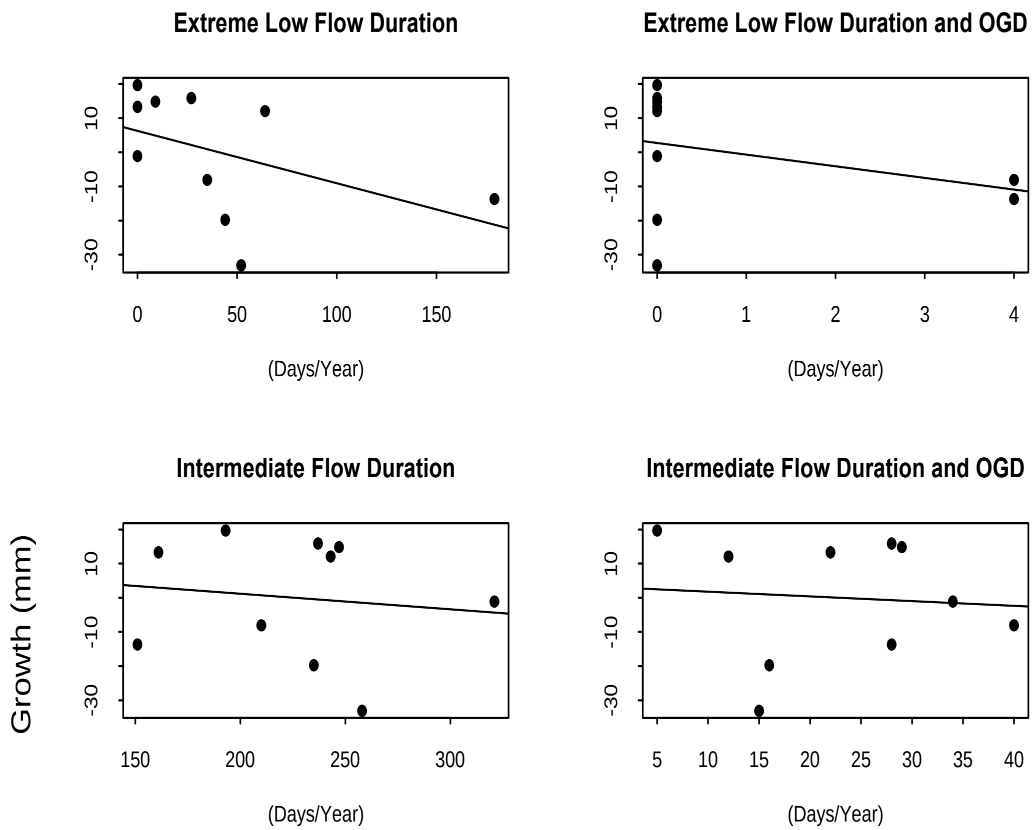
Appendix D. Continued.

Flathead Catfish



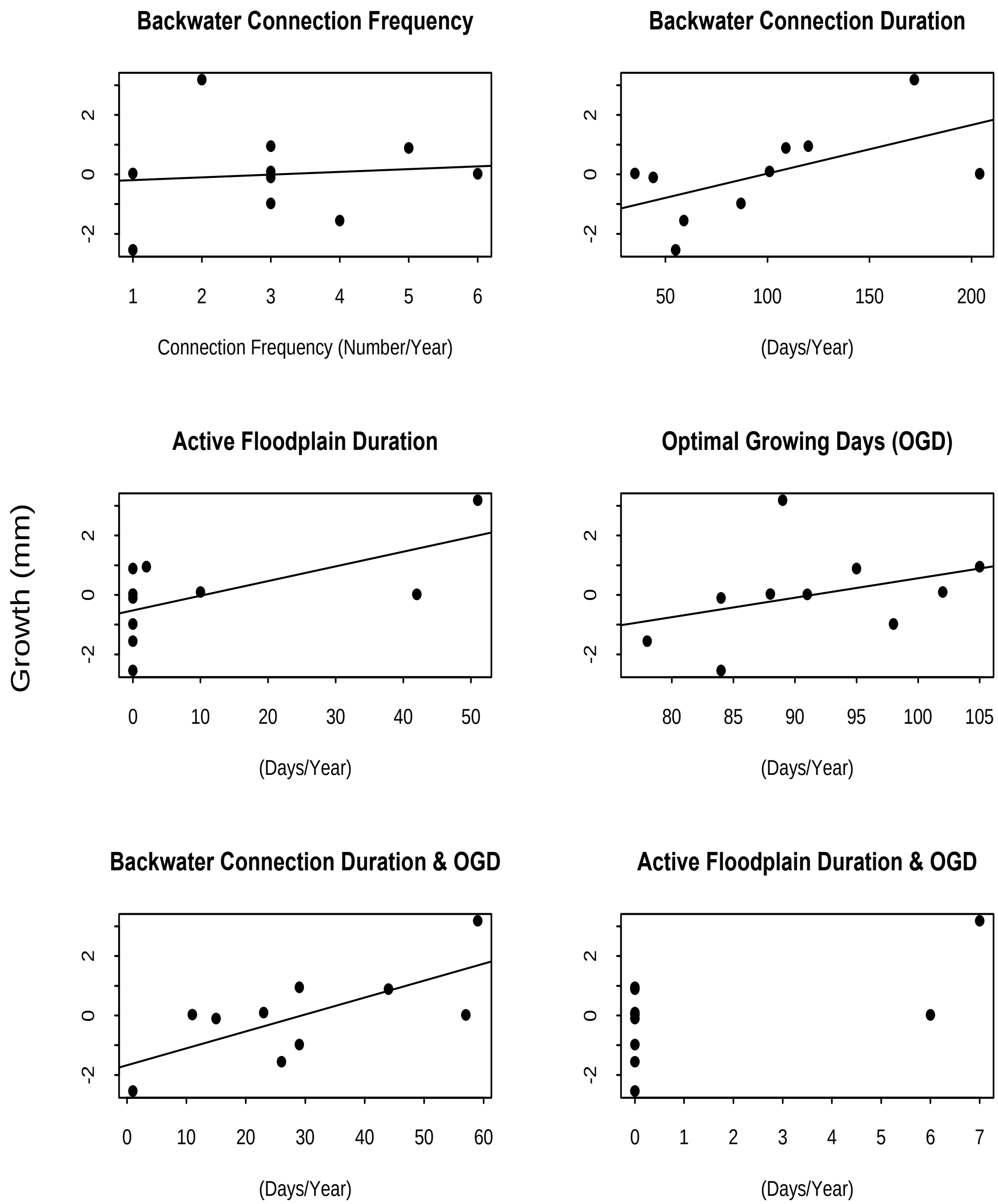
Appendix D. Continued.

Flathead Catfish



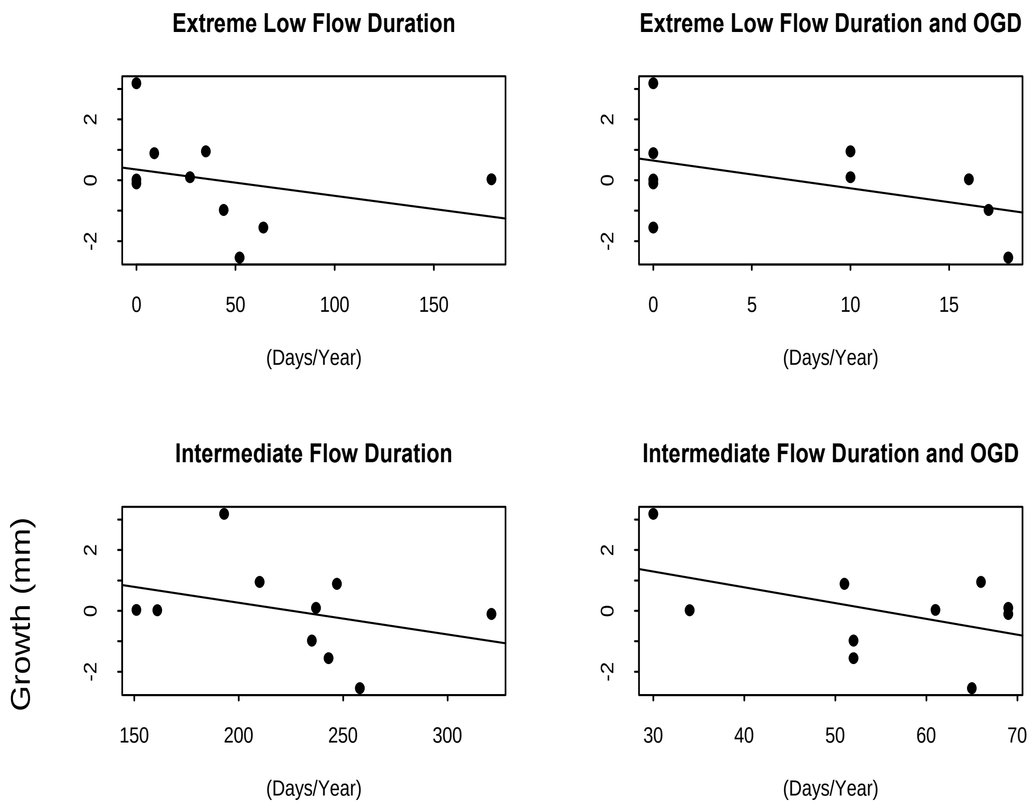
Appendix D. Continued.

Freshwater Drum



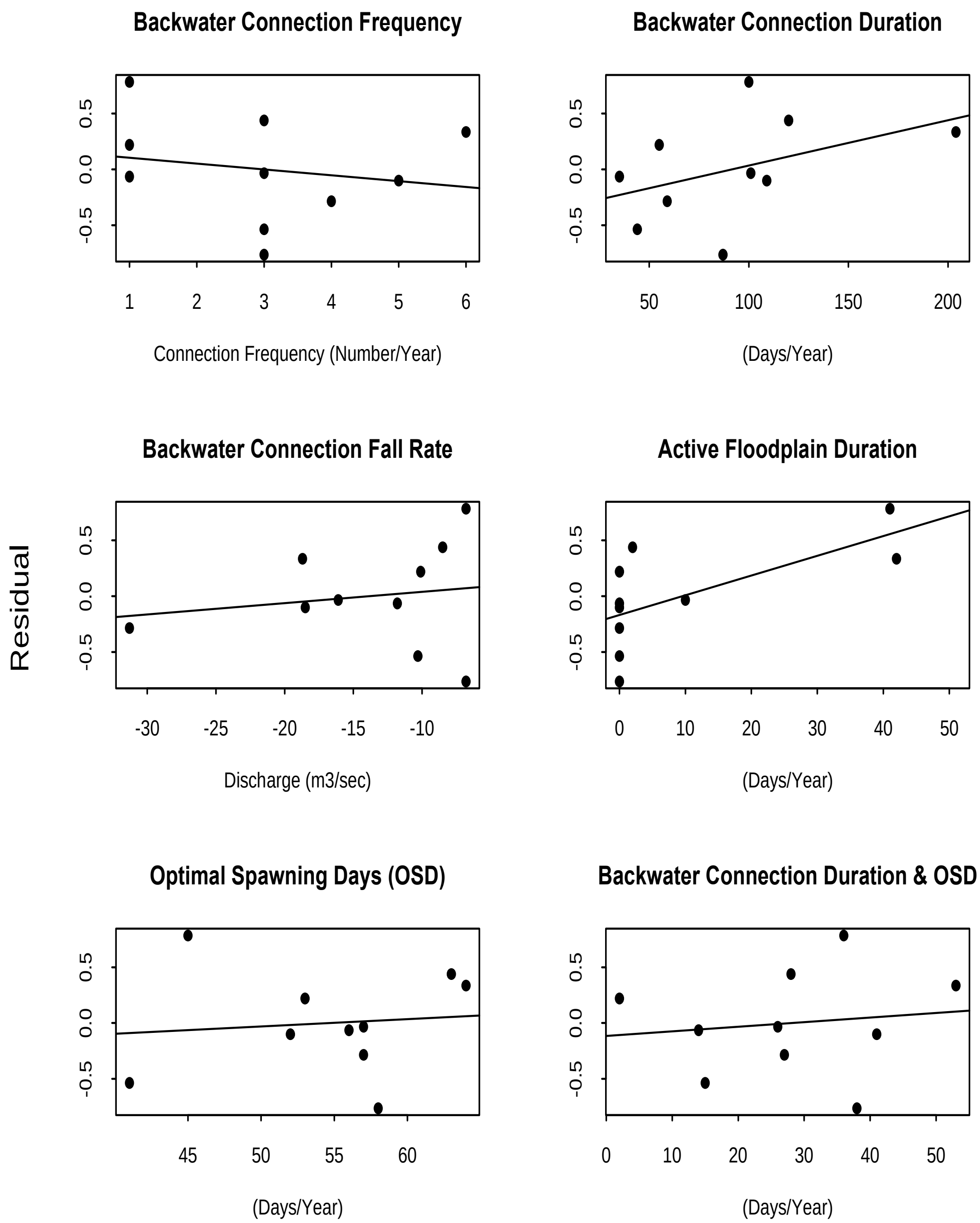
Appendix D. Continued.

Freshwater Drum



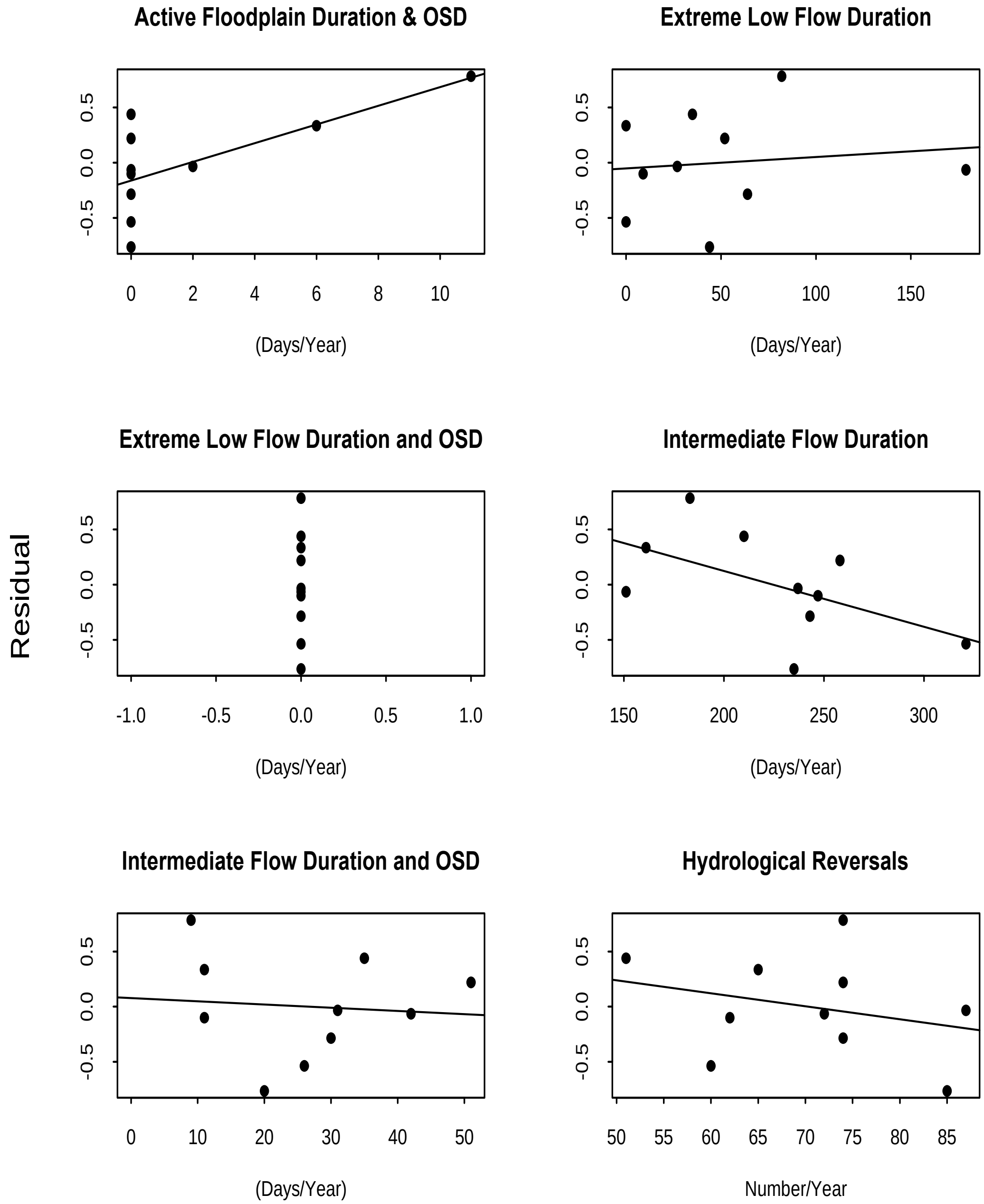
Appendix D. Continued.

Freshwater Drum



Appendix D. Continued.

Freshwater Drum



APPENDIX E: Linear Regression Models and Support Data

Linear regression models for selected fish species from the Minnesota River, 2012. Included for each species is the number of parameters (K), Akaike's Information Criterion (AIC_c), the difference between each model and the model with the minimum AIC_c (ΔAIC_c), *P*-Values, R^2, and regression slope relationship (Relationship). Highlighted data denotes supported models ($\Delta AIC_c<2$ and/or *P*-value <0.10). The species for which each table applies is listed above each table.

Common Carp

Growth Models	K	AICc	Δ AICc	*P*-Value	R^2	Relationship
Flood Pulse Concept						
AFCD	3	42.22	0.00	0.02	0.48	+
Intercept	2	44.54	2.32	NA	NA	
BWCD	3	44.66	2.44	0.07	0.32	+
BWCDOGD	3	46.01	3.79	0.12	0.21	+
BWCF	3	46.21	3.99	0.13	0.19	+
OGD	3	48.91	6.69	0.58	0.00	+
Low Flow Recruitment Concept						
Intercept	2	44.54	0.00	NA	NA	
ELFD	3	48.78	4.24	0.53	0.00	-
OGD	3	48.91	4.37	0.58	0.00	+
Intermediate Flows Concept						
Intercept	2	44.54	0.00	NA	NA	
IFD	3	45.95	1.41	0.12	0.22	-
IFDOGD	3	48.63	4.09	0.47	0.00	-
OGD	3	48.91	4.37	0.58	0.00	+
Combined Growth Models						
Intercept	2	44.54	0.00	NA	NA	
AFCD+BWCF	4	45.95	1.41	0.03	0.59	+
BWCD+BWCF	4	51.15	6.61	0.17	0.27	+
Recruitment Models	K	AICc	Δ AICc	*P*-Value	R^2	Relationship
Flood Pulse Concept						
Intercept	2	29.13	0.00	NA	NA	
BWCD	3	32.63	3.50	0.23	0.10	+
BWCF	3	32.67	3.54	0.23	0.10	+
AFCD	3	32.89	3.76	0.26	0.07	+
BWCFR	3	33.65	4.52	0.39	0.00	-
OSD	3	34.35	5.22	0.61	0.00	+
BWCDOSD	3	34.72	5.59	0.92	0.00	-
Low Flow Recruitment Concept						
Intercept	2	29.13	0.00	NA	NA	
OSD	3	34.35	5.22	0.61	0.00	+
ELFD	3	34.63	5.50	0.79	0.00	-
Intermediate Flows Concept						
HR	3	24.57	0.00	0.01	0.67	-
Intercept	2	29.13	4.56	NA	NA	
IFD	3	32.73	8.16	0.24	0.09	-
IFOSD	3	34.32	9.75	0.60	0.00	+
OSD	3	34.35	9.78	0.61	0.00	+
Combined Recruitment Models						
Intercept	2	29.13	0.00	NA	NA	
BWCF+IFOSD	4	37.12	7.99	0.11	0.41	+
BWCD+IFOSD	4	38.01	8.88	0.15	0.34	+
AFCD+IFOSD	4	41.18	12.05	0.41	0.02	+
AFCD+BWCF	4	41.59	12.46	0.46	0.00	+
BWCD+BWCF	4	41.72	12.59	0.48	0.00	+

Appendix D Continued.

Bigmouth Buffalo

Growth Models	K	AICc	Δ AICc	*P* -Value	R^2	Relationship
Flood Pulse Concept						
Intercept	2	61.92	0	NA	NA	
OGD	3	64.46	2.53	0.30	0.02	+
BWCF	3	65.7	3.77	0.73	0.00	+
AFCD	3	65.83	3.91	0.90	0.00	+
BWCD	3	65.84	3.91	0.91	0.00	-
BWCDOGD	3	65.84	3.92	0.92	0.00	+
Low Flow Recruitment Concept						
Intercept	2	61.92	0	NA	NA	
ELFD	3	63.9	1.98	0.22	0.07	+
OGD	3	64.46	2.53	0.30	0.02	+
Intermediate Flows Concept						
Intercept	2	61.92	0	NA	NA	
IFDOGD	3	63.93	2.00000	0.22	0.07	+
IFD	3	63.99	2.06	0.23	0.06	-
OGD	3	64.46	2.53	0.30	0.02	+
Combined Growth Models						
Intercept	2	61.92	0	NA	NA	
BWCF+ELFD	4	66.35	4.43	0.18	0.19	+
ELFD+IFDOGD	4	66.99	5.06	0.22	0.14	+
BWCDOGD+ELFD	4	67.37	5.45	0.26	0.11	+
AFCD+ELFD	4	68.82	6.9	0.44	0.00	+
AFCD+IFDOGD	4	69.12	7.2	0.49	0.00	+
BWCDOGD+IFDOGD	4	69.14	7.22	0.49	0.00	+
BWCF+IFDOGD	4	69.16	7.24	0.50	0.00	+
BWCF+AFCD	4	70.91	8.99	0.94	0.00	+
BWCF+BWCDOGD	4	70.93	9.01	0.94	0.00	+
AFCD+BWCDOGD	4	71.07	9.14	0.99	0.00	+

Appendix D Continued.

Shorthead Redhorse

Growth Models	K	AICc	Δ AICc	*P*-Value	R^2	Relationship
			Flood Pulse Concept			
Intercept	2	42.47	0	NA	NA	
BWCDOGD	3	47.16	4.69	0.22	0.14	+
AFCD	3	48.21	5.73	0.37	0.00	+
BWCF	3	48.68	6.21	0.47	0.00	-
OGD	3	48.84	6.37	0.52	0.00	+
BWCD	3	49.14	6.66	0.64	0.00	+
			Low Flow Recruitment Concept			
Intercept	2	42.47	0	NA	NA	
ELFD	3	48.46	5.98	0.42	0.00	-
OGD	3	48.84	6.37	0.52	0.00	+
			Intermediate Flows Concept			
Intercept	2	42.47	0	NA	NA	
OGD	3	48.84	6.37	0.52	0.00	+
IFDOGD	3	49.12	6.64	0.63	0.00	-
IFD	3	49.41	6.94	0.84	0.00	-
Recruitment Models	K	AICc	Δ AICc	*P*-Value	R^2	Relationship
			Flood Pulse Concept			
Intercept	2	24.63	0.00	NA	NA	
OSD	3	40.33	15.70	0.14	0.44	+
BWCF	3	43.46	18.83	0.44	0.00	-
BWCFR	3	43.84	19.21	0.52	0.00	-
BWCD	3	43.85	19.21	0.53	0.00	-
BWCDOSD	3	44.15	19.52	0.62	0.00	-
			Low Flow Recruitment Concept			
Intercept	2	24.63	0.00	NA	NA	
OSD	3	40.33	15.70	0.14	0.44	+
ELFD	3	44.60	19.97	0.90	0.00	+
			Intermediate Flows Concept			
Intercept	2	24.63	0.00	NA	NA	
OSD	3	40.33	15.70	0.14	0.44	+
IFOSD	3	41.58	16.95	0.21	0.28	+
IFD	3	43.52	18.89	0.45	0.00	+
HR	3	44.61	19.98	0.92	0.00	-
			Combined Recruitment Models			
Intercept	2	24.63	0.00	NA	NA	
ELFD+IFDOSD	4	Inf	Inf	0.44	0.11	+
ELFD+IFD	4	Inf	Inf	0.80	0.00	+

Appendix D Continued.

Channel Catfish

Growth Models	K	AICc	Δ AICc	*P*-Value	R^2	Relationship
Flood Pulse Concept						
BWCDOGD	3	72.03	0	0.02	0.42	+
AFCD	3	74.05	2.02	0.05	0.30	+
AFCDOGD	3	75.14	3.11	0.08	0.23	+
Intercept	2	75.27	3.24	NA	NA	
OGD	3	75.85	3.82	0.11	0.18	+
BWCD	3	76.94	4.91	0.19	0.10	+
BWCF	3	78.49	6.46	0.46	0.00	+
Low Flow Recruitment Concept						
Intercept	2	75.27	0	NA	NA	
OGD	3	75.85	0.58	0.11	0.18	+
ELFDOGD	3	78.34	3.08	0.42	0.00	-
ELFD	3	78.87	3.6	0.62	0.00	-
Intermediate Flows Concept						
Intercept	2	75.27	0	NA	NA	
OGD	3	75.85	0.58	0.11	0.18	+
IFD	3	78.28	3.01	0.40	0.00	-
IFDOGD	3	78.77	3.51	0.57	0.00	-
Combined Growth Models						
Intercept	2	75.27	0	NA	NA	
BWCDOGD+BWCF	4	76.98	1.72	0.07	0.37	+
AFCD+BWCF	4	78.24	2.97	0.11	0.29	+
AFCD+BWCD	4	79.23	3.96	0.15	0.22	+
AFCDOGD+BWCF	4	80.29	5.02	0.22	0.14	+
BWCD+BWCF	4	82.16	6.89	0.44	0.00	+

Recruitment Models	K	AICc	Δ AICc	*P*-Value	R^2	Relationship
Flood Pulse Concept						
Intercept	2	33.93	0.00	NA	NA	
AFCD	3	35.08	1.15	0.12	0.18	+
OSD	3	36.23	2.30	0.22	0.08	+
BWCD	3	36.86	2.93	0.31	0.02	+
BWCDOSD	3	37.27	3.35	0.40	0.00	+
BWCF	3	38.12	4.19	0.79	0.00	-
BWCFR	3	38.21	4.28	0.97	0.00	+
Low Flow Recruitment Concept						
Intercept	2	33.93	0.00	NA	NA	
OSD	3	36.23	2.30	0.22	0.08	+
ELFD	3	38.15	4.23	0.83	0.00	+
Intermediate Flows Concept						
Intercept	2	33.93	0.00	NA	NA	
HR	3	35.55	1.63	0.16	0.14	-
IFD	3	36.12	2.20	0.21	0.09	-
OSD	3	36.23	2.30	0.22	0.08	+
IFDOSD	3	37.45	3.52	0.45	0.00	+
Combined Recruitment Models						
Intercept	2	33.93	0.00	NA	NA	
AFCD+IFOSD	4	40.23	6.31	0.25	0.14	+
AFCD+BWCDOSD	4	40.77	6.84	0.30	0.09	+
AFCD+ELFD	4	40.81	6.88	0.30	0.09	+
AFCD+BWCFR	4	41.08	7.15	0.33	0.06	+
AFCD+BWCD	4	41.08	7.15	0.33	0.06	+
BWCD+ELFD	4	41.74	7.81	0.42	0.00	+
BWCD+IFDOSD	4	41.96	8.04	0.46	0.00	+
BWCDOSD+ELFD	4	42.16	8.24	0.49	0.00	+
BWCDOSD+IFDOSD	4	42.60	8.68	0.57	0.00	+
BWCD+BWCFR	4	42.83	8.91	0.62	0.00	+
BWCDOSD+BWCFR	4	43.25	9.33	0.71	0.00	+
BWCFR+IFDOSD	4	43.26	9.33	0.72	0.00	+
ELFD+IFDOSD	4	43.42	9.49	0.76	0.00	+
BWCFR+ELFD	4	44.15	10.23	0.98	0.00	+

Appendix D Continued.

Flathead Catfish

Growth Models	K	AICc	Δ AICc	*P* -Value	R^2	Relationship
			Flood Pulse Concept			
BWCDOGD	3	90.41	0.00	0.06	0.30	+
BWCF	3	90.67	0.27	0.07	0.28	+
Intercept	2	90.87	0.47	NA	NA	
BWCD	3	91.48	1.07	0.10	0.22	+
AFCD	3	91.66	1.25	0.10	0.21	+
OGD	3	93.55	3.14	0.27	0.04	+
			Low Flow Recruitment Concept			
Intercept	2	90.87	0.00	NA	NA	
ELFD	3	92.81	1.94	0.18	0.11	-
OGD	3	93.55	2.68	0.27	0.04	+
			Intermediate Flows Concept			
Intercept	2	90.87	0.00	NA	NA	
OGD	3	93.55	2.68	0.27	0.04	+
IFD	3	95.00	4.13	0.73	0.00	-
IFDOGD	3	95.09	4.22	0.82	0.00	-
			Comined Growth Models			
Intercept	2	90.87	0.00	NA	NA	
BWCDOGD+BWCF	4	93.08	2.21	0.06	0.43	+
BWCF+AFCD	4	93.53	2.66	0.07	0.40	+
BWCF+BWCD	4	95.48	4.61	0.14	0.27	+

Appendix D Continued.

Freshwater Drum

Growth Models	K	AICc	Δ AICc	*P*-Value	R^2	Relationship
Flood Pulse Concept						
BWCDOGD	3	39.44	0	0.025	0.42	+
AFCD	3	41.37	1.93	0.06	0.30	+
Intercept	2	41.84	2.4	NA	NA	
BWCD	3	41.94	2.5	0.08	0.26	+
OGD	3	44.72	5.28	0.30	0.02	+
BWCF	3	46.03	6.6	0.79	0.00	+
Low Flow Recruitment Concept						
Intercept	2	41.84	0	NA	NA	
ELFDOGD	3	43.7	1.86	0.18	0.12	-
OGD	3	44.72	2.88	0.30	0.02	+
ELFD	3	45.18	3.35	0.40	0.00	-
Intermediate Flows Concept						
Intercept	2	41.84	0	NA	NA	
IFDOGD	3	43.67	1.83	0.17	0.12	-
OGD	3	44.72	2.88	0.30	0.02	+
IFD	3	44.95	3.11	0.35	0.00	-
Combined Growth Models						
BWCDOGD+BWCF	4	40.49	0	0.017	0.60	+
Intercept	2	41.84	1.34	NA	NA	
BWCDOGD+AFCD	4	45.21	4.72	0.09	0.36	+
BWCD+BWCF	4	46.75	6.26	0.15	0.25	+
AFCD+BWCF	4	47.33	6.83	0.19	0.20	+

Recruitment Models	K	AICc	Δ AICc	*P*-Value	R^2	Relationship
Flood Pulse Concept						
BWCDOSD	3	27.66	0.00	0.01	0.60	+
BWCF	3	28.84	1.18	0.01	0.54	+
Intercept	2	32.20	4.54	NA	NA	
AFCD	3	32.47	4.81	0.07	0.31	+
BWCD	3	33.58	5.92	0.12	0.22	+
BWCFR	3	35.53	7.87	0.30	0.03	-
OSD	3	36.82	9.16	0.72	0.00	+
Low Flow Recruitment Concept						
Intercept	2	32.20	0.00	NA		
ELFD	3	36.28	4.08	0.47	0.00	-
OSD	3	36.82	4.62	0.72	0.00	+
Intermediate Flows Concept						
IFDOSD	3	24.68	0.00	0.003	0.71	-
Intercept	2	32.20	7.52	NA	NA	
IFD	3	36.30	11.62	0.48	0.00	-
OSD	3	36.82	12.15	0.72	0.00	+
HR	3	36.83	12.15	0.73	0.00	+
Combined Recruitment Models						
Intercept	2	32.20	0.00	NA	NA	
BWCF+HR	4	32.94	0.74	0.02	0.62	+
BWCDOSD+HR	4	33.75	1.55	0.03	0.58	+
BWCDOSD+AFCD	4	34.16	1.96	0.03	0.56	+
BWCF+AFCD	4	35.22	3.02	0.05	0.51	+
BWCF+BWCD	4	35.98	3.78	0.06	0.47	+
AFCD+HR	4	39.21	7.01	0.19	0.23	+
BWCD+HR	4	39.81	7.61	0.23	0.18	+