U.S. Fish and Wildlife Service

Gulf Coast Prairie Landscape Conservation Cooperative Regional Hypotheses of Ecological Responses to Flow Alteration

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Cooperator Science Series # 107-2014

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Contractual References:

This document fulfills reporting requirement for Wildlife Management Institute Grant Number GCP LCC 2012-003. Previously published documents that partially fulfilled any portion of this contract are referenced within, when applicable. (USGS IPDS #: IP-056672)

Recommended citation:

Davis M. and S. K. Brewer. 2014. Gulf Coast Prairie Landscape Conservation Cooperative Regional Hypotheses of Ecological Responses to Flow Alteration. U.S. Department of Interior, Fish and Wildlife Service, Cooperator Science Series FWS/CSS-107-2014, Washington, D.C.

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Gulf Coast Prairie Landscape Conservation Cooperative

Regional Hypotheses of Ecological Responses to Flow Alteration

Photo credit: Brandon Brown

A report by the

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Wildlife Management Institute Grant Number GCP LCC 2012-003

April 2014

ACKNOWLEDGMENTS

We thank the GCP LCC Flow-Ecology Hypotheses Committee members for their time and thoughtful input into the development and testing of the regional flow-ecology hypotheses. Shannon Brewer, Jacquelyn Duke, Kimberly Elkin, Nicole Farless, Timothy Grabowski, Kevin Mayes, Robert Mollenhauer, Trevor Starks, Kevin Stubbs, Andrew Taylor, and Caryn Vaughn authored the flow-ecology hypotheses presented in this report. Daniel Fenner, Thom Hardy, David Martinez, Robby Maxwell, Bryan Piazza, and Ryan Smith provided helpful reviews and improved the quality of the report. Funding for this work was provided by the Gulf Coastal Prairie Landscape Conservation Cooperative of the U.S. Fish and Wildlife Service and administered by the Wildlife Management Institute (Grant Number GCP LCC 2012-003). Any use of trade, firm, or product names is for descriptive purposes and does not imply endorsement by the U.S. Government. We thank Brandon Brown and Ryan McManamay for thoughtful comments on an earlier draft.

Contents

SECTION 1: CONTEXT FOR THE REGIONAL FLOW-ECOLOGY HYPOTHESES

The information in Section 1 orients the users of this report to the regional flow-ecology hypotheses presented in Section 2. Chapter 1 presents information about the project under which the GCP LCC regional flow hypotheses were developed and how the hypotheses are intended to be used. Chapter 2 provides some background on ecological responses to flow alteration and general summary information about the hydrologic and ecological conditions identified in the hypotheses.

Chapter 1. INTRODUCTION

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The streams and rivers of the GCP LCC are delicately balanced ecosystems that link diverse habitats with the people, plants and animals that rely on clean and abundant water supplies to thrive. The natural patterns of seasonal flows in streams and rivers – called instream or environmental flows - are the drivers for many of the ecosystem functions and processes on which the riverine and coastal natural and human economies rely. Extreme droughts and population growth in the GCP LCC region have forced the recognition that water resources are limited and need to be better managed. Excessive extractions and diversions of water alter instream flows and threaten the ecological processes that are dependent upon them. Dams on large rivers, for example, often reduce high flows and maintain unnaturally high baseflows. Climate change is yet another threat to natural flows as temperature and precipitation patterns are predicted to shift dramatically in the future. Failure to prepare for these pressures on the aquatic resources in the face of the uncertainties of climate change threatens the health of the region's economy and sustainability of aquatic resources.

The importance of natural flow regimes to the ecological integrity of rivers has been established for decades, but more specific information is needed to develop and implement scientifically-credible instream flow standards and management practices (Richter 2010). In fact, recent reviews of resources to support state instream flow standards reveal there is little available information that helps define specific ecological responses to flow alteration (Poff and Zimmerman 2010, McManamay et al. 2013). This makes it difficult to specify ecological flow regimes for a river and explain why the regime is critical to maintain and protect the aquatic resources.

A holistic suite of flow-ecology hypotheses about how riverine ecosystems respond to altered flow regimes forms the scientific basis for setting ecological limits of hydrologic alteration for streams and rivers. However, very few of these relationships have been identified in the GCP LCC region, which limits the ability of the states to substantiate instream flow standards and water management practices. The suite of regional flow-ecology hypotheses presented here addresses many components of riverine ecosystems that are sensitive to flow alteration. We present example flow-ecology hypotheses for fish, mussels, birds, and riparian vegetation.

Objectives

The objectives of this report for the SARP-GCP LCC Instream Flow Project are twofold. First, the flow-ecology hypotheses presented in this document are intended to serve as examples for the region. They are conceptual in nature and supported by scientific studies and best professional judgment. They are intended to explain the ecological implications of alterations to the natural flow regime in the GCP LCC region. More quantitative flow-ecology relationships will be required to determine standards and best

management practices. The second objective, therefore, is to provide a basis for testing flow-ecology hypotheses using existing hydrologic and aquatic data in the region. Existing data from state agencies, academic research groups, and others in the region will be used to substantiate and quantify these relationships (For more information about these resources, go to the SIFN page of the SARP website[1]). The adequacy of these data to test hypotheses and develop science-based relationships on which to base water management policy and practices has been assessed in an accompanying report (see Brewer and Davis, in prep). Information gaps that are identified in this process will be prioritized and become the basis of the GCP LCC Instream Flow Science Agenda to advance instream flow science in the region.

Approach

The hypotheses included in this report were developed by the Flow-Ecology Hypotheses Committee of the SARP-GCP LCC Instream Flow Project. The committee was chaired by Dr. Shannon Brewer, Research Scientist (Fisheries) and Assistant Unit Leader of the Oklahoma Cooperative Fish and Wildlife Research Unit. The committee included multidisciplinary aquatic experts from Louisiana, Oklahoma, and Texas: Jacquelyn Duke (Baylor), Kimberly Elkin (TNC), Tim Grabowski (USGS), Kevin Mayes (TPWD), Kevin Stubbs (USFWS), Caryn Vaughn (OU) and others. The committee met regularly via webinars that were facilitated by Dr. Mary Davis, Project Lead and Coordinator of the SARP Southern Instream Flow Network.

The committee meetings addressed a series of topics that led to the development of the flow-ecology hypotheses presented here. After an initial introduction to the Ecological Limits of Hydrologic Alteration (Poff et al. 2010; ELOHA) and alternative forms of flow-ecology hypotheses, the committee deliberated about what constituted a regional hypothesis and representative species. A list was developed of fish, mussel, and other aquatic species that represent regional guilds believed to be sensitive to flow alterations (Appendix A). Regions generally follow Omernik Region IV ecoregions across the three states in the GCP LCC: Texas, Louisiana, and Oklahoma. The committee reached consensus on the format of the hypotheses and measures of hydrologic alteration. Species-specific hypotheses were submitted for this report. The species-level hypotheses were broadened with the concept of a hierarchy of ecological responses to flow alteration that captured how the species responses represented guilds and assemblage responses. These hierarchies of hypotheses were presented in Chapters 3-11 of this report.

The Flow-Ecology Committee met eight times over the course of the year. Summaries of the discussion outcomes with supporting resources are available at the SARP Instream Flow Resources website.[2]

Intended Uses

The flow-ecology hypotheses in this report are intended for broad usage in the region by water and natural resource managers, policy decision-makers, and researchers and as a launching point for development of additional hypotheses using other flow-dependent species and guilds. The hypotheses

[1] http://www.southeastaquatics.net/sarps-programs/sifn
[2] http://southeastaquatics.net/sarps-programs/sifn/instream-flow-resources/regional-flow-ecology-hypotheses/regional-flow-ecology-hypotheses-pages/sifn-flow-ecology-hypotheses-expert-review

provide a basic level of information about the role of instream flows on the ecological integrity of riverine ecosystems. The hypotheses are supported by best professional judgment and scientific studies performed in the region or in similar types of ecosystems. As these flow-ecology hypotheses represent only a small fraction of the myriad ecosystem responses to flow alteration, the hypotheses included here can also serve the following uses:

- Templates for development of additional local, state, or regional flow-ecology hypotheses,
- Basis for evaluation of existing or proposed flow regime alteration,
- Proposals for research studies to quantify the relationships,
- Guides for multidisciplinary research programs to advance instream flow science, and
- Foundation for the development of more complex, multi-variable hypotheses.

Organization of This Report

The audience for this report is potentially broader than just aquatic experts who are already familiar with the concepts of ecological responses to flow alteration. Therefore, Chapter 2 provides a brief primer on the fundamentals of ecological responses to flow alteration. The concept of an ecological hierarchy of responses to flow alteration is presented. Chapter 2 serves as a gateway to resources a reader can pursue for more information. Chapters 3-11 present the regional flow-ecology hypotheses along with supporting information.

Literature Cited

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Poff, N. L. et al. 2010. The Ecological Limits of Hydrologic Alteration (ELOHA): a new framework for developing regional environmental flow standards. Freshwater Biology 55:147–170.

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Chapter 2. FUNDAMENTALS OF FLOW-ECOLOGY HYPOTHESES

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Plants and animals are threatened worldwide, but freshwater biota are most at risk. For example, the extinction rate of fish species is estimated to be 800 greater than historic rates (Burkhead 2012). The top four groups of U.S. species at risk – freshwater mussels, crayfishes, amphibians, and freshwater fish (Master et al. 1998) – all depend on healthy, functioning freshwater ecosystems. Moreover, almost all terrestrial species rely on freshwater ecosystems for at least some part of their life cycles. One of the major threats to freshwater biodiversity in the southeast U.S. is alteration of natural flow patterns (SARP Southeast Aquatic Habitat Plan 2007). Flow alterations result from of a variety of sources including:

- water withdrawals for municipal, agricultural, and industrial purposes;
- dams for water supply, flood control, hydropower, and other purposes;
- runoff from developed areas and other land use changes;
- groundwater pumping; and
- other forms of water diversions and consumption.

The Instream Flow Council (Annear et al. 2004) defines natural flow as:

"[t]he flow regime of a stream as it would occur under completely unregulated conditions, that is, not subjected to regulation by reservoirs, diversions, or other human works."

Riverine species are adapted to natural patterns of flow. Rivers have distinctive patterns of flow – called flow regimes - that are characterized by the magnitude, frequency, duration, rate of change, and time of flow events (Poff et al. 1997). The natural flow patterns work in concert with longitudinal (Vannote et al. 1980) and lateral connectivity (Junk et al. 1989) to provide habitat, food, and nutrients and allow species to complete their life cycles at the appropriate time of year. The ability of species to respond to flow alterations is limited (Bunn and Arthington 2002). For example, water abstractions from streams can produce unseasonal periods of low-flow conditions that can lead to water quality degradation, habitat and connectivity loss, and allow invasion by non-native species (Bunn and Arthington 2002,

Meyer et al. 2003). Substantial evidence implicates degradation of aquatic ecosystems due to changes in flow but there are also changes in ecosystem services (defined as the human benefits derived from ecosystems, see Meyer et al. 2003 for a review).

Streams provide many ecosystem services (see Brauman et al. 2007 for a review of hydrologic services), including

- dispersal of sediment and contaminants that influence the quality of downstream waters,
- recharge of groundwater that is necessary for long-term water availability in many regions,
- habitat for many unique plants and animals,
- economically important recreational opportunities, and
- water provisions, aesthetic and cultural and spiritual value (Costanza et al. 1997).

Research indicates high replacement costs for many of these ecosystem services if they fail. For example, billions of dollars would be necessary to sustain water purification alone (see Salzman et al. 2001 for a review). To protect the integrity of waterways and ensure humans benefit from ecosystem services, tools are needed to provide a foundation for the protection of instream flows and the services they provide.

The primary purpose for developing flow-ecology hypotheses is to serve as a scientific basis for setting instream flow standards and water management practices. The framework necessary to support the hypotheses is described as the Ecological Limits of Hydrologic Alteration (ELOHA; Poff et al. 2010), where hydrologic and aquatic data are used to quantify ecological responses to flow alteration. Once tested and shown to be ecologically significant, the flow-ecology hypothesis becomes formalized as a relationship. Flow-ecology relationships can be used to inform decisions as to how much a flow regime can be altered while maintaining acceptable ecological condition of rivers and streams.

A full treatment of the topic of instream flows and ecological responses to flow alteration is beyond the scope of this report. However, anyone involved with the science, policy, or management of river water resources should be very familiar with the general concepts of how flow affects the ecological condition of rivers and how human activities alter natural flow regimes. There are many general and regional sources of instream flow information. Readers are encouraged to explore the references listed below.

General Instream Flow Resources:

- Poff, N. L. et al. 1997. The natural flow regime - a paradigm for river conservation and restoration. BioScience 47:769–784. Available at: http://www.jstor.org/stable/1313099.
- Postel, S. and B. Richter. 2005. *Rivers for Life: Managing Water for People and Nature.* Island Press, Washington, Covelo, London.
- The Nature Conservancy's ELOHA resources (nature.ly/ELOHA)
- Selected flow-ecology references for southern rivers and elsewhere (http://www.mendeley.com, Group name "Flow-Ecology Literature").
- The Instream Flow Council publishes a reference list on instream flow literature and other resources (http://www.instreamflowcouncil.org).

- The Global Environmental Flow Network is source for an international perspective on protection of environmental flows (http://www.eflownet.org/).
- Other Links
    - American Fisheries Society (http://www.fisheries.org/afs/)
    - American Rivers (http://www.americanrivers.org)

GCP LCC Regional Instream Flow Resources

- GCP LCC Conservation Planning Atlas (http://GCP LCC.databasin.org/)
- Southeast Aquatic Resources Partnership (http://www.southeastaquatics.net)
- Texas Parks and Wildlife Department River Program (http://www.tpwd.state.tx.us/landwater/water/conservation/fwresources/)
- Oklahoma Departments of Wildlife Conservation (http://www.wildlifedepartment.com/) and Water Resource Board (http://www.owrb.ok.gov/)
- Louisiana Department of Wildlife and Fisheries (http://www.wlf.louisiana.gov/)

Ecologically Significant Components of the Flow Regime

Each river has characteristic patterns of natural flow. The amount of water in a river at any time depends on its physical setting (e.g., catchment area, slope, soil type, vegetation cover, land use, etc.), climate (e.g., rainfall and temperature), and groundwater interactions. The range of flow magnitude can vary widely and differs seasonally, although some streams have relatively steady baseflow via groundwater contributions to the stream channel. As discharge changes in a river over seasons and years, it interacts with the physical setting of the river channel (e.g., depth, velocity, erosion, inundation, connectivity, etc.) and creates a variety of geomorphic features (e.g., riffles, pools, floodplains) that represent the habitat mosaic used by aquatic and terrestrial biota.

Natural variability in discharge is often described for ecological purposes in terms of changes in the following flow attributes:

- Magnitude - the amount of water at a given point in time,
- Duration - amount of time a specified magnitude occurs,
- Frequency - number of times a specified flow event occurs in a month, season, or year,
- Timing - when an event usually occurs, and
- Rate of change - the amount water rises or falls in a given amount of time.

A challenge for quantifying ecological responses to flow alteration is to specify the ecologically significant component of the flow regime and calculate the degree of alteration. A clear definition of the hydrologic metrics is necessary.

Definitions and Hydrologic Metrics

For the purposes of the GCP LCC Instream Flow Project and regional flow-ecology hypotheses, the following definitions (Texas Instream Flow Program 2008) and metrics (Index of Hydrologic Alteration 2012) will be used to describe significant ecological flow components (EFCs) of the natural flow regime. More information about the environmental conditions and consequences of flow alteration associated with these components of the flow regime is given in Appendix B.

Overbank or flood flows: Overbank or flood flow is when there is a sufficient amount of water in the river to exceed the physical constraints of the channel. During overbank or flood flow events, the river expands into lateral areas inundating riparian areas and floodplains. This usually occurs during periods of high or continuous rainfall or following snow melt. Floods are differentiated from high flow pulses by exceeding bankfull water levels for some period of time. **Example metrics**: 1-day maximum, 3-day maximum, 7-day maximum, date of maximum, small flood peak, duration, timing, frequency, rise rate and fall rate, and large flood peak, duration, timing, frequency, rise rate and fall rate.

High flow pulses: High flow pulses are defined as those short-term flow events that occur following rainfall or other precipitation events when water levels rise above baseflow levels and stay within banks. High flow pulses occur more frequently than overbank flows and add variability to daily flows in streams. The amount of variability depends on the relative amount of runoff from the watershed, with "flashy" streams receiving large amounts of runoff relative to the amount of groundwater. The natural rates of rise and fall of the pulse are characteristic of the stream location and physiography. The energy of flowing water is at its maximum during high flow pulses, particularly when pulses reach bank full level. **Example metrics**: 30-day maximum, 90-day maximum, low pulse count and duration, high pulse count and duration, rise and fall rates, number of reversals, and high flow peak, duration, timing, frequency, rise rate, and fall rate.

Baseflow: Baseflow is defined as the normal flow conditions between precipitation events. Baseflow is the contribution of groundwater to streamflow when precipitation is minimal and fluctuates seasonally. For example, many rivers in the southeastern U.S. have high baseflow in the winter and low summer baseflows. Rivers that have a large groundwater influence are perennial and have relatively stable flow levels. Rivers with more surface water runoff influence can be intermittent or perennial and usually have a relatively large range of daily and seasonal flow levels. The relative influence of groundwater and surface water can change within a watershed and often is related to the size of the watershed, with small watersheds having less groundwater influence and lower baseflows. **Example metrics**: Mean or median monthly flow (cfs), mean or median annual flow (cfs), baseflow index (7-day minimum flow/mean flow for year).

Subsistence or extreme low flows: Extreme low flows or subsistence flows are defined as flow levels that occur less than 10% of the time (alternatively stated, exceeded 90% of the time). These lowest flow conditions usually occur during droughts when baseflows are at their seasonal low levels, such as during summer months in the southeastern US. Flow rates are very slow or even zero in pools that have become disconnected from flowing water. The frequency and duration of extreme low flows is driven

by the climate, but can occur naturally on a yearly basis for short periods of time. Suitable habitats are at a minimum extent during extreme low flow events. **Metrics**: 1, 3, or 7-day minimum flows, monthly low flow, extreme low flow magnitude (cfs), frequency (count), duration (# days), and timing (ordinal date).

Hydrologic metrics used in the GCP LCC flow-ecology hypotheses

It is well established that all of the components of the natural flow regime are ecologically important (Bunn and Arthington 2002, Poff et al. 2010). Development of the scientific basis for instream flow policy and water management practices, therefore, should address as many of the flow components as is necessary but also practical. The hydrologic metrics identified in the suite of flow-ecology hypotheses should support this principle. This substantiates the ecological significance of policy decisions or management actions that can affect these aspects of the flow regime.

For the 28 flow-ecology hypotheses developed for the GCP LCC region, 17 hydrologic metrics were identified (Table 2.1). The metrics represent all of the ecological flow components. Baseflow metrics were the most commonly identified in these hypotheses. Specifically, magnitude and duration of the ecological flow components were the most common flow attributes. Although rate of change was not identified in these specific hypotheses, variability of baseflows (i.e., coefficient of variation) was identified as a new flow attribute.

Distinctions among many of the hydrologic metrics were associated with different seasons (Table 2.1). Reproductive seasons of fishes vary seasonally, for example, so magnitude and duration metrics reflected the hydrologic conditions for the appropriate time of year for each species. Hypotheses for riparian forests specified the growing season. Annual metrics were specified for hypotheses about physical habitat condition. For example, high flow pulses are important for maintaining habitat quality and availability regardless of when the habitat is actually used.

Metrics used to calculate the central tendency of hydrologic metrics varied but median values were used most often (Table 2.1). Medians are generally favored as being more representative of riverine conditions (C. Apse and C. Konrad, 2010, personal communications) because mean values tend to be influenced by extreme events (i.e., large floods). This is especially problematic in the GCP LCC region as many of the rivers are considered very flashy or vary substantially by season. The adequacy of using means or medians for ecological applications is an area for future research and will not be addressed further in this report.

Ecological Condition

Riverine ecosystems are comprised of interacting physical, chemical, and biotic components. The flow regime is considered the “master variable” (Figure 2.1, Poff et al. 1977) because of its controlling influence on the other components. Natural flow regimes establish the physical mosaic of habitats and influence the water quality conditions (e.g., temperature, dissolved oxygen, and nutrient

concentrations). These physical and water quality attributes interact to establish and maintain the suite of aquatic fauna and other resources within river systems.

Riverine ecosystems respond when attributes of the flow regime are changed. Change in the condition of the ecosystem beyond its range of natural conditions, whether plus or minus, is considered an ecological impairment. For example, when species richness is reduced due to reduction in water quantity, it is considered an ecological impairment. A decrease in flow may also allow invasive species to become established, resulting in an increase in species. In this example, the increase in species richness is an ecological impairment.

The objective of flow-ecology relationships is to quantify the amount of change in ecological condition for a given change in one or more flow metrics so that management decisions can be informed using acceptable limits of alteration to the biota. Acceptable limits are defined by stakeholders involved in the decision-making process. Ideally, decisions are based on a suite of flow-ecology relationships and represent different components of alteration to the river system.

Selected species used in the GCP LCC flow-ecology hypotheses

The flow-ecology hypotheses were developed for the GCP LCC region using riverine biota. Species were selected based on several criteria:

- sensitive to flow alteration,
- widely distributed or represented widely distributed guilds,
- representative of common types of rivers and streams in the region,
- representative of a range of types of riverine-dependent biota in the region,
- studied or their congeners were studied to understand their responses to flow alteration,
- included the focal aquatic species for the GCP LCC, and
- collectively, illustrated how rivers of the region are affected by flow alterations.

The full set of flow-sensitive species identified by the GCP LCC Flow-Ecology Hypotheses Committee is provided in Appendix A. The flow-sensitive species and associated guild selected for the GCP LCC flow-ecology hypotheses are provided in Table 2.2.

Ecological metrics used in the GCP LCC flow-ecology hypotheses

The ecological metrics for the GCP LCC capture many of the major ecosystem responses that occur when flow is altered. For the 27 flow-ecology hypotheses for the GCP LCC region, 20 ecological metrics were identified (Table 2.3). Six hypotheses pertained to physical habitat availability, quantity, and quality. Another six hypotheses represented population metrics of species richness and abundance of individuals. Most hypotheses using fish population metrics will be tested with the existing data (Brewer and Davis, in prep). Finally, eight fitness-related metrics considered the relationships for reproduction, growth, survival, and body condition.

Regional Flow-Ecology Hypotheses

The regional flow-ecology hypotheses presented here differ from other efforts in two ways: 1) geographic extent, and 2) level of ecological organization. Flow-ecology hypotheses are most often specified for large watersheds (e.g., Potomac and Susquehanna River basins) or states (e.g., Massachusetts and Michigan). These are intended to inform environmental flow management for individual basins or entire states. The committee that developed these hypotheses recognized the value of regional relationships because of the:

- commonalities of relationships in similar types of rivers across watershed and political boundaries,
- more efficient use of limited data to test the hypotheses,
- applicability as examples and templates for many users, and
- possibility of more consistent standards and management practices across jurisdictions.

We present the flow-ecology hypotheses for the GCP LCC region in a hierarchy of ecological organization (Figure 2.2). Hypotheses were first developed for individual species but they are applicable to higher levels of the ecosystem (e.g., guild or assemblage). This recognizes responses to flow alteration at the species level affect the guilds and biological assemblages they comprise. The hypotheses are therefore presented in Chapters 3-11 as hierarchies that show how mechanisms of hydrologic alteration are reflected through this ecological organization. Testing the function of river systems would be ideal, however, data availability are often limited to the other levels of the hierarchy (see Brewer and Davis report).

Interpretation and Use of the Hypothesis Graphs

The flow-ecology hypotheses are presented in X-Y graphs that show how the ecological condition is expected to change with change in the associated flow attribute (Figure 2.3). The ecological condition is on the Y-axis and can be expressed as a measurement (e.g., number of individuals, growth rate, etc.) or less often as a change in condition between current and reference conditions (e.g., reference ecological measurement – current ecological measurement). The hydrologic attribute is on the X-axis and is usually expressed as a change in flow attribute (e.g., reference hydrologic measurement – current hydrologic measurement). Reference condition is indicated on each axis. The hypothesized relationship indicates how the ecological condition is expected to increase or decrease with change in flow. The hypothesis statement describes the relationship and primary mechanisms (if known) that drive the response.

The flow-ecology hypotheses in this report represent the relationship between single ecological metrics and some measure of the flow regime. It is important to recognize that while these relationships help managers understand the relationship between these metrics, they do not necessarily imply causation. This is important to consider as flow regime changes are often correlated with other events (e.g., fragmentation of the landscape, changes in dissolved oxygen concentrations). Thus, there are very likely multiple factors that interact to cause ecological responses such as declines in a species abundance or fitness. _Consideration of the multiple factors that create the observed response by species or guilds is

important as managers consider the proposed hypotheses, even if single metrics are shown to be statistically significant. This is one of several reasons that post-hoc evaluations and adaptive management cycles have been suggested as follow up to environmental flow designations (see Davis et al. 2014).

The objective of statistically testing the flow-ecology hypotheses and substantiating it as a significant flow-ecology relationship is to quantify how much ecological change occurs for a given change in hydrologic condition. These tests use field measurements taken over time at points where flow alteration is quantified (i.e., time for space) or more often at locations that differ in the amount of flow alteration (i.e., space for time). Standard or quantile regression approaches are most commonly used, but certainly other approaches are suitable. Where data are not available, best professional judgment may be used to establish the flow-ecology relationships. The results are intended to help determine the amount of change in flow that is within limits of tolerable ecological change for that metric. The feasibility of testing the GCP LCC regional flow-ecology hypotheses using existing data is addressed in another report (Brewer and Davis, in prep).

The hypotheses in this report represent general relationships that have been developed by regional aquatic experts and supported with results of studies in the region. Their general nature makes them amenable to identification of areas of concern in the landscape where the species occur and helps identify threats to particular components of the flow regime that should be considered for protection. The hypotheses can be used to support instream flow standards and water management policies. Development of quantitative flow standards can be best supported by these hypotheses once they have been statistically tested and threshold levels of hydrologic alteration identified (see Brewer and Davis, in prep).

Although it is beyond the scope of this report, it a holistic suite of relationships should be used when determining instream flow standards from flow-ecology relationships. The objective of setting instream flow standards and management practices is to protect the whole aquatic ecosystem by protecting the ecologically significant components of the flow regime. Ideally, many statistically tested and significant relationships are available to inform these decisions. Where this is not the case, focus should be given to those relationships that are clearly most sensitive to the types of flow alterations that are expected to be most stressful to the riverine ecosystem (e.g., water withdrawals during hot, low flow periods in rivers with sedentary species).

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Table 2.1. Suite of ecological flow components represented by GCP LCC flow-ecology hypotheses. The Flow-Ecology Hypotheses Codes refer to the hypothesis found in Chapters 3-11.

Ecological Flow Component	Flow Attribute	Hydrologic metric	Flow-Ecology Hypotheses Codes *
Extreme low flow (Q90)	Magnitude	Median monthly cfs (June-September)	M.1.a
	Duration	Annual number of days	F.4.a
		Median Monthly Number of days (June-September)	M.1.b
		Median Monthly number of days (March - October)	R.1.a, R.1.b, R.1.c
Baseflow	Magnitude	Median cfs (June-August or September)	F.2.a, F.3.a, F.5.a
		Median annual cfs	F.2.c
		Mean annual cfs	F.4.b, F.6.b
		Monthly low cfs (February-May)	F.6.a
	Variability	Daily flow coefficient of variation (June-August)	F.2.b
High flow pulse (< 1.5 yr return)	Magnitude	Median Annual peak (cfs)	F.6.c, B.1.a
	Duration	Median monthly number of days (June-August)	B.1.b
	Frequency	Median Monthly count (April-June)	F.3.b, F.4.c
		Median Annual count	R.1.d, R.1.e, R.1.f, R.1.g
Overbank flow (>1.5 yr return)	Magnitude	Median Monthly cfs (April-June)	F.1.b
	Frequency	Median Annual count	F.6.d, R.1.h, R.1.i
	Timing	Median ordinal date of peak flow (April-June)	F.1.a

*** Flow-Sensitive species:**

Fish – Alligator Gar (F1), Arkansas River Shiner (F2), Freckled Madtom (F3), Guadalupe Bass (F4), Orangethroat Darter (F5), and suckers (F6)
Mussels – Steamboat Mucket (M1)
Birds – Interior Least Tern (B1)
Vegetation – riparian woody species (R1)

Table 2.2. Selected fluvial-specialist species representative of riverine ecosystems of Louisiana, Oklahoma, and Texas. Species code is associated with flow-ecology hypotheses presented in this report. See the "Guild Level Response" section for each species in Chapters 3-11 for guild assignment citations.

Group	Species code	Scientific name	Common name	Guild or associated species
Fish	**F.1**	*Atractosteus spatula*	Alligator Gar	Floodplain spawner
	F.2	*Notropis girardi*	Arkansas River Shiner	Pelagic, broadcast spawning cyprinid
	F.3	*Noturus nocturnus*	Freckled Madtom	speleophil
	F.4	*Micropterus treculii*	Guadalupe Bass	Riffle-run dependent
	F.5	*Etheostoma spectabile*	Orangethroat Darter	Lithophil
	F.6	*Moxostoma* spp and other Catostomidae	suckers	suckers
Mussel	**M.1**	*Actinonaias ligamentina*	Steamboat Mucket	Mussels and other sedentary, filter-feeding macroinvertebrates
Bird	**B.1**	*Sterna antillarum athalassos*	Interior Least Tern	Sandbar nesting spp
Plant	**R.1**	*Salix nigra*	Black Willow	Woody riparian vegetation
	R.1	*Taxodium distichum*	Bald Cypress	Woody riparian vegetation

Table 2.3. Ecological metrics associated with species, guilds, and biotic assemblages used in the GCP LCC Flow-Ecology Hypotheses. The Flow-Ecology Hypotheses Codes refer to the hypotheses found in Chapters 3-11.

Ecological Metric	Category	Ecological metric	Flow-Ecology Hypotheses Codes*
Habitat	Availability	Nest habitat (WUA)	F.3.b
	Amount	Spawning habitat (acres)	F.1.b
	Condition	Habitat quality	F.4.b, F.6.a
		Depth to groundwater	R.1.a
	Formation	Acre/year	B.1.a
		Sediment deposition rate	R.1.f
Population	Presence	Persistence	F.2.c
	Abundance	Catch per Unit Effort	F.2.b, F.3.a, F.5.a
	Invasive	Number of individuals	R.1.b, R.1.g, R.1.i
Physiological	Body condition	Catabolism	M.1.a
		Weight/Length	F.6.d
Reproduction	Nesting success	Number per year	B.1.a
	Reproductive success	Number of YOY	F.1.a, F.2.a, F.4.c
	Seed dispersal	Percent of area	R.1.h
Growth	YOY and Juvenile Seedling roots	Growth rate (cm/yr)	F.4.a, F.6.b
	Trees	Height (cm/yr)	R.1.e
Survival	Young	Number of individuals	F.6.c, R.1.d
Mortality	Adults	Number per year	M.1.b, R.1.c

*** Flow-Sensitive species:**

Fish – Alligator Gar (F1), Arkansas River Shiner (F2), Freckled Madtom (F3), Guadalupe Bass (F4), Orangethroat Darter (F5), and suckers (F6)
Mussels – Steamboat Mucket (M1)
Birds – Interior Least Tern (B1)
Vegetation – riparian woody species (R1)

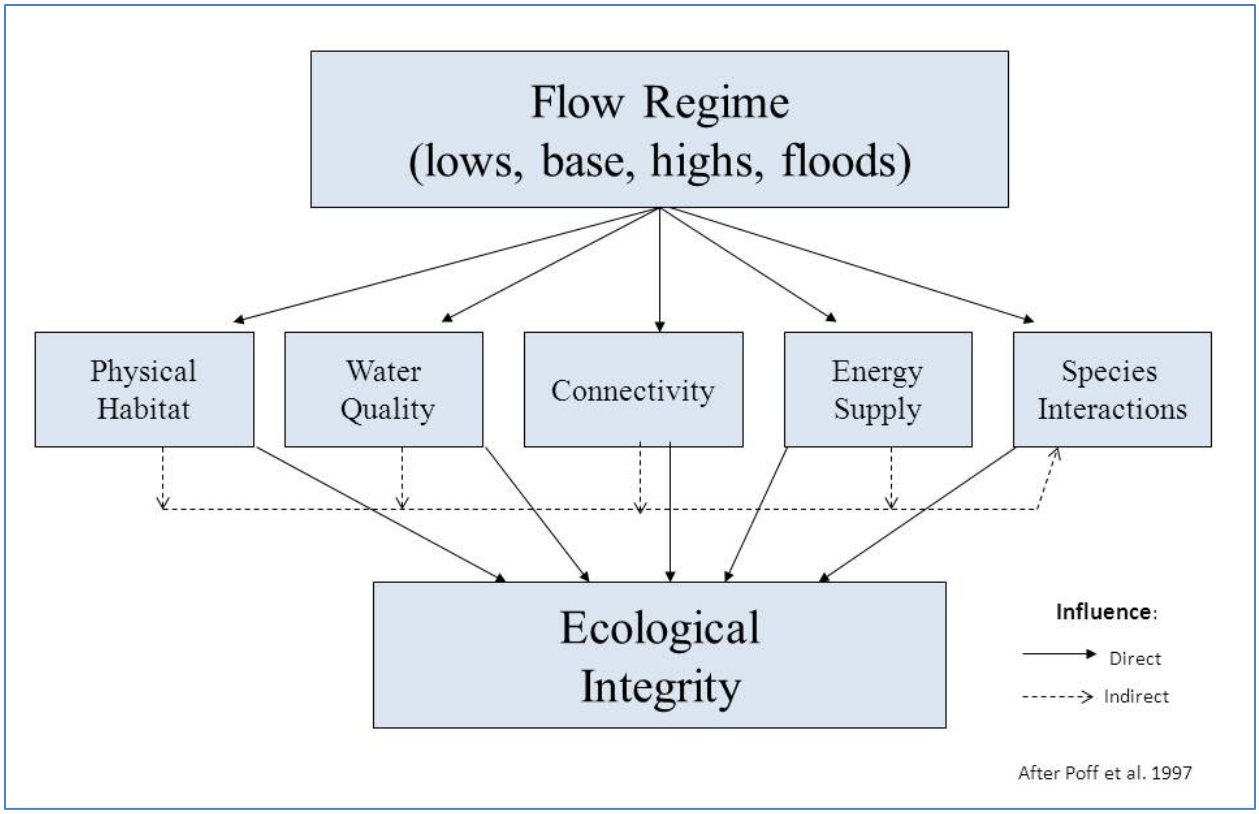

Figure 2.1. The flow regime is the "Master variable" in controlling the ecological integrity of aquatic ecosystems. Changes in extreme low, baseflow, high flow pulses, and overbank flow have direct influence on physical, chemical and biological components of the ecosystem as well as indirect mechanisms that change the quality and availability of habitat for aquatic species.

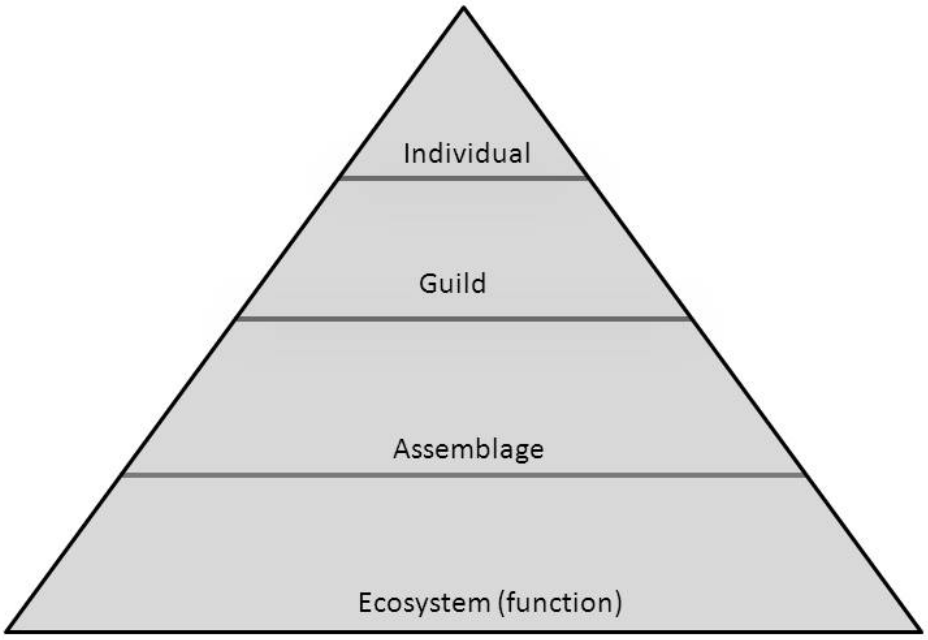

Figure 2.2. Pyramid of ecological organization used in GCP LCC flow-ecology hypotheses.

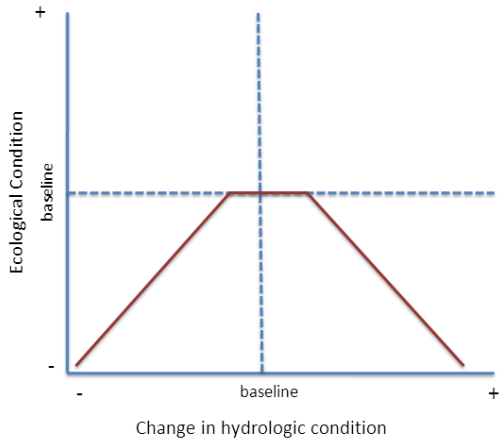

Figure 2.3. General example of the graphical format for a GCP LCC flow-ecology hypothesis.

SECTION 2: REGIONAL FLOW-ECOLOGY HYPOTHESES

Riverine biota represented in the GCP LCC regional flow-ecology hypotheses inhabit a wide range of hydrologic conditions that span from the arid plains of western Texas and Oklahoma to the great swamps of Louisiana. Found from headwaters to great rivers, these species help comprise the native biologic assemblages that we want to maintain as part of healthy rivers. The sustainability of these species helps indicate that the riverine ecosystem is in balance, including the presence of a flow regime that supports completion of their life cycles. The flow-ecology hypotheses presented in Chapters 3-11 will be useful for defining the types and degree of flow alteration that need to be managed to sustain viable populations and the ecological integrity of riverine ecosystems in the GCP LCC region.

Twenty-eight flow-ecology hypotheses were developed for this region. The hypotheses are presented with information and citations to support the flow-ecology relationships captured in the associated X-Y graphs. They are organized by major biological group (i.e., fish, mussels, birds, vegetation). The code for each hypothesis indicates the species within the biological group (e.g., Alligator Gar is the first fish species, hence the two hypotheses are coded F.1.a and F.1.b, respectively). The reader is referred to Table 2.1 for hypotheses using specific hydrologic metrics and Table 2.3 for specific ecological metrics. Table 2.2 lists the species and guilds used in these hypotheses.

Chapter 3. Alligator Gar (*Atractosteus spatula*)

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Flow-Ecology Hypothesis Species Code: F.1

STATUS: Species of Greatest Conservation Need in Texas (Texas Parks and Wildlife 2012) and Oklahoma (Oklahoma Department of Wildlife Conservation 2005).

SPECIES DESCRIPTION: Alligator Gar possess a dual row of large teeth in their upper jaw. Its name derives from the alligator-like appearance of these teeth along with the fish's elongated snout. The dorsal surface of the Alligator Gar is brown or olive, while the ventral surface tends to be lighter. Their ganoid scales are diamond-shaped and interlocking. Young have a light mid-dorsal stripe which is bordered by a dark brown area, extending from the tip of the snout to the origin of the dorsal fin. A dark irregular mid-lateral band may be present. These long-lived (up to 95 years) primitive fish can reach 3 m (nearly 10 ft) and weigh more than 130 kg (>300 lbs; Thomas et al. 2007).

REPRODUCTION AND DEVELOPMENT: Alligator Gar prefer slow-moving waters of rivers, bayous, and oxbows most of the year, and require access to inundated floodplain fields or wetland vegetation for spawning and successful recruitment (Inebnit 2009, Kluender 2011). Alligator Gar form spawning aggregations typically comprised of one female and multiple males over submerged vegetation upon which adhesive eggs attach. Spawning usually occurs April through June (Etnier and Starnes 1993, Ferrara 2001).

RANGE AND POPULATION LEVEL: Gulf of Mexico drainages from Florida to Mexico including Ohio and Missouri rivers of the Mississippi River drainage. Alligator Gar are well distributed across coastal rivers and streams in Texas and Louisiana extending to large rivers in Oklahoma. Estuarine populations are found on the Gulf Coast, but effects of freshwater inflows on the ecology of these populations are unknown.

HABITAT: Alligator Gar inhabit lakes, bayous, and bays and are able to tolerate brackish and even salt water, but prefer large, slow-moving rivers, particularly those with wide floodplains. They are generally associated with near surface habitats in slack water and backwater habitats. Juvenile Alligator Gar appear to remain in backwater spawning areas as they develop.

BIOLOGY/LIFE HISTORY*:* Young may be seen at the surface in debris such as leaves and twigs and along shorelines and flooded wetlands. Adults typically inhabit main channel pool and backwater habitats but have been found to congregate in high densities at certain locations for pre-spawn staging (typically April-May), spawning (typically April-June), and over wintering (December-February;Buckmeier et al. 2013). Observations and data suggest solitary or territorial behavior post-spawn and through the fall

months. Alligator Gar are considered to be opportunistic predators and scavengers, in most studies, food items have been predominately forage fishes and some larger sport fish.

THREATS: Alligator Gar populations are believed to be declining throughout much of their historical range. The severity of these declines is unknown. Habitat alteration and overfishing are believed to be partially responsible (Ferrara 2001). Habitat changes due to disruption/fragmentation of river-floodplain corridors, impoundments, channelization, loss of wetlands, and urbanization may have impacted populations. Alligator Gar are vulnerable to overfishing especially in shallow spawning areas. Several states have enacted creel limits and no-fishing seasons or zones.

RESPONSE TO FLOW ALTERATION:

Species-level response - Alligator Gar spawn in tributaries and inundated floodplain habitats depositing eggs on vegetation. Timing (during spawning months, April to June) and duration (short duration could strand adults and/or desiccate eggs) of inundation are important. In addition, reduced high flow pulses and overbank flow magnitudes limit hydrologic connectivity to floodplain habitats reducing Alligator Gar spawning habitat.

- **Overbank Flow Timing Hypothesis F.1.a**: Altered timing of overbank flows during Alligator Gar spawning season (April-June) reduces their spawning success. The occurrence of early or late overbank flow events diminish habitat accessibility and spawning success by shortening the time spawning fish can access floodplains. (Figure 3.1)
- **Overbank Flow Magnitude Hypothesis F.1.b**: Altered magnitude of overbank flow during Alligator Gar spawning season (April-June) alters the availability of and access to spawning habitats. Reduced magnitudes reduce frequency of overbank flow events that create connectivity with the floodplain and access for spawning fish. (Figure 3.2)

Guild-level response – There are many species that utilize floodplain habitats for spawning and recruitment (Inebnit 2009, Kluender 2011) in riverine systems. Riverine populations of these species could be similarly affected if connections to floodplains are not consistently available (Zeug and Winemiller 2008). However, consideration of species longevity within the guild must be accounted for when applying Alligator Gar hypothesis at the guild and assemblage levels. For example, Alligator Gar may live up to 50 years while other fishes, such as minnows, may only live 2-3 years and will require more frequent lateral connections. Spawning seasons may also differ and may need to be adjusted.

<u>Potential Floodplain Spawner Guild Associates</u>

1. Spotted Gar *Lepisosteus oculatus*
2. Pugnose Minnow *Opsopoeodus emiliae*
3. Gizzard Shad *Dorosoma cepedianum*
4. White Crappie *Pomoxis annularis*
5. Black Crappie *Pomoxis nigromaculatus*
6. Bluegill *Lepomis macrochirus*
7. Largemouth Bass *Micropterus salmoides*

Assemblage-level response – Fauna and flora that utilize floodplain habitats may require inundation at certain times, or for different durations and frequencies. Because Alligator Gar are top predators, food web dynamics could be altered if their populations are reduced or eliminated. Assemblage dynamics (i.e., abundance, richness, and distributions) of floodplain-dependent fish species could also be altered (Winemiller et al. 2000, Zeug et al. 2005) potentially reducing important prey species such as Gizzard Shad and nest building species with parental care such as Bluegill and White Crappie (Zeug and Winemiller 2008). Riparian communities and habitats may be impacted if the area/elevation of inundation or timing is significantly altered (see the Flow-Ecology Hypotheses for woody riparian vegetation below).

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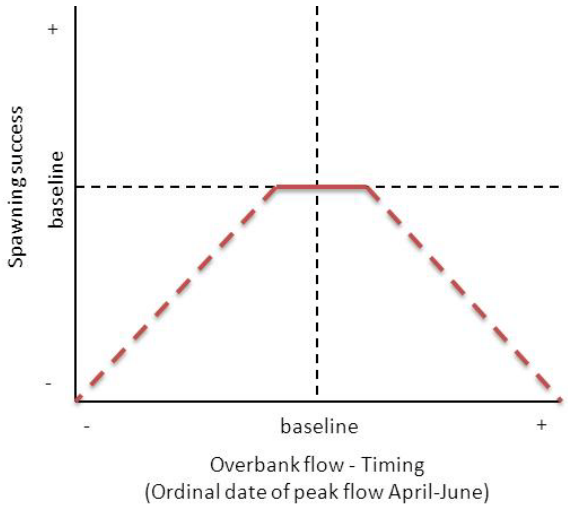

Figure 3.1. Alligator Gar Overbank Flow Timing Hypothesis F.1.a: Altered timing of overbank flows during Alligator Gar spawning season (April-June) reduces their spawning success. The occurrence of early or late overbank flow events diminish habitat accessibility and spawning success by shortening the time spawning fish can access floodplains.

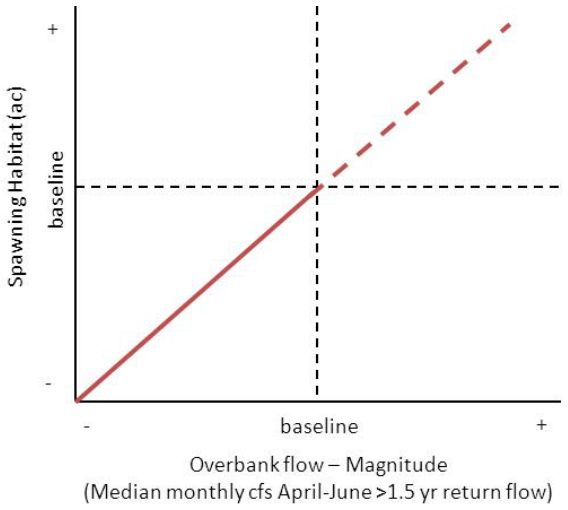

Figure 3.2. Alligator Gar Overbank Flow Magnitude Hypothesis F.1.b: Altered magnitude of overbank flow during Alligator Gar spawning season (April-June) alters the availability of and access to spawning habitat. Reduced magnitudes reduce frequency of overbank flow events that create connectivity with the floodplain and access for spawning fish. Increased magnitudes can increase spawning habitat acreage up to the physical limits of the floodplain.

Chapter 4. Arkansas River Shiner (*Notropis girardi*)

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Flow-Ecology Hypothesis Species Code: F.2

STATUS: Federally listed as threatened (63 FR 64771 64799, November 23, 1998) with critical habitat (66 FR 18001 18034, April 4, 2001).

SPECIES DESCRIPTION: A small minnow with a relatively flat head, round snout (but more pointed than other minnows), small mouth and relatively small eyes. Arkansas River Shiner (ARS) usually has 8 anal rays but can range between 7 and 9. The body is slender and curved with a faint or absent mid-dorsal line and a small spot on the caudal fin. Dorsal coloration tends to be light tan, with silvery sides gradually grading to white on the belly (Hendrickson and Cohen 2010).

REPRODUCTION AND DEVELOPMENT: Arkansas River Shiner ARS is a member of the pelagic broadcast spawning reproductive guild. These species release semi-buoyant eggs in the main channel and are thought to require extensive lengths (>100 km) of unfragmented river to complete their early development (Moore 1944, Platania and Altenbach 1998, Perkin and Gido 2011, Worthington et al. 2014). The length of river required for egg development is likely impacted by a range of factors including: temperature, total suspended and dissolved solids (Mueller 2013) and habitat complexity (Brewer and Grabowski 2013). Elevated discharge has been proposed as the trigger for spawning for ARS and similar species (Moore 1944, Bestgen et al. 1989, Durham and Wilde 2008, 2009, however, see Durham and Wilde 2006). Reduced discharge conditions render eggs vulnerable to abrasion due to being transported downstream near the channel floor (Bestgen et al. 1989, Osborne et al. 2006, Worthington et al. 2013). Impoundment of Great Plains rivers for water supply (see Limbird 1993) may truncate both downstream ichthyoplankton drift and upstream adult migration (see Bonner 2000, Durham and Wilde 2008, Walters et al. 2014).

RANGE AND POPULATION LEVEL:

Arkansas River Shiner was once common throughout Oklahoma, southern Kansas, western Arkansas, northern Texas, and northwest New Mexico (Gilbert 1980). The species is now though to be confined to

two fragments of the Canadian River between Ute Reservoir, New Mexico and Lake Eufaula, Oklahoma (Wilde 2002, Parham 2009, Worthington et al. 2014).

Habitat- Arkansas River Shiner was historically recorded in the Arkansas River catchment of New Mexico, Kansas, Texas, Oklahoma, and Arkansas. The species is most often found in shallow, sandy, braided rivers that are typical of the Great Plains (Matthews 1998). Arkansas River Shiner was most likely to be present in fifth order or larger streams with a mean annual discharge between 17 and 590 m^3/s (Worthington et al. 2014).

Threats- Much of the region has been impacted by water supply impoundments resulting in high levels of fragmentation and altered flow regimes that have been related to the decline of ARS (Perkin and Gido 2011, Worthington et al. 2014). Increased groundwater pumping has resulted in many smaller tributaries being dry for a large portion of the year and main river channels are often restricted to a simple, narrow thalweg (Woods et al. 2005). Other threats include water-quality degradation, competition with non-native species such as the Red River Shiner *Notropis bairdi*, increased water temperatures, persistent drought, and altered instream channel dynamics (Brewer and Grabowski 2013).

RESPONSE TO FLOW ALTERATION:

Species-level response - Life histories strategies such as those displayed by ARS and other pelagic broadcast spawning cyprinids have evolved in direct response to the conditions these species historically encountered (see Bunn and Arthington 2002, Poff et al. 1997). Physicochemical conditions in Great Plains rivers are harsh and highly variable, with extremes in temperature, salinity and flow (Matthews 1987). Pelagic broadcast spawning cyprinids have evolved physical adaptations to tolerate these conditions. These species have cutaneous sense organs and specialized brain morphology (Moore 1950, Davis and Miller 1967, Huber and Rylander 1992) that allows them to feed in highly turbid waters. Changes in the flow regime may result in reduced turbidity and thus create a competitive advantage for sight-feeding fishes. An altered flow regime may also modify geomorphological processes. Increased channel habitat complexity has been linked to reduced downstream egg and larval drift and therefore the length of river required for ichthyoplankton to complete their development (Dudley and Platania 2007, Medley et al. 2007, Widmer et al. 2012, Worthington et al. 2013).

Arkansas River Shiner spawning is thought to be related to high-discharge events. Alteration of the natural flow regime (see Poff et al. 1997), such as reduced flow variability and removal of high-flow events, has been linked to the reduction in range and abundance of ARS. In the Pecos River where an introduced ARS population has spread rapidly (Bestgen et al. 1989), the flow regime has been less impacted than other Great Plains rivers (Costigan and Daniels 2012). However, Bonner (2000) did not find a consistent relationship between gonad maturity stages, gonadosomatic index (GSI), and stream flow. The ability of Arkansas River Shiners to persist in an area depends on sufficient fragment length and flow magnitude to allow access to habitat and for eggs and larvae to remain in suspension while not being swept downstream into unsuitable areas (e.g., reservoirs; Platania and Altenbach 1998, Durham and Wilde 2006, Worthington et al. 2013).

- **Baseflow Magnitude Hypothesis F.2.a:** Reproductive success (# of young of year) of Arkansas River Shiners decreases with reduced baseflow during the spawning season (June-August) as the riverine habitat becomes fragmented to isolated pools. Increased baseflow results in increased reproductive success until a threshold is reached where flows are sufficiently high to carry eggs further downstream where they may reach reservoirs or encounter an increased risk of predation. (Figure 4.1)
- **Baseflow Variability Hypothesis F.2.b:** Abundance of Arkansas River Shiner will decrease with decrease in baseline flow variability during spawning months (June-August) due to mechanisms that are not known. An increase in flow variability above baseline may result in increased abundance of ARS. (Figure 4.2)
- **Baseflow Magnitude Hypothesis F.2.c:** The likelihood of Arkansas River Shiners being present decreases from baseline probabilities with decrease in mean annual flow due to fragmentation of habitat. The likelihood of fish presence also decreases with an increase in mean annual flow above some threshold due to increased predation on young that have been carried into reservoirs. (Figure 4.3, this hypothesis is supported by Worthington et al. 2014)

Guild-level response - There are approximately 20 species (see below) within the pelagic broadcast spawning cyprinid guild (see Williams and Bonner 2006, Hoagstrom et al. 2011, Perkin and Gido 2011) although guild membership for some species has been questioned (see Medley and Shirley 2013). Of these species, thirteen are considered of conservation concern (Warren et al. 2000, Jelks et al. 2008) with others being recognized as of conservation importance at the state level.

Pelagic broadcast spawning cyprinids

1. Rio Grande Silvery Minnow - *Hybognathus amarus*
2. Western Silvery Minnow - *Hybognathus argyritis*
3. Plains Minnow - *Hybognathus placitus*
4. Speckled Chub - *Macrhybopsis aestivalis*
5. Prairie Chub - *Macrhybopsis australis*
6. Sturgeon Chub - *Macrhybopsis gelida*
7. Shoal Chub - *Macrhybopsis hyostoma*
8. Burrhead Chub - *Macrhybopsis marconis*
9. Sicklefin Chub - *Macrhybopsis meeki*
10. Silver Chub - *Macrhybopsis storeriana*
11. Peppered Chub - *Macrhybopsis tetranema*
12. Red River Shiner - *Notropis bairdi*
13. Smalleye Shiner - *Notropis buccula*
14. Arkansas River Shiner - *Notropis girardi*
15. Rio Grande Shiner - *Notropis jemezanus*
16. Sharpnose Shiner - *Notropis oxyrhynchus*
17. Sabine Shiner - *Notropis sabinae*
18. Pecos Bluntnose Shiner - *Notropis simus pecosensis*
19. Flathead Chub - *Platygobio gracilis*

Assemblage-level response - In a study on the Canadian River, a 76% reduction in mean annual discharge led to the replacement of the fish assemblage from one dominated by Arkansas River Shiner and Plains Minnow *Hybognathus placitus* to one formed of species (Red Shiner *Cyprinella lutrensis* and Sand Shiner *N. stramineus*) formerly associated with tributary streams (Bonner and Wilde 2000). The authors suggest the extent of fish assemblage change is related to the magnitude in alteration of the discharge, particularly during the reproductive period (Bonner and Wilde 2000).

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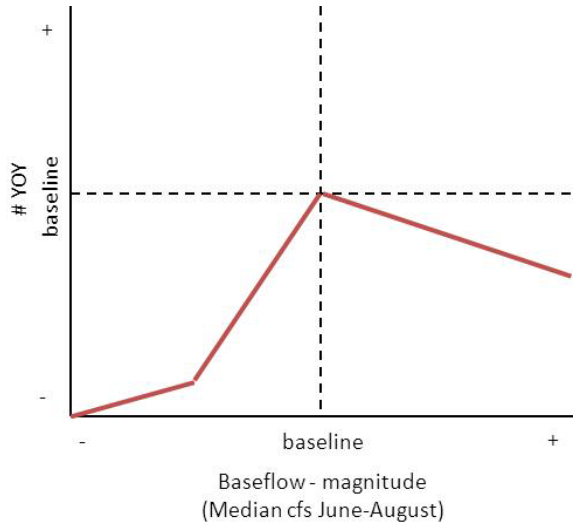

Figure 4.1. Arkansas River Shiner Seasonal Baseflow Magnitude Hypothesis F.2.a: Reproductive success (# of young of year) of Arkansas River Shiners decreases with reduced baseflow during the spawning season (June-August) as the riverine habitat becomes fragmented to isolated pools. Increased baseflow results in increased reproductive success until a threshold is reached where flows are sufficiently high to carry eggs further downstream where they may reach reservoirs or encounter an increased risk of predation.

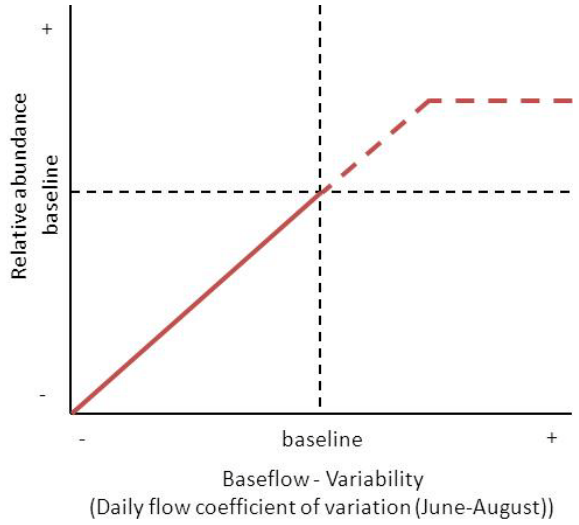

Figure 4.2. Arkansas River Shiner Baseflow Variability Hypothesis F.2.b: Abundance of Arkansas River Shiner will decrease with decrease in baseline flow variability during spawning months (June-August) due to mechanisms that are not known. An increase in flow variability above baseline may result in increased abundance of ARS until some threshold is reached.

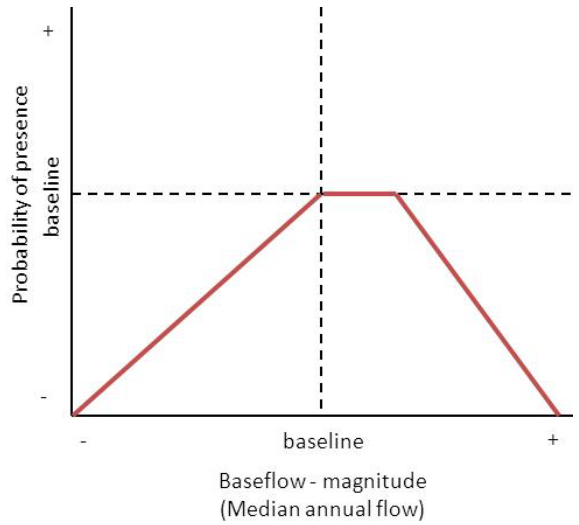

Figure 4.3. Arkansas River Shiner Annual Baseflow Magnitude Hypothesis F.2.c: The likelihood of Arkansas River Shiners being present decreases from baseline probabilities with decrease in mean annual flow due to fragmentation of habitat. The likelihood of fish presence also decreases with an increase in mean annual flow above some threshold due to increased predation on young that have been carried into reservoirs.

Chapter 5. Freckled Madtom *(Noturus nocturnus)*

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Flow-Ecology Hypothesis Species Code: F.3

STATUS: Freckled Madtom is not a federally endangered species and is not found on the International Union for Conservation of Nature (IUCN) endangered species lists; however, the species is considered endangered in some states (e.g., Iowa).

SPECIES DESCRIPTION: Freckled Madtom is small, often less than three inches long. The adipose fin is low and barely notched, and the pectoral fin spines are toothless. The species has 16-18 anal rays and 8-9 pelvic rays. The body color of Freckled Madtom is brown or gray dorsally and grades to a lighter shade, sometimes white in color, on the belly. The underside the head and body is finely speckled (Pflieger 1997, Miller and Robison 2004).

REPRODUCTION AND DEVELOPMENT: Freckled Madtom spawn from spring to early summer in riffle habitats (May-July; Illinois, Burr and Mayden 1982). The species becomes sexually mature after the first or second year of life (Burr and Mayden 1982).

RANGE AND POPULATION LEVEL: The genus *Noturus* (Madtoms) comprises 28 diminutive catfish species (Ictaluridae) of eastern North America (Willink et al. 2006) and includes Freckled Madtom. In the GCPLCC, this range includes select streams of the central and lower Mississippi valley and several tributaries of the Gulf Coast from Alabama to Texas. The species is found in both the Red and Arkansas River catchments of Oklahoma. This range encompasses roughly the eastern one-third of Oklahoma and the species occurs westward to Johnson, Marshall, and Kiowa counties (Miller and Robison 2004). There have also been multiple reports of Freckled Madtom occurring west of its known range in Oklahoma (Orth and Jones 1980, Lemmons et al. 1991).

HABITAT: Freckled Madtom is associated with riffles and shallow near-shore stream habitats (Willink et al. 2006). The species is typically found in the vicinity of undercut banks or near other forms of instream cover (Hendrickson and Cohen 2010) and tends to occur in stream areas where twigs, leaves, and other debris accumulate (Burr and Mayden 1982). Freckled Madtom typically inhabit small to medium-sized streams (Willink et al. 2006).

BIOLOGY/LIFE HISTORY: Freckled Madtom is a nocturnal feeder and uses ambush tactics. The species feeds primarily on benthic invertebrates including mayfly, black-fly, caddisfly, and midge larvae (Hendrickson and Cohen 2010). Freckled Madtom is also known to consume crustaceans (Willink et al. 2006) and other Madtom species (Burr and Mayden 1982).

THREATS: Anthropogenic activities such as damming and mining may be contributing to decreased populations of *Noturus spp*. (Wildhaber et al. 2000, Tiemann et al. 2004). Gravel-bar scalping (David and Paukert 2008) and excess sedimentation (Kemp et al. 2011) likely threaten the availability and quality of instream habitat. Freckled Madtom is considered intolerant of low-flow conditions and poor water quality (Herbert and Gelwick 2003) Invasive species also have the potential to displace native *Noturus* species (e.g., Round Goby; see Poos et al. 2009 for a review).

RESPONSE TO FLOW ALTERATION:

Species-level response – Increasing or decreasing the frequency of high-flow pulses (beyond an unknown threshold) reduces nesting habitat quality and availability. Decreased high-flow pulses leads to increased sedimentation and decreased oxygen whereas increased high-flow pulses may reduce habitat availability through increased bed scour and movement, and may increase unsuccessful spawning attempts. We also hypothesize that increases or decreases in summer baseflow (June-September) would results in decreased abundance of Freckled Madtom due to changes in shallow-habitat availability or invasion by non-native species.

Shallow areas in streams may become dry during low-flow events and reduce the amount of available habitat for Freckled Madtom (Orth and Maughan 1982, Wildhaber et al. 2000). The availability of these habitats is particularly important for madtom survival during winter and during periods of drought (Wildhaber et al. 2000, David and Paukert 2008). Increased madtom abundance has been correlated with both increased mean annual flow (David and Paukert 2008) and increased depth (Wildhaber et al. 2000). Deeper water and depth diversity is also associated with the environmental stability of streams in general (Herbert and Gelwick 2003). However, being a shallow-water fish species, a nonlinear relationship exists between increased Freckled Madtom abundance and increased depth (Orth and Maughan 1982).

- **Baseflow Hypothesis F.3.a**. Increases or decreases in summer baseflow (June-September) result in decreased abundance of Freckled Madtom due to changes in shallow-habitat availability or invasion by non-native species. (Figure 5.1)

Freckled Madtom construct nests in rocky, shallow areas with moderate to fast-flowing current. High-flow pulses flush sediment from these areas and help maintain a clean, well-aerated substrate. Orth et al. (1980) found a significant positive relationship between Weighted Usable Area (WUA) and standing

stock of Freckled Madtom, especially during summer. A decrease in the frequency of high-flow pulses leads to increased sedimentation and less oxygen availability for eggs and juvenile fish. The frequency of high-flow pulses necessary to sustain viable populations of Freckled Madtom is unknown. The decreased quality of nesting habitat is also likely to lower larval and juvenile survivorship of Freckled Madtom.

- **High Flow Pulse Frequency Hypothesis F.3.b**. Alteration of the natural frequency of high-flow pulses diminishes nesting habitat availability for Freckled Madtom. Decreased high-flow frequency may also increase sedimentation and decrease dissolved oxygen. Increased high-flow frequency increases the energy required for fish to tend nests. (Figure 5.2)

Guild-level response - Freckled Madtom belong to the guarding nest spawners or speleophil reproductive guild (Willink et al. 2006). Speleophils guard a clutch of eggs in holes or cavities (Balon 1975). Some fish species of the speleophil guild, such as Freckled Madtom, may use rootwads and undercut banks (Burr and Mayden 1982). The reduction of the duration of high flows, particularly during spawning season, will negatively influence recruitment of speleophils. High-flow events provide many fishes access to important spawning habitats (Junk et al. 1989). Undercut banks and near-shore root masses may be inaccessible during low-flow periods. Spawning areas must also be inundated for a period of time sufficient for the survival of young-of-the-year (Poff et al. 1997). Newly-hatched Freckled Madtom require approximately two months in nursery areas (Burr and Mayden 1982). Ideal conditions for Freckled Madtom recruitment would include sustained higher flows from May to September. Increased duration of high flows is likely more vital to the successful recruitment of speleophils than increased flow magnitude. In fact, extreme high-flow events have been negatively associated with speleophils (Detenbeck et al. 1992). The relationship between increased recruitment success of speleophils and high flow duration is likely nonlinear. A threshold will exist at the time period where eggs have been inundated long enough to hatch and larvae can vacate the habitat if drying occurs. Further, decreases in the frequency of flood pulses may allow sediment to accumulate and degrade spawning habitat suitable for fishes (Kemp et al. 2011).

Other speleophils in the region include (FishTraits database; www. http://fishtraits.info/; accessed March 26, 2014):
:

1. Bluntnose Minnow - *Pimephales notatus*
2. Fathead Minnow - *Pimephales promelas*
3. Bullhead Minnow - *Pimephales vigilax*
4. Tadpole Madtom - *Noturus gyrinus*
5. Speckled Madtom - *Noturus leptacanthus*
6. Brindled Madtom - *Noturus miurus*
7. Johnny Darter - *Etheostoma nigrum*

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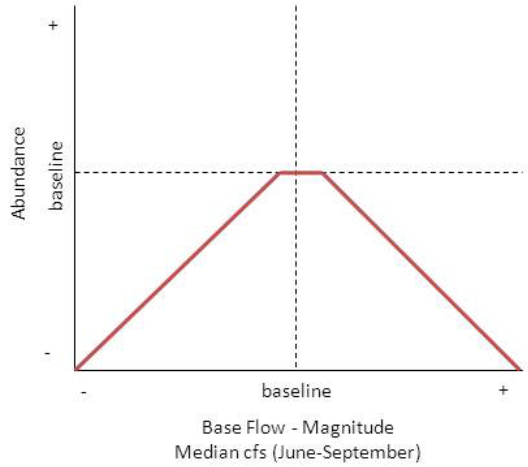

Figure 5.1. Freckled Madtom Baseflow Magnitude Hypothesis F.3.a. Increases or decreases in summer baseflow (June-September) result in decreased abundance of Freckled Madtom due to changes in shallow-habitat availability or invasion by non-native species.

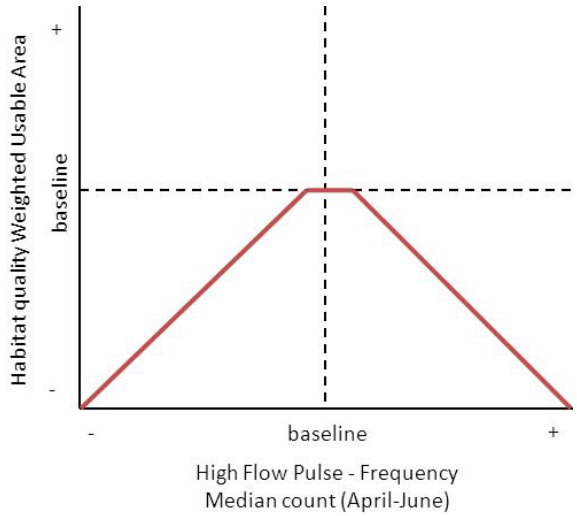

Figure 5.2. Freckled Madtom High Flow Pulse Frequency Hypothesis F.3.b. Alteration of natural frequency of high flow pulses diminishes nesting habitat quality and availability for Freckled Madtoms. Decreased frequency allows increased sedimentation and decreased oxygenation. Increased frequency increases the energy required for the fish to tend its nest.

Chapter 6. Guadalupe Bass (*Micropterus treculii*)

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Flow-Ecology Hypothesis Species Code: F.4

STATUS: Stable

SPECIES DESCRIPTION: The Guadalupe Bass is a black bass species that is generally green in color and may be distinguished from similar species found in the region in that it does not have vertical bars like Smallmouth Bass (*Micropterus dolomieu)*, its jaw does not extend beyond the eyes as in Largemouth Bass (*Micropterus salmoides*), and coloration extends much lower on the body than in Spotted Bass (*Micropterus punctulatus*; Hubbs and Bailey 1942, Hendrickson and Cohen 2010).

REPRODUCTION AND DEVELOPMENT: Both males and females are capable of reaching sexual maturity at age-1. Guadalupe Bass spawning begins as early as March and continues through May and June. A secondary spawn is possible in late summer or early fall. Guadalupe Bass prefer to nest in shallow water. However, it is unclear whether Guadalupe Bass construct nests or use natural depressions in the substrate for spawning. As with Spotted Bass and Smallmouth Bass, males tend to build nests in areas with higher flow rates than Largemouth Bass. When a male has successfully attracted a female to the nest she may lay 400 to over 9,000 eggs. The female is then chased away and the male stands guard over the incubating eggs. After hatching, fry feed on invertebrates and switch to piscivory as they grow older. Very young fish and older Guadalupe Bass adults tend to include more invertebrates in their diet than do Largemouth Bass (Edwards 1980 and Koppelman and Garrett 2003).

RANGE AND POPULATION LEVEL: Guadalupe Bass is endemic to portions of the San Antonio, Guadalupe, Colorado River and Brazos Rivers on the Edwards Plateau of central Texas (Guilory 1980, Thomas et al. 2007, Hubbs et al. 2008, Hendrickson and Cohen 2010). In addition, there is an introduced population in the Nueces River, a population in the lower Colorado River below Austin, and populations in many of the reservoirs in this region (Guilory 1980, Thomas et al. 2007, Hubbs et al. 2008, Hendrickson and Cohen 2010).

HABITAT: The species is typically associated with higher current velocities in riffle habitat types (Edwards 1980, Perkin et al. 2010), but older individuals may shift to runs and even pools (Groeschel 2013). As such, Guadalupe Bass populations are dependent upon a relatively undisturbed mosaic of stream habitats (Perkin et al. 2010) and may represent a riffle-run dependent guild of fish species.

BIOLOGY/LIFE HISTORY*:* Guadalupe Bass are adapted to small streams and fast flowing water (Edwards 1980, Koppelman and Garrett 2003) and do not grow to very large size (maximum total length 450-460 mm).

THREATS: Guadalupe Bass may be particularly susceptible to the threat of flow alteration because most of its range is immediately upstream of some of the fastest-growing urban areas in the United States. The population of the Dallas-Fort Worth-Austin-San Antonio corridor is expected to double over the next 25-50 years, placing increased demands on the aquifers and watersheds of the Edwards Plateau (Texas Water Development Board 2012) and altering land use patterns throughout the region. The spring-fed streams and rivers of the Brazos River, Colorado River, San Antonio River, and Guadalupe River watersheds on the Edwards Plateau are all likely to experience flow alterations due to increasing demands being placed on both these streams and the Edwards Aquifer, which supplies them (Texas Water Development Board 2012).

Furthermore, most Guadalupe Bass populations have experienced severe introgressive hybridization with introduced Smallmouth Bass (Whitmore et al. 1982, Whitmore 1983, Bean 2012). The consequences of this hybridization on the sensitivity of affected populations to disturbance are unknown (Bean 2012).

RESPONSE TO FLOW ALTERATION:

Species-level response: The response of Guadalupe Bass to flow alteration is largely unknown and is an area of active investigation. However, it is reasonable to expect that its response would be similar to that of other species with similar habitat use patterns, life-history, and reproductive ecology. In particular, hydrological alterations resulting in persistent changes to the availability, productivity, connectivity, or accessibility of riffle-run complexes are likely to have negative consequences to the persistence of Guadalupe Bass populations.

Reduced low flow conditions associated with agricultural and municipal water withdrawals and exacerbated by drought conditions can alter the availability, productivity, connectivity, or accessibility of riffle-run complexes. Guadalupe Bass growth exhibits a negative correlation with the annual proportion of flow observations classified as extreme low flows (Groeschel 2013). Changes in availability, productivity, or accessibility of these preferred Guadalupe Bass habitats may force individuals into pool habitats and increase the potential for predation by or competition with Largemouth Bass (*Micropterus salmoides)*. Furthermore, the availability of insect drift, a potentially important component of the diets of younger Guadalupe Bass (Edwards 1980, Garrett 1991, Edwards 1997), may be reduced.

The effects of flow conditions on the recruitment and reproductive success of Guadalupe Bass has not been investigated. However, recruitment in congeners with similar reproductive strategies, such as Smallmouth Bass (*Micropterus dolomieu)* and Shoal Bass (*Micropterus cataractae)*, exhibit a negative correlation to the frequency and magnitude of high flow pulses when brooding eggs and juveniles in nests (Lukas and Orth 1995, Smith et al. 2005, Bitz et al. 2013). In addition, high flow pulses may flush young bass from their nests.

- **Extreme Low Flow Duration Hypothesis F.4.a.** Altered extreme low flows (<Q90) can alter the availability, productivity, connectivity, or accessibility of riffle-run complexes used by Guadalupe Bass. Growth rates of Guadalupe Bass are reduced with increased duration of extreme low flow events. (Figure 6.1)

- **Baseflow Magnitude Hypothesis F.4.b**. Alteration of mean annual flow diminishes the quality and availability of Guadalupe Bass habitat. Guadalupe Bass are strongly associated with riffle and run habitats and are more dependent upon drifting insects and insect larvae than other black bass species. The quality and availability of Guadalupe Bass habitat therefore likely increases with increasing flows. However at some point, flows become high enough that the increased current velocities reduce the quality (energetically expensive to maintain position) or availability (velocities too high to maintain position) of Guadalupe Bass habitat. (Figure 6.2)
- **High Pulse Flow Frequency Hypothesis F.4.c**. Alteration of high flow pulse frequency alters reproductive success of Guadalupe Bass. Like most centrarchids, Guadalupe Bass build and defend nests while spawning. These nests tend to be placed in shallow, sheltered areas adjacent to the main flow of the stream. Increases in high pulse flow frequency during the nesting season increases energy requirements of guarding adults to stay near the nest and decreases reproductive success. Reproductive success may increase with a decrease in high flow pulse frequency during the nesting season. (Figure 6.3)

Guild-level response: Other species dependent upon or associated with undisturbed riffle-run complexes are likely to exhibit a response to flow alterations similar to Guadalupe Bass (Lee et al. 1980, Thomas et al. 2007, Hubbs et al. 2008, Hendrickson and Cohen 2010). These species include:

1. Texas Logperch - *Percina carbonaria*, (endemic)
2. Greenthroat Darter - *Etheostoma lepidum*, (endemic)
3. Fountain Darter - *Etheostoma fonticola* (endemic, endangered)
4. Blacktail Shiner - *Cyprinella venusta*,
5. Texas Shiner - *Notropis amabilis,*
6. Central Stoneroller - *Campostoma anomalum*,
7. Gray Redhorse - *Moxostoma congestum*,
8. Guadalupe Roundnose Minnow - *Dionda nigrotaeniata*,
9. Flathead Catfish - *Pylodictis olivaris*,
10. Orangethroat Darter - *Etheostoma spectabile*,
11. Mexican Tetra - *Astyanax mexicanus*, and
12. Rio Grande Cichlid - *Herichthys cyanoguttatus*.

Assemblage-level response: Guadalupe Bass is a middle to high trophic level predator (Edwards 1980, Garrett 1991, Edwards 1997) and is likely an important link within aquatic food webs and between aquatic and terrestrial food webs. Impacts to the guild of species dependent upon or associated with riffle-run complexes would potentially represent a dramatic shift in the functionality of the stream system. However, no changes in faunal assemblage have been attributed to the replacement of Guadalupe Bass with Guadalupe Bass-Smallmouth Bass hybrids in systems with substantial introgression rates.

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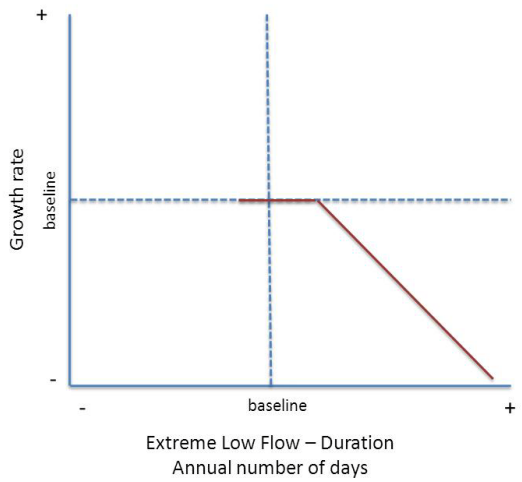

Figure 6.1. Guadalupe Bass Extreme Low Flow Duration Hypothesis F.4.a: Altered extreme low flows (<Q90) can alter the availability, productivity, connectivity, or accessibility of riffle-run complexes used by Guadalupe Bass. Growth rates of Guadalupe Bass are reduced with increased duration of extreme low flow events.

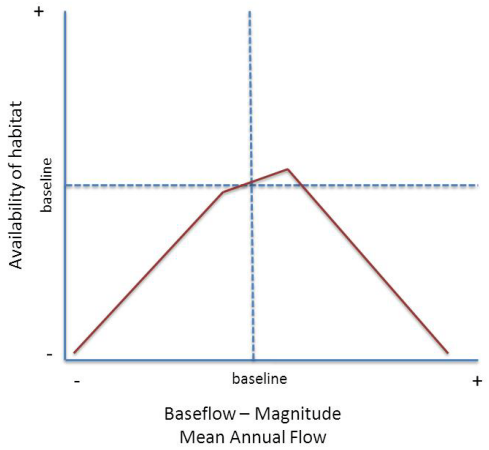

Figure 6.2. Guadalupe Bass Baseflow Magnitude Hypothesis F.4.b: Alteration of mean annual flow diminishes the quality and availability of Guadalupe Bass habitat. Guadalupe Bass are strongly associated with riffle and run habitats and are more dependent upon drifting insects and insect larvae than other black bass species. The quality and availability of Guadalupe Bass habitat, therefore, likely increases with increasing flows. However at some point, flows become high enough that the increased current velocities reduce the quality (energetically expensive to maintain position) or availability (velocities too high to maintain position) of Guadalupe Bass habitat.

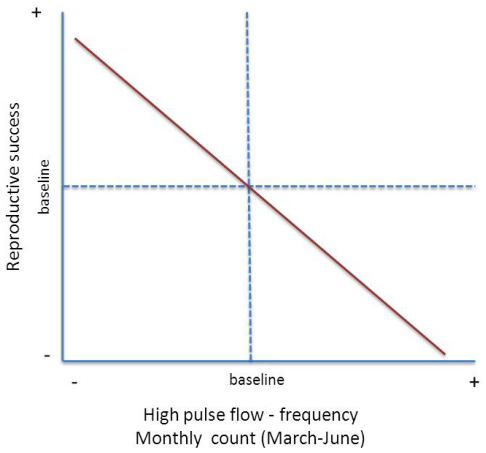

Figure 6.3. Guadalupe Bass High Pulse Flow Frequency Hypothesis F.4.c: Alteration of high flow pulse frequency alters reproductive success of Guadalupe Bass. Like most centrarchids, Guadalupe Bass build and defend nests while spawning. These nests tend to be placed in shallow, sheltered areas adjacent to the main flow of the stream. Increases in high pulse flow frequency during the nesting season increases energy requirements of guarding adults to stay near the nest and decreases reproductive success. Reproductive success may increase with a decrease in high flow pulse frequency during the nesting season.

Chapter 7. Orangethroat Darter (*Etheostoma spectabile*)

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Flow-Ecology Hypothesis Species Code: F.5

STATUS: Populations in the southern United States are currently stable (Warren et al. 2000).

SPECIES DESCRIPTION: An average-sized (maximum of 64 mm standard length; Kuehne and Barbour 1983), colorful (especially breeding males), and robust darter with 6-10 crossbars on the back (Pflieger 1997). Lateral line is incomplete and 38-57 scales span the length of the body (Pflieger 1997). Orangethroat Darter is variable in appearance with numerous subspecies recognized (Pflieger 1997).

REPRODUCTION AND DEVELOPMENT: Spawning season varies with latitude and other environmental factors (e.g., springflow). Length of the spawning season in the GCP LCC region may last three (Missouri populations: Pflieger 1997) to seven months (Texas population: Reviewed by Hubbs 1985). Orangethroat darters are lithophils that spawn over or within rock and gravel crevices and do not guard their eggs. Large eggs are buried in gravel depressions or interstitial spaces of rocks (Page 1985, Simon 1999). Spawning occurs within and below shallow gravel riffles (10-35 cm; Winn 1958) with moderate flows (Edwards 1997), as well as in fine substrate in areas with very little to no flows (i.e. shallow backwaters, edgewaters, and pools; B. Brown, personal communication).

RANGE AND POPULATION LEVEL: Orangethroat Darter ranges from Michigan west to Colorado and south to Texas and Tennessee. Orangethroat Darter is one of the most frequently encountered darter species in Ozark and prairie tributaries of the lower Missouri and upper Mississippi rivers. It is found in the highland regions of Oklahoma in both the Red River and Arkansas drainages. (Miller and Robison 2004) and also the Wichita Mountains in southwest Oklahoma (B. Brown, personal communication).

Habitat- Orangethroat Darter use gravel to cobble substrates in relatively clear headwater streams (Pflieger 1997, Musselman and Brewer 2009) with moderate flow (Etnier 1994, Pflieger 1997). This species has been shown to be negatively associated with mud and silt substrates (Berkman and Rabeni 1987, Anderson et al. 1995), though Trautman (1957) indicates it becomes more abundant than Rainbow Darter(*E. caeruleum)* when turbidity increases. Habitat use varies by season and life stage. Adults often occupy riffles during the spawning season but use of pools is disproportionate during the winter with riffles only used by the larger adults during that period (Musselman and Brewer 2009). The species is often associated with some form of cover (large substrates: Page 1985, Musselman and Brewer 2009; undercut or woody banks: Etnier and Starnes 1993; vegetation: Kuehne and Barbour 1983).

BIOLOGY/LIFE HISTORY*:* Spawning occurs for three to seven months beginning as early as November in Texas streams (Hubbs and Armstrong 1962). Spawning in Oklahoma is thought to occur from late February to May (Miller and Robison 2004), similar to other more northern populations (Pfliefer 1997, see also review by Hubbs 1985). Females release and bury their eggs on clean substrates (Balon 1975) in riffles (Winn 1958, Kuehne and Barbour, 1983). Young-of-year darters are thought to move to pool habitats during extreme cold (first overwinter period); however, older darters that have obtained a larger size appear to be able expend the energy needed to occupy riffle habitats (Craig 1987). Pflieger (1966) reported larvae occupying nests of Smallmouth Bass *(Micropterus dolomieu)* where they are apparently afforded some protection against small predators, and are able to find an abundance of food items.

THREATS: Orangethroat Darter is threatened by impacts to habitat quality and availability due to excess sedimentation, excessive water withdrawals, dams, and thermal pollution.

RESPONSE TO FLOW ALTERATION:

Species-level response – Changes in habitats occur in the stream with alterations in baseflow, thereby affecting availability and quality of habitat for Orangethroat Darter. Young of year select habitat along stream edges in shallow pools. A decrease in baseflow magnitude during summer months may lead to a loss in suitable habitat. A reduction in the magnitude of base flow can cause an increase in fine sediment that will fill the interstitial spaces of substrates (Poff et al. 1997) that Orangethroat Darters use for spawning. The increase in siltation could cause increased egg mortality, decreased available spawning habitat (Berkman and Rabeni 1987), and decreased macroinvertebrate food sources (Rabeni et al. 2005). In addition, as baseflow magnitude decreases, water temperature increases thereby creating a situation where Orangethroat Darter fitness may decline (thermal tolerances; Smale and Rabeni 1995, Beitinger et al. 2000). More tolerant species such as Red Shiner, and Green Sunfish could dominate with increased water temperatures (Jester et al. 1992). Increasing baseflow magnitude would likely favor non-native species that have the potential to outcompete native darters.

- **Base Flow Duration Hypothesis F.5.a.** The abundance of Orangethroat Darter is reduced with decreased monthly baseflow magnitude during the summer as water temperatures increase, and aeration of substrates and availability of habitat decreases. Increased baseflow magnitude during summer may result in decreased abundance due to competition with other natives (e.g.,

Rainbow Darter *Etheostoma caeruleum*; Pflieger 1997) or non-native species that favor higher baseflow conditions. (Figure 7.2)

Guild-level response – Darters and other lithophils (59 other freshwater fishes in the U.S.) are generally fluvial specialists that need flowing water (Frimpong and Angermeier 2009). Lithophils are anticipated to be impacted by several components of flow. Specifically, changes in the flow regime that affect the quality and availability of clean, aerated substrates can lead to declines in flow-sensitive species. With the loss of fluvial specialists, more tolerant fish species may become dominant (Freeman and Marcinek 2006). At the community level, declines in native species diversity may allow invasives to establish with more ease (Elton 1958, Fargione et al. 2003), which further confounds conservation of natives.

Spawning by lithophils is the life-history component most likely to be negatively affected by flow alteration. Spawning activities by members of this guild rely on crevices of rock and gravel that are relatively free of sediment (Berkman and Rabeni 1987, Sutherland et al. 2002). These characteristics are typical of riffle and run habitat in many streams. Thus, flow prior to and during the spawning months must be of sufficient magnitude to keep spawning habitats aerated and eggs free of excess sediment to prevent egg suffocation (Kemp et al. 2011). However, if the magnitude of the high flow pulse increases above normal baseline, we anticipate negative impacts to spawning success because of nest damage or mechanical abrasion between eggs and substrate (Erman et al. 1988). Also, riffles become depositional areas during high-flow events (Keller 1971) and deposited fine sediments in the spawning area may smother or bury deposited eggs (Kemp et al. 2011). As with Orangethroat Darter, other lithophils may be affected by changes in monthly low flow durations during summer.

Examples of other lithophilic species in the GCP LCC region (FishTraits database; www.http://fishtraits.info/; accessed April 24, 2014) include the

1. Blackspotted Top Minnow-*Fundulus olivaceous*
2. Northern Hog Sucker-*Hypentelium nigricans*
3. Spotted Sucker-*Minytrema melanops*
4. River Redhorse-*Moxostoma carinatum*
5. Black Redhorse-*Moxostoma duquesnei*
6. Wedgespot Shiner-*Notropis greenei*
7. Pearl Darter -*Percina aurora*
8. Slim Minnow-*Pimephales tenellus*
9. Alabama Shad-*Alosa alabamae*
10. White Sucker-*Catostomus commersonii*
11. Creek Chub-*Semotilus atromaculatus*
12. Brighteye Darter-*Etheostoma lynceum*
13. Clear Chub-*Hybopsis winchelli*
14. Golden Redhorse-*Moxostoma erythrurum*
15. Blacktail Redhorse-*Moxostoma poecilurum*
16. Arkansas River Shiner-*Notropis girardi*

17. Bigeye Shiner-*Notropis boops*
18. Longnose Shiner-*Notropis longirostris*
19. Silverband Shiner-*Notropis shumardi*
20. Suckermouth Minnow-*Phenacobius mirabilis*
21. Central Stoneroller-*Campostoma anomalum*
22. Largescale Stoneroller-*Campostoma oligolepis*
23. Orangethroat Darter-*Etheostoma spectabile*
24. Chestnut Lamprey-*Ichthyomyzon castaneus*
25. Cardinal Shiner-*Luxilus cardinalis*
26. Striped Shiner-*Luxilus chrysocephalus*
27. Texas Logperch-*Percina carbonaria*
28. Leopard Darter-*Percina pantherina*
29. Speckled Darter-*Etheostoma stigmaeum*
30. Gulf Darter-*Etheostoma swaini*
31. Southern Brook Lamprey-*Ichthyomyzon gagei*
32. Common logperch-*Percina caprodes*
33. Dusky Darter-*Percina sciera*
34. River Darter-*Percina shumardi*
35. Redspot Chub-*Nocomis asper*
36. Bluehead Chub-*Nocomis leptocephalus*

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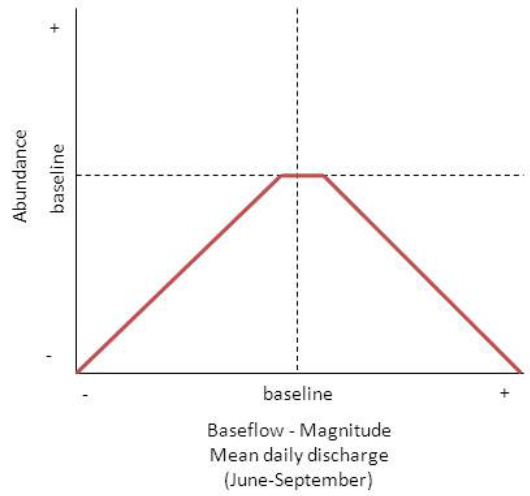

Figure 7.2. Orangethroat Darter Baseflow Magnitude Hypothesis F.5.a: The abundance of Orangethroat Darter declines with increased monthly low-flow magnitude during the summer as water temperatures increase, aeration of substrates decrease, and availability of habitat declines. Decreases in monthly low-flow magnitude during summer may result in decreased abundance due to competition with non-native species.

Chapter 8. Suckers (particularly *Moxostoma* spp.)

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Flow-Ecology Hypothesis Species Code: F.6

STATUS: Generally considered stable within the boundaries of the Gulf Coast Prairie LCC, though there is little information available to adequately assess the status of most species. Several species are listed as being of conservation concern, e.g., Blue Sucker (*Cycleptus elongates).*Throughout North America, many sucker species are regionally threatened and an increasing number are listed as federally threatened or endangered (Cooke et al. 2005).

SPECIES DESCRIPTION: There are at least 76 recognized species of suckers within the family Catostomidae characterized by their fleshy, protrusible lips usually located sub-terminally which they use to feed upon benthic invertebrates, algae, and detritus (Smith 1992, Etnier and Starnes 1993, Jenkins and Burkhead 1994). Suckers are closely related to the minnows and carps (Family Cyprinidae) and many species superficially resemble carp in body shape and general behavior, though there is a wide range of body shapes and sizes within the family (Smith 1992). Suckers may comprise a large proportion of freshwater fish assemblages in terms of the number of individuals and can account for a high percentage of fish biomass in rivers and streams (Bunt and Cooke 2001).

REPRODUCTION AND DEVELOPMENT: Suckers are generally non-guarders and lithophilic, broadcast spawners (Balon 1975, Frimpong and Angermeier 2009). They may form large spawning aggregations in shallow riffles and runs.

RANGE AND POPULATION LEVEL: The sucker family is widely distributed throughout the rivers, streams, and lakes of North America and (Lee et al. 1980, Smith 1992) and as such display a wide range of specializations in morphology, behavior, and life-history strategies (Smith 1992, Etnier and Starnes 1993, Jenkins and Burkhead 1994).

HABITAT: Suckers are generally found in rivers, but can occur in lakes and reservoirs. While the species composition changes along the length of a riverine system (Smith 1992), suckers can be found in most stream types from the headwater streams to the highest stream-order rivers. Contrary to common misconceptions, healthy sucker populations are generally indicative of healthy, intact freshwater ecosystems and not degraded conditions (Cooke et al. 2005).

BIOLOGY/LIFE HISTORY*:* Suckers feed by "vacuuming up" invertebrates and clams on river bottoms, and generally do not thrive in heavily silted or anaerobic river bottoms. Their food ranges from detritus and bottom dwelling organisms (such as crustaceans and worms), to surface insects and small fishes. They may make mass upstream spawning migrations in the early spring. Telemetry studies suggest that most catostomid species are sedentary and strongly oriented to a benthic existence.

THREATS: Sucker populations throughout North America are threatened by numerous stressors, including habitat fragmentation and degradation, flow alteration, environmental contamination, and introduced species, usually acting in concert (Cooke et al. 2005).

RESPONSE TO FLOW ALTERATION:

Species-level response – A total of 14 species of suckers has been reported from waters within the boundaries of the GCP LCC (Lee et al. 1980, Miller and Robison 2004, Thomas et al. 2007, Hubbs et al. 2008, Hendrickson and Cohen 2010):

1. River Carpsucker - *Carpiodes carpio*
2. Quillback - *Carpiodes cyprinus*
3. Highfin Carpsucker - *Carpiodes velifer*
4. Blue Sucker - *Cycleptus elongatus*
5. Southeastern Blue Sucker - *Cycleptus meridionalis*
6. Lake Chubsucker - *Erimyzon sucetta*
7. Smallmouth Buffalo - *Ictiobus bubalus*
8. Bigmouth Buffalo - *Ictiobus cyprinellus*
9. Black Buffalo - *Ictiobus niger*
10. Spotted Sucker - *Minytrema melanops*
11. Gray Redhorse - *Moxostoma congestum*
12. Black Redhorse - *Moxostoma duquesnei*
13. Golden Redhorse - *Moxostoma erythrurum*
14. Shorthead Redhorse - *Moxostoma macrolepidotum*

A fifteenth species is likely to be recognized in the near future, as the Rio Grande populations of Blue Sucker receive recognition as a distinct species (Buth and Mayden 2001, Bessert 2006). However, virtually nothing is known about the status of these species, or their response to flow alteration. That said, sucker populations throughout North America are threatened by numerous stressors, including habitat fragmentation and degradation, flow alteration, environmental contamination, and introduced species, usually acting in concert (Cooke et al. 2005). It is worth noting that these same stressors also are common issues in watersheds within the Gulf Coastal Prairie ecoregion.

In general suckers seem to be negatively affected by decreases in baseflow and the frequency, duration, and magnitude of flood events. Low flows during the spawning season can reduce the availability or quality of spawning habitats (Grabowski and Isely 2007, 2007b), potentially leading to nest site superimposition and reduced reproductive output (Grabowski and Isely 2007b). Several studies have linked depressed growth rates and/or recruitment to low flows and a lack of access to off-channel habitats (Dutterer et al. 2012, Grabowski et al. 2012). Furthermore, small scale fluctuations in discharge associated with regulated rivers also can result in dramatic changes in spawning habitat quality and quantity (Grabowski and Isely 2007), while larger scale fluctuations associated with hydropower generation, e.g., “hydropeaking,” can result in mortality of early life history stages (Weyers et al. 2003). Increases in the frequency and magnitude of high flow pulse events can negatively impact the development and survival of larva by flushing downstream (Robust Redhorse *Moxostoma robustum:*

Ruetz and Jennings 2000; Shorthead Redhorse: DePhilip and Moberg 2010) or by negatively affecting growth (carpsuckers *Carpiodes* spp.: Peterson and Jennings 2007).

Alterations to the timing, duration, or frequency of flood events have the potential to disrupt spawning cues (Bunn and Arthington 2002), render fish passage through natural or anthropogenic barriers difficult or even impossible (Bunn and Arthington 2002), or render spawning habitats unsuitable (Grabowski and Isely 2007). In large rivers, adults may enter off-channel, floodplain habitats during flooding events, but return to channel with receding water levels (Robust Redhorse, Grabowski and Isely 2006, Grabowski and Jennings 2009). It is unclear whether this is solely to take refuge from high current velocities or if the fish are accessing new food resources made available by the high water.

In general, flow alterations may also affect suckers by creating conditions favorable to introduced species, potentially leading to higher levels of competition or predation (Cooke et al. 2005), as well as result in dramatic, long-term shifts in substrate composition, habitat availability, and productivity patterns (Poff et al. 1997, Bunn and Arthington 2002). Elevated turbidity levels associated with altered flows due to changing land use practices and erosion patterns have been implicated in the extinction of at least one sucker species, Harelip Sucker (*Moxostoma lacerum*; Etnier and Starnes 1993), and the decline of several others, most notably Robust Redhorse (*Moxostoma robustum*; Bryant et al. 1996).

The availability and quality of shallow water, coarse substrate habitats that seem to be the preferred spawning location for many sucker species (Page and Johnston 1990), as well as off-channel, floodplain habitats and in-channel sand bar habitats that may be important nursery habitats, are all potentially impacted on both short and long time scales by flow alterations. Connectivity within a watershed tends to be reduced under altered flow conditions, resulting in changed nutrient and sediment transport patterns.

- **Baseflow Magnitude Hypothesis F.6.a.** Altered monthly low flow discharge from February through May reduces the quality and availability of sucker spawning habitat. Spawning habitat availability and quality is related to discharge. At low flows, water flow may not be sufficient to keep the gravel substrates used for spawning free of silt resulting in mortality. At higher flows, current velocities may make it energetically expensive for individuals to participate in spawning aggregations. (Figure 8.1)
- **Baseflow Magnitude Hypothesis F.6.b.** Altered mean annual flow reduces growth rates of young of the year and juvenile suckers. Growth rates of young-of-year and juvenile Redhorses may be negatively correlated with low flow events (Grabowski et al. 2012). However, growth is positively correlated to increasing proportion of high flows (i.e., flows < Q_{10} but >Q_{25}). This relationship does not hold for all catostomids. (Figure 8.2)
- **High Flow Pulse Magnitude Hypothesis F.6.c.** Altered magnitude of high flow events alters sucker larval survival rates. Increase of extreme high flow events (frequency and magnitude) can negatively impact the development and survival of larva by flushing downstream (Shorthead Redhorse, DePhilip and Moberg 2010). (Figure 8.3)
- **Overbank Flow Frequency Hypothesis F.6.d.** Decreases in the frequency of overbank events reduce the condition of adult suckers. This is a hypothetical relationship between adult

condition and overbank events for a species that is using its access to floodplain habitats for feeding. (Figure 8.4)

Guild-level response Most lithophillic broadcast-spawning and egg-depositing species, i.e., species dependent upon gravel or cobble substrates in shallow, flowing water for successful reproduction (Balon 1975; Frimpong and Angermeier 2009) are likely to exhibit similar responses. Potamodromous species and/or those dependent upon access to off-channel floodplain habitats or other specialized habitat within the river to complete their life histories also are likely to exhibit similar responses.

Assemblage-level response - The overall faunal assemblage would suffer a decline in diversity and likely see a change in the trophic structure as the biomass locked up in suckers was distributed amongst other species.

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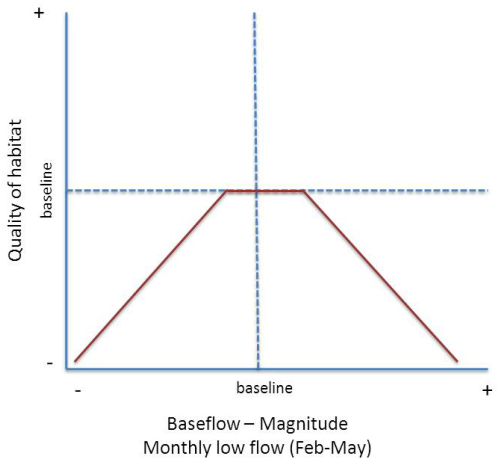

Figure 8.1. Sucker Seasonal Baseflow Magnitude Hypothesis F.6.a: Altered monthly low flow discharge from February through May reduces the quality and availability of sucker spawning habitat. Spawning habitat availability and quality is related to discharge. At low flows, water flow may not be sufficient to keep the gravel substrates used for spawning free of silt resulting in mortality. At higher flows, current velocities may make it energetically expensive for individuals to participate in spawning aggregations.

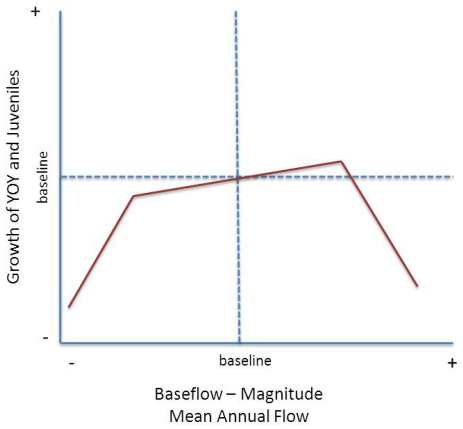

Figure 8.2. Sucker Annual Baseflow Magnitude Hypothesis F.6.b: Altered mean annual flow reduces growth rates of young of the year and juvenile suckers. Growth rates of young-of-year and juveniles Redhorses may be negatively correlated with low flow events (Grabowski et al. 2012). However, growth is positively correlated to increasing proportion of high flows (i.e., flows < Q_{10} but >Q_{25}). This relationship does not hold for all catostomids.

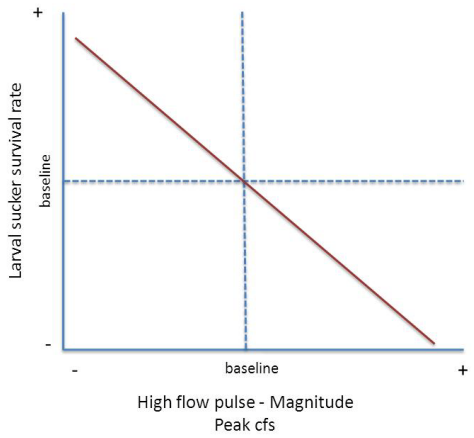

Figure 8.3. Sucker High Flow Pulse Magnitude Hypothesis F.6.c: Altered magnitude of high flow events alters sucker larval survival rates. Increase of extreme high flow events (frequency and magnitude) can negatively impact the development and survival of larva by flushing downstream (shorthead Redhorse, DePhilip and Moberg 2010).

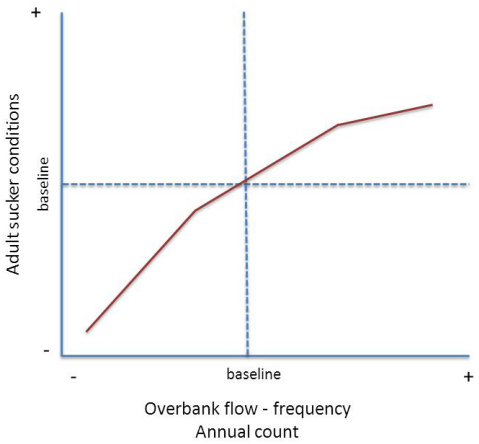

Figure 8.4. Sucker Overbank Flow Frequency Hypothesis F.6.d: Decreases in the frequency of overbank events reduces the condition of adult suckers. This is a hypothetical relationship between adult condition and overbank events for a species that is using its access to floodplain habitats for feeding.

Chapter 9. Steamboat Mucket (*Actinonaias ligamentina*)

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Flow-Ecology Hypothesis Species Code: M.1

STATUS: Assessed by IUCN as Least Concern because it has a large distribution, Steamboat Mucket is considered stable across its range and not impacted by any major threat processes. (Cordeiro 2011)

SPECIES DESCRIPTION: The Steamboat Mucket's shell is oblong, moderately thick, up to 15 cm (6 in.) long, and the posterior is sometimes bluntly pointed. The outside of the shell is yellowish to dark brown, with wide green rays often present, especially in young mussels. The beak sculpture is largely absent, and the pseudocardinal teeth are heavy and triangular. The mucket resembles the male Fat Mucket (*Lampsilis siliquoidea*) and the male Plain Pocketbook (*L. cardium*), but can be distinguished from these species by its uniformly oblong shape, heavier pseudocardinal teeth, and lack of beak sculpture (Sietman 2003, Haag 2012).

REPRODUCTION AND DEVELOPMENT: Mussels have a complex and distinctive reproductive cycle. Males release sperm into the water, which are drawn in by females through their incurrent siphon. Fertilized eggs are brooded in the female's gills, where they develop into tiny larvae called glochidia. The mucket is bradytictic or longterm brooder, with females brooding their young long-term, from August through May, before they are released as glochidia (Parmalee and Bogan 1998). Once the glochidia are expelled from the female's gills, they attach to fish gills or fins by clamping onto them with their valves. The glochidia live as parasites on the host fish until they develop into juvenile mussels, at which point they detach from the fish and fall to the streambed as free-living mussels. Fish hosts for the mucket's glochidia include crappies (*Pomoxis* spp.), sunfish (*Lepomis* spp.), and bass (*Micropterus* spp.; Watters 1994). Watters (1994) lists twelve different fish hosts for the glochidia of this species (Cordeiro 2011).

Specifics of gravidity, fecundity, and fertilization success of this species were examined by Moles and Layzer (2008) below the Green River Dam in Kentucky. They observed females undergoing a resting stage, which suggested that this species might not become gravid every year. Fecundity increased with distance from the dam. High fertilization rates observed in the upstream portions of mussel beds indicated that females are not necessarily dependent upon nearby males for fertilization. Steamboat muckets had successful fertilization despite low mussel densities indicating that host fish and suitable conditions for juvenile survival and growth were present.

RANGE AND POPULATION LEVEL: The Steamboat Mucket is widely distributed and found throughout the Mississippi River system, with the exception of extreme southern and western reaches. It is known from Alabama, Arkansas, Illinois, Indiana, Iowa, Kentucky, Michigan, Minnesota, Missouri, Ohio, Oklahoma, Pennsylvania, Tennessee, Virginia, West Virginia and Wisconsin. NatureServe (2009) have

classified it as critically imperiled in Kansas, Mississippi, and New York, and possibly extirpated in Louisiana (Cordeiro 2011). It occurs in small to medium rivers, typically in gravel shoals. In the Gulf Coastal Plain and Ozarks (GCPO) LCC it is known from the Glover, Kiamichi, Little, Mountain Fork and Poteau Rivers and Fourteen Mile Creek in Oklahoma, the Arkansas, Cache, Ouachita, Poteau, Saint Francis and White Rivers in Arkansas, and the Tensas River in Louisiana. It does not occur in the Gulf Coast Prairie (GCP) LCC in Oklahoma (NatureServe 2012; Vaughn 2000)

HABITAT: This species is found at depths of 1 m or less in riffles with strong current but also quiet water in streams. The preferred substrates range from cobble and gravel to sand or mud bottoms (Parmalee and Bogan 1998).

BIOLOGY/LIFE HISTORY*:* Mussels are long-lived animals. Members of many species may live for several decades and in some instances, a century or more (Haag and Rypel 2011). They spend most of their lives buried in the bottom sediments of permanent water bodies, and often live in multi-species communities called mussel beds (Strayer 2008, Haag 2012).

Mussels are primarily sedentary, but they can move around with the use of their "foot", which is a hatchet shaped muscle that can be extended out between the valves (shells). A mussel will burrow its foot into the sediment and then contract it to pull itself slowly along the bottom of its aquatic habitat (Sietman 2003).

Mussels are suspension feeders that use their enlarged gills to filter material suspended in the water, primarily algae, but also bacteria, protozoans, and other organic matter (Vaughn 2009). They draw water into their body through their incurrent siphon, remove food and oxygen with their gills, and then expel the filtered water through their excurrent siphon. Food particles are carried to the mussel's mouth by tiny hairlike cilia located on the gills. Waste is expelled through the excurrent siphon (McMahon and Bogan 2001).

THREATS: The Steamboat Mucket mussel was once extremely important in the pearl button industry. As the mussel is now found alive in only a small number of drainages, it is vulnerable to habitat degradation and catastrophic events. The continued persistence of mucket populations in many rivers is threatened by the hydrologic alteration of streams and their watersheds; the continuing decline in habitat conditions associated with river management as a navigation canal; and water and sediment pollution from non-point and point sources. Dams, channelization, and dredging increase siltation, physically alter habitat conditions, and block the movement of fish host (Allen et al. 2013, Galbraith et al. 2010).

RESPONSE TO FLOW ALTERATION:

Species-level response - Because adult mussels are sedentary and relatively immobile, all species are affected by altered flows and the accompanying changes in water temperature and dissolved oxygen. However, some species are more sensitive to these changes than others. The physiological ecology of muckets was studied by Spooner and Vaughn (2008). They found that muckets are sensitive to high water temperatures and they classified them as “thermally sensitive” species. Specifically, at warm

water temperatures (35°C in their study) muckets become so stressed that they catabolize their tissue, resulting in high ammonia excretion rates, decreased filtration and poor body condition. Warm water temperatures are common in rivers in the GCP LCC and GCPO LCC during the summer months when flows are low, particularly in drought conditions. Galbraith et al. (2010) found that in the Kiamichi River, Oklahoma, water temperature is directly related to water depth and air temperature. During a multi-year drought in the early 2000s, more thermally sensitive species, including muckets, died than thermally tolerant species and mortality rates were directly related to water depth. Because muckets are so sensitive, they makes a good "model mussel" to protect other mussel species.

- **Extreme Low flow Magnitude Hypothesis M.1.a:** Reduced magnitude of extreme low flows (Q10) during summer months leads to increased water temperature, decreased body condition and eventual death of *A. ligamentina*. (Figure 9.1)
- **Extreme Low flow Duration Hypothesis M.1.b:** *A. ligamentina* body condition decreases and mortality increases under increased duration of extreme low flows (Q10) which do not maintain access to mussel habitat and interrupt delivery of high quality food and access to fish hosts. (Figure 9.2)

Guild-level response – Muckets are typical of all mussels in that delivery of food and maintenance of habitat quality is critical to healthy populations. Base flows carry high quality food. Higher flows keep sediment from accumulating in mussel beds. Increased duration of subsistence or extreme low flows decreases the time periods when food is delivered and sediments flushed.

Assemblage-level response – Mussels can comprise a large portion of the faunal biomass in rivers. Historic studies and anecdotes record mussel beds dense enough that one could not walk for stepping on mussels. Their effect on energy transfer, water quality and nutrient cycling can be substantial (Vaughn et al. 2008; Atkinson et al. 2013). They are an important link in the food chain as prey for suckers and other benthic dwelling species (Haag 2012). The loss of mussels and other sedentary, filter-feeding macroinvertebrates in a river can cause significant changes in the physical, chemical, and biological characteristics of the site (Vaughn 2010).

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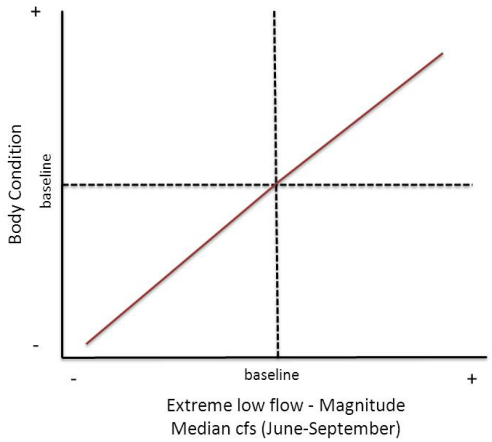

Figure 9.1. Mussel Extreme Low Flow Magnitude Hypothesis M.1.a: Reduced magnitude of extreme low flows (Q10) during summer months leads to increased water temperature, decreased body condition and eventual death of Steamboat mucket.

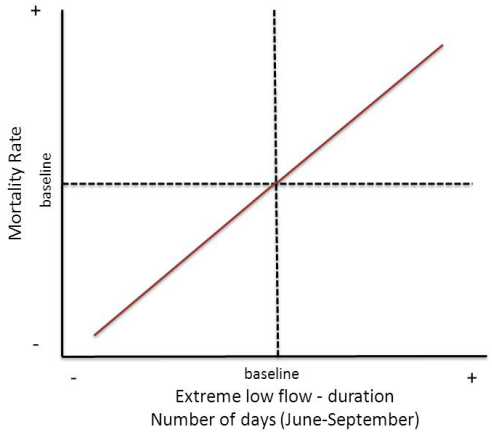

Figure 9.2. Mussel Extreme Low Flow Duration Hypothesis M.1.b: Steamboat mucket body condition decreases and mortality increases under increased duration of extreme low flows (Q90) which do not maintain access to mussel habitat and interrupt delivery of high quality food and access to fish hosts.

Chapter 10. Interior Least Tern (*Sterna antillarum athalassos*)

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Flow-Ecology Hypothesis Species Code: B.1

STATUS: The interior population of Least Terns (ILT) has been federally-listed as endangered since 1985. ILTs have been extirpated or drastically reduced in river reaches due to impoundments and navigation projects, but are stable in some portions of river systems and have increased in some areas like the lower Mississippi River.

SPECIES DESCRIPTION: The Least Tern is the smallest member of the tern family at about 9 inches long (23 cm) with a wingspan of 20 inches (50 cm). They have a grayish back and wings, and snowy white undersides. Least Terns have a forked tail and narrow pointed wings. First-year birds have a dark bill, a dark gray eye stripe, and a dusky brown cap. Their plumage and coloration is similar for both sexes and all ages. They can be distinguished from all other terns by their combination of a black crown, white forehead, and a variable black-tipped yellow bill (Watson 1966, Davis 1968, Boyd and Thompson 1985).

REPRODUCTION AND DEVELOPMENT: Most Least Terns begin breeding at age 2 or 3 and spend 4 to 5 months of each year at their breeding sites. They arrive at breeding areas from late April to early June (Youngworth 1930, Hardy 1957, Wycoff 1960, USFWS 2003). Courtship occurs at the nesting site or at some distance from the nest site (Tomkins 1959, as cited in USFWS 2003). It includes the "fish flight", an aerial display involving pursuit and maneuvers culminating in a fish transfer on the ground between two displaying birds. Other courtship behaviors include nest scraping, copulation and a variety of postures and vocalizations (Hardy 1957, Wolk 1974, Ducey 1981, as cited in USFWS 2003).

The nest is a shallow and inconspicuous depression in an open, sandy area, gravelly patch, or exposed flat. Small stones, twigs, pieces of wood and debris usually lie near the nest. Least Terns nest in colonies as small as a single pair to 100+ pairs and nests can be as close as just a few feet apart or widely scattered up to hundreds of feet (Anderson 1983, Ducey 1988, Hardy 1957, Kirsch 1990, Smith and Renken 1990, Stiles 1939, as cited in USFWS 2003). The birds usually lay two to three eggs (Anderson 1983, Faanes 1983, Hardy 1957, USFWS 2003). Both sexes share incubation which generally lasts 20 to 25 days but has ranged from 17 to 28 days (Moser 1940, Hardy 1957, Schwalbach 1988, as cited in USFWS 2003). Least Tern chicks hatch within one day of one another, are brooded shortly after hatching, but are mobile and strong enough to leave the nest within 1-2 days. ILT may re-nest, or relocate and re-nest if nests or chicks are destroyed early in the season (Massey and Fancher 1989, pg. 353-354, Thompson et al. 1997).

ILT chicks leave their nests within a few days of hatching (semipecocial), but remain near the nests and are fed by their parents until fledging (Thompson et al. 1997). Chicks are able to fly by about 20 days after hatching, but depend on some parental care even after they become strong fliers (Hardy 1957, Tomkins 1959, Massey 1972, 1974, as cited in USFWS 2000). Paige (1968) noted young eastern Least Terns actively foraging by about 5 weeks of age. Least Tern chicks usually fledge in about three weeks. Departure from colonies by both adults and fledglings varies, but is usually complete by early September (Bent 1921, Stiles 1939, Hardy 1957, as cited in USFWS 2003).

RANGE AND POPULATION LEVEL: The listed population includes only those Least Terns that breed and nest within the boundary of the U.S. on interior rivers and other water bodies. ILT breeding populations are associated with large river habitats from Montana southward through North Dakota, South Dakota, Nebraska, Colorado, Iowa, Kansas, Missouri, Illinois, Indiana and Kentucky to eastern New Mexico, Oklahoma, Arkansas, Tennessee, central Texas, central Louisiana, and central Mississippi. This portion of the range of these migratory birds is only used for nesting and foraging during the spring/summer reproductive season (May – August). Other breeding populations of Least Terns are found along coastal and estuarine habitats in the U.S. from Texas to Maine, and along islands of the Gulf, Atlantic, and Caribbean. The ILT is separated from coastal populations by a combination of physical and ecological factors unique to their nesting habitats. The ILT and Eastern Least Tern are geographically separated from the California Least Tern (*S. antillarum brownii*), which nest and forage in brackish and marine habitats of the pacific coast of the U.S. and Mexico.

HABITAT: Coastal habitats are created and maintained by daily and seasonal tidal and storm surges, while inland habitats of ILT are primarily created and maintained by fluctuating riverine hydrographs. They nest on a variety of habitats, but ILT prefer sandbars and islands in major rivers. They also nest on large salt flats associated with some rivers or lakes. Nests are simple scrapes in the sand, and nesting sites are characterized by coarser and larger substrate materials, more debris, and shorter and less vegetation compared to surrounding areas (Stucker 2012, pg. 49). Natural nesting habitat features are maintained and influenced by magnitude and timing of riverine flood events (Sidle et al. 1992, pg. 134, Renken and Smith 1995, pp. 194-195, Pavelka *in litt*. 2012). Vegetation free sand or gravel islands are preferred for nesting, although, sand banks, point bars, and beaches may also be utilized. ILT prefer areas remote from trees or other vegetation that may hide or support predators. Least Terns will also nest on anthropogenic sites (Jackson and Jackson 1985, pg. 57, Lott 2006, pg. 10) near water bodies with appropriate fish species and abundance, including industrial sites (Ciuzio et al. 2005, pg 102, Mills 2012, pg. 2), dredge spoil (Ciuzio et al. 2005, pg. 102), sand pits (Smith 2008, pg. 2), created habitats (Stucker 2012), and rooftops (e.g., Boylan 2008, Watterson 2009).

Lott and Wiley (2012, pp. 9-11) described five physical and biological conditions that are necessary for ILT nest initiation and successful reproduction: 1) nest sites that are not inundated during egg laying and incubation, 2) nesting sites that are not inundated until chicks can fly, 3) nesting sites with <30% ground vegetation, 4) nesting sites that are >250 ft. from large trees or vertical structures, and, 5) availability of prey fishes to support chick growth until fledging.

Peak flood events create high sandbars and islands through deposition of sediments that create good ILT nesting habitat. These sandbars and islands can become dominated by vegetation through succession and subsequent high flow events need to occur on a frequency to scour and deposit new sand to maintain or create new nesting sites. ILTs need relatively vegetation free (less than 30 %) sandbars or islands with enough elevation to preclude frequent flooding from more minor increases in flows. Flooding events do impact nesting if they occur during the nesting season, but are necessary to create and maintain good islands and sandbars for future nesting.

BIOLOGY/LIFE HISTORY*:* ILT are long-lived, with records of recapture more than 20 years following banding (Thompson et al. 1997), however, the average life span is probably less. They begin breeding in their second or third year, and breed annually throughout their lives (Thompson et al. 1997). ILT are strong fliers, migrating as far as 2000 miles between their summer nesting habitats and winter habitats in South America (Thompson et al. 1997).

ILT are primarily opportunistic piscivores, feeding on small fish species or fingerlings of larger species (Stucker 2012, pg. 6). Surveys of nesting colonies on the lower Mississippi River have identified 21 fish species dropped by foraging terns (USACE 2008, pp. 16, 26). ILTs capture small fish by diving into the water and catching fish with their bill.

Fall ILT migrants are believed to generally follow major river basins to the south to the Gulf of Mexico, however, late summer observations of Least Terns >150 km (93 mi) from major river drainages suggests some birds migrate cross-country (Thompson et al. 1997). ILT may exhibit distinct migration flocking in August prior to migration. Once they reach the Gulf Coast, they cannot be distinguished from other Least Tern populations migrating to their winter habitats (i.e., Gulf of Mexico, Caribbean islands, Central and South America), therefore the limited information on migration and winter habitat is inclusive of other populations (i.e., Caribbean, Gulf Coast, East Coast). Least Terns appear to migrate in small, loose groups along or near shore, feeding in shallows and resting onshore (Thompson et al. 1997). Very little is known of Least Tern winter habitats, other than the birds are primarily observed along marine coasts, in bays and estuaries, and at the mouths of rivers (Thompson et al. 1997).

THREATS: The primary threats identified for ILT in the listing rule and the recovery plan were the destruction of habitat and curtailment of range due to channel engineering practices on large rivers of the Interior Basin (i.e., damming, channelization, and channel stabilization), and low numbers of surviving birds throughout the range (USFWS 1985a, pp. 21789-21790, USFWS 1990, pp. 22-23). The 1985 Factor A, threat analysis found that reservoirs had inundated hundreds of miles of historical or potential ILT riverine habitat in many drainages of the Mississippi River Basin. Reservoir releases for hydropower, navigation, and flood control also were found to adversely affect ILT populations surviving below these same dams (USFWS 1990, pp. 22-23). Reduced sediment input into channels below dams had resulted in channel constriction and loss of ILT nesting islands. Channel training structures (dikes) and bank stabilization measures in the Arkansas, Missouri, Mississippi, and Ohio rivers had prevented natural geomorphic response to loss of sediments, resulting in deepened and narrowed channels, and loss or vegetation encroachment of nesting sandbars and islands. However, channel training structures have potential to create nesting habitat in large rivers. Dikes on the lower Mississippi River created or

enhanced large areas of sandbar habitat that support the largest Least Tern nesting colonies and population within the interior portion of the species range.

ILT eggs, chicks, and adults are susceptible to a wide variety of avian and terrestrial predators. While predation is a high natural source of mortality, ILT eggs and chicks are cryptically colored to avoid detection, chicks exhibit "freeze" behavior when threatened, and adults cooperate in alarm calls and attack flights on potential predators to the colonies (Thompson et al. 1997, pg. 9).

Human disturbance of nesting colonies is a major impact in some river reaches. Recreational uses such as boating and off-road vehicle use are frequently associated with disturbance of nesting ILTs. Human-related actions such as cattle trampling nests or chicks and predation or disturbance by pets have also been documented.

RESPONSE TO FLOW ALTERATION:

Species-level response - ILT nesting habitat availability and quality are primarily controlled by stochastic events (droughts and floods) affecting river flow and habitat quantity and quality (e.g., Sidle et al. 1992, pg. 134, Renken and Smith 1995, pp. 194-195, Lott et al. 2012). Productivity peaks may also be influenced by stochastic drought events or cycles in some drainages (e.g., Pavelka *in litt*. 2012).

A major hydrologic effect of reservoirs on nesting habitat is the reduction in the magnitude, frequency, and duration of peak flows that are necessary to move sediments to form new sandbars, maintain channel widths, and scour existing sandbars. For example, the frequency of high flow events on the Arkansas River downstream of Keystone Dam has declined significantly due to flood control operations (Wood 1994). Reservoirs also retain large volumes of sediment (sand) that normally would be distributed throughout an unregulated river system. For example, on the Red River, Lake Texoma traps an average of 17,700 acre-feet of sediment annually (USACE 2012). This sediment is the basic building block of Least Tern nesting habitat. The substantial reduction of sediment movement by reservoirs impacts the distribution, abundance, and quality of Least Tern nesting habitat.

Many Least Terns are currently nesting on relatively low elevation islands and sandbars. A lack of flood events and scouring flows has allowed vegetation to encroach on the majority of moderate to higher elevation nesting habitat. Reduced flood frequencies and sediment deposition has impacted the creation or maintenance of nesting habitat. This increases the flooding risk for the nesting Least Terns that are forced to nest at low, flood-prone elevation.

Flood control through reservoirs also impacts habitat and nesting success by reducing the peaks and extending the periods of moderate flows through releases of stored waters. The natural hydrographs for most rivers would have peak flow events in April through early June that quickly dissipate, but reservoirs with flood pool storage hold water and evacuate the storage over time to reduce downstream flooding. Nesting would typically begin in late May to early June, but flood storage releases can inundate nesting habitat and delay nesting for weeks (USFWS 2013a). ILTs are adapted to flooding events and will renest if high flows inundate their nests or take their chicks early in the nesting season. Flood events in June or July can seriously impact reproduction by flooding nests and subsequent flood storage releases can

extend the inundation of sandbars and islands and delay renesting. ILTs need at least 38-42 days to renest and fledge young and will only renest until about early-mid July. Fledglings and adults migrate south in August-early September at the latest. The time required to reduce flows to a level that will provide suitable nesting habitat can be critical and delays can affect the reproductive success of terns by reducing or eliminating potential for renesting. Reservoirs can have the compounding effects of reducing the elevations of downstream ILT nesting habitat (through reduced peak flows and sediment transport) and delaying nesting and renesting (by altering flows and extended inundation of nesting habitat) through prolonged releases of stored flood water (USFWS 2013a).

Normal hydropower operations (when reservoirs are not in the flood pool) consist of peaking hydropower generation during portions of the day with the most demand and highest price for electricity. Little or no generation occurs during off peak hours. This results in higher downstream water releases (frequently 10,000-12,000 cfs on the Arkansas River, Keystone Dam) for a portion of the day and low flows (frequently less than 1,000 cfs) for the remainder of the day (USFWS 2013a). Attenuation reduces the effects of these fluctuations as you move downstream. During weekends and other periods of low demand, little or no generation occurs and the flows are correspondingly low. These periods of low flows contribute to landbridging of nesting islands and increase access for mammalian predators and humans. Least Terns are frequently forced to nest on islands or sandbars that are not flooded at the higher flows, but become landbridged at the lower flows (USFWS 2005). The unnatural daily fluctuation in flows results in a change in stage or water height on the river of several feet for miles downstream of the reservoirs (USFWS 2005). These changes in flow and stage are moderated in intensity moving downstream, but severely limit the suitable nesting habitat available to Least Terns for at least 40 miles below Keystone Dam, all of the Canadian River below Lake Eufaula, and a large reach of the Red River below Lake Texoma (USFWS 2013a).

- **High Flow Pulse Magnitude Hypothesis B.1.a:** Altered magnitude of high flow pulses impacts creation of sandbars and islands that serve as Interior Least Tern nesting habitat. Decreasing magnitude reduces creation of new and scouring of existing open sand areas and reduces nesting habitat. Increasing magnitude may improve maintenance of existing and increase creation of new open sand nesting habitats. (Figure 10.1)
- **High Flow Pulse Duration Hypothesis B.1.b:** Altered duration of high flow pulses during the nesting season impacts nesting success of Interior Least Tern. Increased duration of high flows can delay nesting establishment and reduce the availability of nesting habitat. Decreased duration allows encroachment of vegetation and improved access for predators. (Figure 10.2)

Guild-level response: Interior Least Tern s represent a suite of species that depend on the expanses of open sand habitats on islands and sand bars of large rivers for their reproductive and other life-cycle needs. Other species in this group are expected to respond similarly to flow alterations.

<u>Sand bar dependent species</u>

1. Turtles- soft shell turtles (*Trionychidae),* Common Snapping Turtle *(Chelydra serpentine)*
2. Other birds- nesting: Killdeer (*Charadrius vociferous); foraging/loafing during migration-*

multiple shorebirds: primarily Scolopacidae and Charadriidae

Assemblage-level response: Interior Least Tern provide important ecosystems functions during their nesting period. As predators on young fish (Stucker 2012, pg. 6), they help to regulate the composition and abundance and other population dynamics of fish species within foraging range of the nests. They concentrate and transfer nutrients from the river to terrestrial habitats. In addition, as prey themselves, they support populations of predators such as raccoons and fox. Flow alterations that affect ILT nesting will also affect these functions and the ecological integrity of the riverine ecosystem and surrounding landscape.

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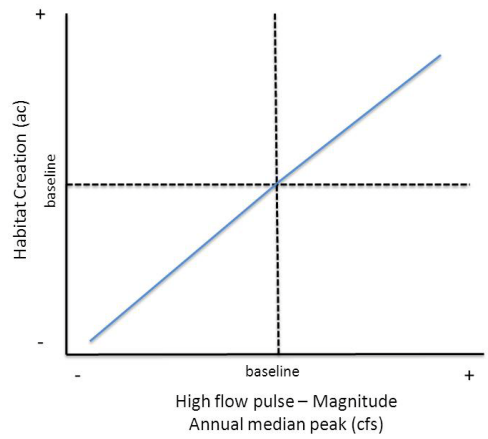

Figure 10.1. Bird High Flow Pulse Magnitude Hypothesis B.1.a: Altered magnitude of high flow pulses impacts creation of sandbars and islands that serve as Interior Least Tern nesting habitat. Decreasing magnitude reduces creation of new and scouring of existing open sand areas and reduces nesting habitat. Increasing magnitude may improve maintenance of existing and increase creation of new open sand nesting habitats.

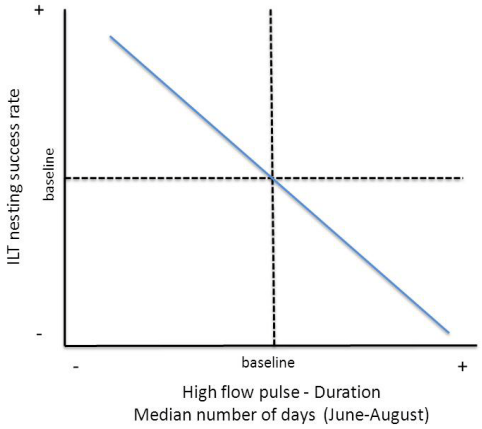

Figure 10.2. Bird High Flow Pulse Duration Hypothesis B.1.b: Altered duration of high flow pulses during the nesting season impacts nesting success of Interior Least Tern. Increased duration of high flows can delay nesting establishment and reduce the availability of nesting habitat. Decreased duration allows encroachment of vegetation and improved access for predators.

Chapter 11. Woody Riparian Vegetation

Focused on Black Willow (*Salix nigra*) and Bald Cypress (*Taxodium distichum*)

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Flow-Ecology Hypothesis Species Code: R.1

STATUS: Riparian forests are being degraded throughout the US because of human-influenced processes. Past studies have shown a 60-75% loss across the US, and up to 80% reduction in the Mississippi valley (Smith et al. 1989).

DESCRIPTION: Riparian zones are transitional areas between an upland terrestrial environment and an aquatic environment (Mitsch and Gosselink 2000). Habitats in riparian zones include sandbars, banks, and floodplains. Riparian forests are comprised of woody vegetation that is subject to frequent inundation. Organisms found in this zone are adapted to periodic flooding. Many not only tolerate it, but require it in order to maintain health and complete their life cycles (Wharton et al. 1982). While they make up a small portion of the overall area, riparian zones are generally more productive in plant and animal biomass than the surrounding areas, and are high in diversity (Messina and Conner 1998). Riparian forests help control sediment, reduce the damaging effects of flooding, and aid in stabilizing stream banks (Davis et al. 1996).

REPRODUCTION AND DEVELOPMENT: Reproduction is generally by seeds, although vegetative regeneration of many tree species is common. Season of seed production differs by species, but generally occurs in the spring and fall (Mitsch and Gosselink 2000). Seeds are dispersed by water, wind, and animals. Conditions necessary for successful germination and establishment are species-dependent. Generally, seedlings require adequate soil moisture to germinate and grow. Seedling root growth must keep up with rates of water table decline following seed deposition for adequate water availability, particularly in sandy soils of within-channel habitats such as on sandbars (Scott et al. 1999). Anaerobic conditions created by saturated soils are not tolerated until the plant is established. In order to survive, seedlings must grow tall and strong enough to withstand inundation and scouring by flowing water in subsequent flooding events.

RANGE AND POPULATION LEVEL: Riparian forests occur along all streams and rivers of the GCP LCC region, as well as along lake and reservoir edges. Black Willow is widely distributed across the Eastern Temperate Forest and Great Plains ecoregions, with the exception of the High Plains (though its

presence is assumed likely (Simpson 1999)) and the Southwestern Tablelands sub-regions. Bald Cypress is located in the Edwards Plateau, Texas Blackland Prairies, and Western Gulf Coastal Plain sub-regions of the Great Plains and across much of the Eastern Temperate Forest Region, with the exception of the Ozark Highlands and Ouachita Mountains (Duncan and Duncan 1987, Marsinko et.al. 1991). As mentioned, either species can be found along many streams ranging from headwater to large-scale, and from slow-moving (wetlands) to rapidly flowing streams.

HABITAT: Riparian forests occur along a gradient of elevations that receive different levels of inundation and exposure to energy of flowing water (Wharton et al. 1982). Within the channel, riparian forests occupy sand and point bars and islands. The progression generally follows an increase in elevation from stream banks and levees to various terrace levels in floodplains. Riparian forests generally include floodplain forests and extend to upland areas that are rarely flooded during extremely high flow events. Black Willow is a ubiquitous riparian species that grows in standing water, flowing streams, dry streams, and low points where water pools, or has pooled in the recent past (Godfrey and Wooten 1981). Bald Cypress is also widely distributed along riparian zones, growing along both flowing streams and in wetland-associated areas (Godfrey and Wooten 1981).

BIOLOGY/LIFE HISTORY*:* Black Willow usually drops seeds from April to July. Though also wind dispersed, adequate flow during these months must be maintained to allow for water dispersal (Burns et. al. 1990). Seeds germinate immediately (no dormancy) and must reach moist, fertile soils within a day or two of dispersal, highlighting the importance of adequate, correctly-timed flood flow to survival success (Junk and Piedade 1997, Hodges and Switzer 1979). Black Willow saplings have been shown to thrive when wetted frequently (daily to weekly) with a period of several dry days in between to allow for soil draining (Li et. al. 2004). Black Willow has been shown to be consistently limited to regions where the water table is within 3-4m below the soil surface (Duke 2011), and is constrained to the lowest, wettest regions of stream channel banks where hydric soils exist (Danjon et. al. 2008). An important feature of Black Willow is its intolerance to drought and extreme tolerance to flooding (Burns et. al. 1990). Black Willow functions to stabilize banks with its shallow, but highly branched roots that extensively penetrate laterally in soils, so alterations that stress root development compromise this function.

Bald Cypress seeds are water dispersed typically between November and June (Middleton 2000), requiring adequate flow for successful recruitment (McCaughey and Weaver 1991, Newling 1990). Seeds have no dormancy and require adequate soil moisture immediately and for up to 3 months after dispersal for successful germination. Seeds show extreme resilience to flooding, germinating even after 30 months of submersion once waters recede. Their drought intolerance includes a failure to germinate without adequate surface water present (Wilhite and Toliver 1990). All life stages of Bald Cypress require both abundant and relatively consistent soil moisture (Abernethy and Turner 1987, Monk 1965).

THREATS: Riparian forests are threatened by regulated flows, erosion and clearing.

RESPONSE TO FLOW ALTERATION:

Species-level response - A lack of subsistence flow lowers the water table and affects both species more negatively in maturity than at other life stages, as both have root systems that are adapted to (and thrive in) hydric soils with very high soil moisture/saturated conditions (Guilloy 2011). Vigor, productivity, and fruit/seed production are compromised with loss of subsistence flow (Middleton 2002, Myers 1989). This in turn reduces future recruitment potential.

S. nigra and *T. distichum* are sensitive to the loss of high flow pulses in that seedling survival decreases without relatively consistent wetting of soil in the unsaturated zone. Rooting development of established trees is lessened, and a lack of sediment deposition onto stream banks decreases nutrients necessary for plant vigor (Middleton 2002). These pulses also protect riparian trees from upland encroachment as hydric/near hydric soils inhibit growth of upland species into the zone (Groffman 2003).

Loss of overbank flow decreases the spatial coverage of seed dispersal, sediment/nutrient deposition, and soil moisture availability to trees, as well as allows for upland encroachment in the outermost edges of riparian zone coverage.

Decreased magnitude and increased duration and frequency of extreme low flow result in falling water table depths. Falling water table depths - a key defining feature to which obligate riparian species are constrained (Crow 2005, Danjon et al. 2008, White et al. 2002) reduce bank storage and soil moisture. As shallow groundwater has been shown to be the primary water source for these, and many other riparian trees, its persistence depends on subsistence flow as well as the recharging potential of flood flows (Smith et al. 1989).

Contributions to loss of high flow periods include channel incision, which dries out stream banks to such an extent that vegetation may be converted from riparian-healthy to upland-invasive species (Micheli and Kirchner 2002). Additionally stream damming, which attenuates floodwater delivery of nutrient-rich sediments, changes the natural pulsing (Pennington and Cech 2010), and may cause high-energy water surges that increase bank erosion; all of which disrupt seasonal seed dispersal and/or seedling and sapling survival of riparian forests (Pearce 2006).

High velocity flows/overbanking may cause excessive erosion. Extremely high flows can cause mass wasting of slopes. This is especially true for an already stressed riparian zone with less soil stability because of a loss of riparian species' root mass. Prolonged high flows may kill seedlings and saplings. Loss of high pulses and overbank flows decrease sediment and seed deposition, and the scouring effects of streambank/channel soils.

Additionally riparian zones have been negatively impacted by processes outside of the stream, including both direct destruction of the riparian zone and conversion of upland landscapes. Degraded uplands

may change stream discharge, overland flow, erosion, etc., disrupting both riparian sustainability and functionality within the stream system.

Shown below are various flow ecology hypotheses for riparian woody species-level responses in light of stream alterations.

- **Extreme Low Flow Hypothesis R.1.a**: Habitat quality for woody riparian species is affected by alterations in the duration of extreme low flow events during the growing season. Woody plants depend on bank storage/soil moisture associated with extreme low events and baseflow during low surface water availability and non-rainy seasons. Habitat quality decreases as depth to water table increases with duration of extreme low flow. Habitat quality increases with reduced duration of extreme low flow events. (Figure 11.1)
- **Extreme Low Flow Hypothesis R.1.c**: Mortality rates of Black Willow and Bald Cypress are affected by alteration in the duration of extreme low flow events during the growing season. Falling water tables caused by increased duration of extreme low flow events result in loss of plant vigor, increased mortality rates, and entire stand loss. (Figure 11.1)
- **High-Flow Pulse Hypothesis R.1d**: Black Willow and Bald Cypress seedling survival rates are affected by alterations in the frequency of high flow pulse events. The survival of seedlings becoming established along channel slopes decreases with reduced frequency of high flow pulses and subsequent reduced surface soil moisture. Most riparian species are highly tolerant of frequent and prolonged flooding and even adapted to require it. (Figure 11.2)
- **High-Flow Pulse Hypothesis R.1.e**: Growth rates of established Black Willow and Bald Cypress trees are affected by alterations in the frequency of high flow pulse events. Reduced frequency of high flow pulse events reduces soil moisture and reduces rooting mass development, leading to reduced tree growth rates. (Figure 11.2)
- **High-Flow Pulse Hypothesis R.1.f**: Habitat quality for establishment of riparian woody vegetation is affected by alterations in the frequency of high flow pulse events. Reduced frequency of high flow pulses reduces movement of sediments and nutrients along the stream continuum and reduces creation of open habitat for seedling establishment. (Figure 11.2)
- **Overbank Flow Hypothesis R.1.h**: Altered overbank flows change seed dispersal into floodplains/upper riparian zones. Reductions in the frequency of overbank events reduce opportunities for Black Willow and Bald Cypress seeds to be carried into floodplains (Figure 11.3)

Guild-level response – A number of riparian-obligate species contribute to a healthy, functional riparian buffer zone, and can be expected to respond similarly: at least one critical life stage is tightly constrained to the geomorphically-controlled water table depth and to hyporheic connectivity with the stream (Verry et al. 2004). Below are listed some of the more common, widely distributed riparian species within the Gulf Coast Prairies:

1. Maple Box Elder - *Acer negundo*

2. Pecan - *Carya illinoinensis*
3. Green Ash - *Fraxinus pennsylvanica*
4. Walnut - Juglans spp
5. Red Mulberry - *Morus rubra*
6. Sycamore - *Platanus occidentalis*
7. Cottonwood - *Populus deltoids*
8. Wafer Ash - *Ptelea trifoliate*
9. Cedar Elm - *Ulmus crassifolia*

Assemblage-level response – Black Willow and Bald Cypress function to stabilize banks with their shallow, but highly branched roots that extensively penetrate laterally within soils. As "riparian" species, they perform numerous, well-documented ecological functions that ensure a healthy stream system (Fennessy et al. 2004, Naiman et al. 2005) and their loss will be felt across both the riparian zone as well as the larger stream system. The defining characteristic of all riparian species is that they can and do show tight correlations with geomorphic surfaces of a stream, and that those geomorphic surfaces in turn often show tight correlations to flow frequencies (Osterkamp and Hupp 1984). Loss of one or more of these species because of river alterations is usually an indicator that loss of several will soon follow. Seed germination for many riparian-associated species besides Black Willow and Bald Cypress are also critically dependent on flood pulsing to disperse seeds, followed by drawdown to allow for germination and establishment of seedlings (Junk and Piedade 1997). And finally, the loss of key riparian species has been documented to result in upland encroachment into functionally compromised riparian zones (Bush and Van Auken 1984, Bush et al, 2006).

Shown below are various flow ecology hypotheses for riparian woody assemblage-level responses in light of stream alterations.

- **Extreme Low Flow Hypothesis R.1.b**: Abundance of invasive riparian vegetation is affected by alterations in the duration of extreme low flow events. Increased depth to groundwater may allow invasive species with deeper roots and greater stress-tolerance to outcompete native riparian vegetation. (Figure 11.1)
- **High Flow Pulse Hypothesis R.1.g:** Abundance of invasive riparian vegetation is affected by alterations in the frequency of high flow pulse events. Reduced frequency of high flow pulses reduces scouring and removal of invasive riparian species along the active channel region. (Figure 11.2)
- **Overbank Flow Hypothesis R.1.i**: Overbank flows prevent upland species' (less tolerant to flooding) invasion into riparian zones. Reduction in flows allows upland woody species invasion. (Figure 11.3)

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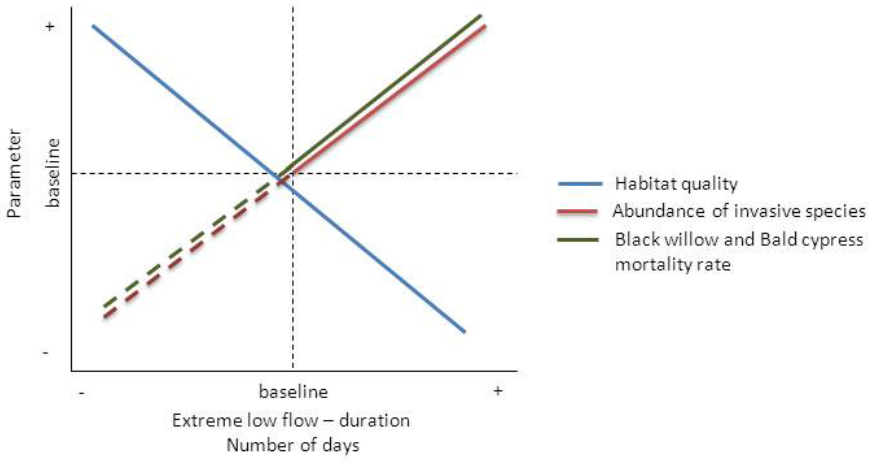

Figure 11.1. Riparian Extreme Low Flow Hypotheses R.1.a, R.1.b, and R.1.c.

R.1.a: Tree growth and vigor depends on bank storage for moisture during extreme low events, low baseflow events, and non-rainy seasons. Habitat quality decreases as depth to water table increases with duration of extreme low flow. Habitat quality increases with reduced duration of extreme low flow events.

R.1.b: Increased depth to groundwater may allow invasive species with deeper roots and greater stress-tolerance to outcompete native riparian vegetation.

R.1.c: Falling water tables caused by increased duration of extreme low flow events result in loss of plant vigor, increased mortality rates, and entire stand loss.

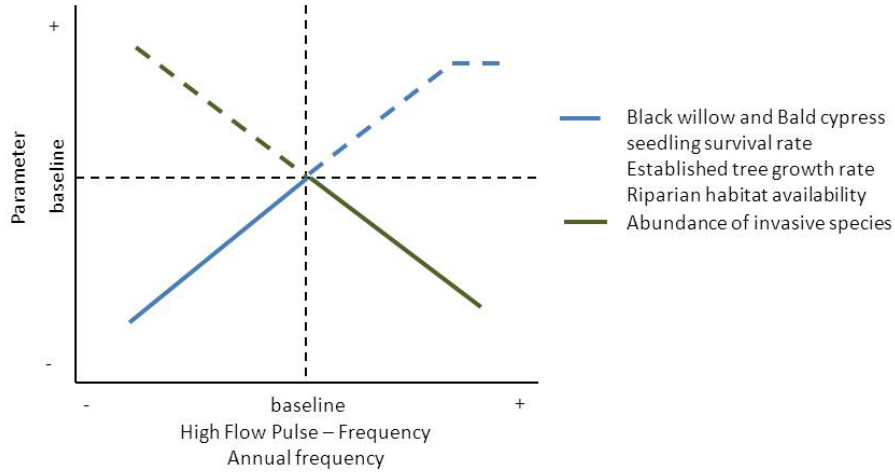

Figure 11.2. Riparian High Flow Pulse Hypotheses R.1d, R.1.e, R.1.f, and R.1.g.

R.1d: The survival of seedlings becoming established along channel slopes decreases with reduced frequency of high flow pulses and subsequent reduced surface soil moisture.

R.1.e: Reduced frequency of high flow pulse events reduces soil moisture and reduces rooting mass development, leading to reduced tree growth rates.

R.1.f: Reduced frequency of high flow pulses reduces movement of sediments and nutrients along the stream continuum and reduces creation of open habitat for seedling establishment.

R.1.g: Reduced frequency of high flow pulses reduces scouring and removal of invasive riparian species along the active channel region.

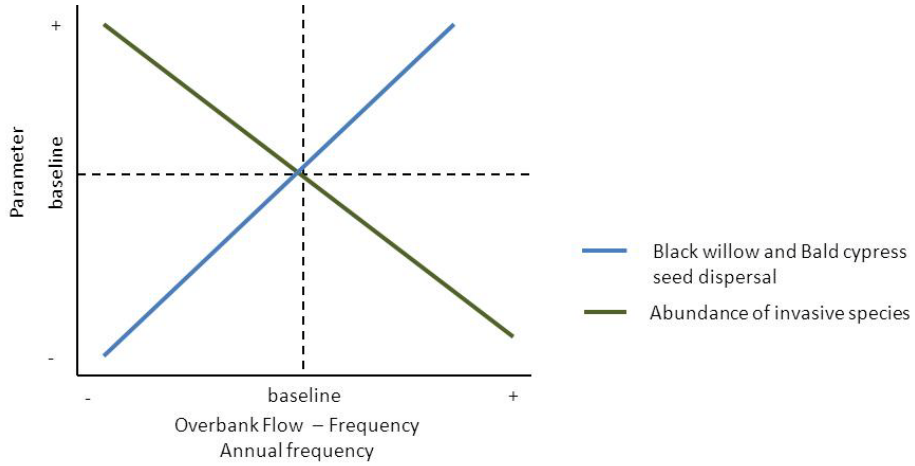

Figure 11.3. Riparian Overbank Flow Hypotheses. R.1.h and R.1.i.

R.1.h: Reductions in the frequency of overbank events reduce opportunities for Black Willow and Bald Cypress seeds to be carried into floodplains

R.1.i: Reduction in overbank flows allows upland woody species invasion.

Appendix A: Distribution of flow-sensitive species of the GCP LCC region.

To view the Excel file, go to http://www.southeastaquatics.net/resources/sifn-resources/documents/GCP LCC-instream-flow-documents/distribution-of-flow-sensitive-species-of-the-gcp-lcc-region/view.

Appendix B: General environmental and biotic responses to alteration of ecologically significant components of the natural flow regime.

Overbank or flood flows:

Direct Environmental Alterations	**Aquatic Biota Responses**
Physical Habitat: • Channel convolutions • Groundwater recharge • Floodplain inundation	• Fish access to floodplain food sources • Fish avoidance of high energy channel
Water Quality: • Dissolved oxygen • Anaerobic soil water • Metal solubility •	• Upland invasive vegetation removed
Connectivity: • Lateral connections of habitats with surface water	• Cue for migratory fish to spawn • Floodplain tree species seeds dispersed • Fish feed in floodplains prior to spawning
Energy Transfer: • Organic carbon	• food sources for downstream reaches

High flow pulses:

Direct Environmental Alterations	**Aquatic Biota Responses**
Physical Habitat: • Water velocity • Water depth • River channel configuration • Stream bed substrate sort • Sediment flushed • Aeration • Groundwater recharge	• Eggs aerated/improved reproductive success • Riparian vegetation succession reinitiated • Riparian vegetation scoured from in-channel
Water Quality: • Turbidity • Salinity	• Oyster parasites killed
Connectivity: • Longitudinal connection of in-channel habitats • Connection to soil moisture	• Limited access to required habitats • Riparian vegetation desiccation
Energy Transfer: • coarse woody debris	• food sources for downstream reaches

Baseflows:

Direct Environmental Alterations	**Aquatic Biota Responses**
Physical Habitat: • Channel drying • Water velocity • Water depth • Groundwater level	• stranding of fish and eggs • suspension of fish eggs • native river-dependent fish species richness • native riparian vegetation species
Water Quality: • Water temperature (seasonal) • Dissolved oxygen • Turbidity • Salinity • Nutrients • Other water chemistry	• physiological processes • reproductive success • mortality rates
Connectivity: • fragmentation of in-channel habitats	• access to required habitats • access to food • reproductive success
Energy Transfer: • dissolved organic carbon	• food sources for downstream reaches

Subsistence or extreme low flows:

Direct Environmental Alterations	**Aquatic Biota Responses**
Physical Habitat: • Channel drying • Groundwater level • Habitat availability	• drought tolerant species abundance • benthic and hyporheic organism abundance • native riparian vegetation species • concentration of individuals and predation
Water Quality: • Water temperature • Dissolved oxygen • Salinity • Nutrient concentrations	• physiological processes • reproductive success • mortality rates
Connectivity: • isolation of in-channel habitats	• access to required habitats • access to food • reproductive success