FLOW REGIME AND RECRUITMENT IN GULF STURGEON

IN THE APALACHICOLA RIVER, FL

by

MARK D'ERCOLE

(Under the direction of Adam G. Fox and Marty Hamel)

ABSTRACT

The Gulf Sturgeon (*Acipenser oxyrinchus desotoi*) historically occurred across the northern Gulf of Mexico from the Mississippi River to Tampa Bay. Overfishing and habitat destruction led to extirpation from some rivers; the species now occurs in seven systems, including the Apalachicola River in Florida. From 2013–2020, University of Georgia researchers have estimated annual recruitment of Gulf Sturgeon in that river. The first objective of this study was to quantify recruitment in 2021–2022 using capture-mark-recapture methods. In 2021, annual recruitment was 139 individuals (95% CI: 100–209), and in 2022 recruitment was 161 individuals (95% CI: 136–197). The second objective was to investigate several hypothesized relationships between recruitment from 2013–2022 and hydrologic conditions. We found annual recruitment to be positively correlated to discharge levels that result in floodplain inundation from July through August ($R^2$adj = 0.60). These results have implications for how flow is managed to improve recovery of Gulf Sturgeon populations in the Apalachicola River.

INDEX WORDS: Apalachicola River, Mark-recapture, Recruitment, Flow regime, *Acipenser oxyrinchus desotoi*

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by

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## DEDICATION

I’d like to dedicate this thesis to my best friend for over 20 years now, Noelle. Without her consistant support and sacrifice I would never would have had the courage to persue, nor the determination to finish this degree.

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# CHAPTER 1

# INTRODUCTION AND LITERATURE REVIEW

## Species Description and Status

Gulf Sturgeon (*Acipenser oxyrinchus desotoi*, Acipenseridae) are a large, long-lived, benthic, species of ray-finned fish (Huff 1975). Growing to over 2 m in length, they are characterized by an inferior mouth lined with barbels, five rows of scutes, and a heterocercal caudal fin (Bemis and Kynard 1997). They are a highly migratory, anadromous species, utilizing both riverine and marine habitats through their life cycle Expected lifespan is 25–40 years, with females taking up to 12 years to become sexually mature. (Huff 1975). Gulf Sturgeon have only minor morphological differences from their sister subspecies Atlantic Sturgeon (*A. o. oxyrinchus*), but the Florida peninsula separates the ranges of the two subspecies (Huff 1975).

Gulf Sturgeon were once abundant across the northern Gulf of Mexico from the Mississippi River to Tampa Bay, FL. Overfishing and impoundment construction led to population declines and extirpation from some rivers (USFWS and GSMFC 1995). The most severe overfishing occurred in the early 20th century, with fisheries moving westward from Florida as stocks were sequentially depleted (Huff 1975, USFWS and GSMFC 1995). Current populations have been reduced to remnants across seven Gulf Coast River systems: the Pearl, Pascagoula, Escambia, Yellow, Choctawhatchee, Apalachicola, and Suwanee rivers (USFWS and GSMFC 1995, USFWS and NMFS 2009). Gulf Sturgeon were listed as threatened under the Endangered Species Act in 1991, which provided some critical habitat protections (USFWS and GSMFC 1995). Prior to their ESA listing, a statewide moratorium was enacted in Florida waters in 1984. Recovery has likely been slowed not only by the Gulf Sturgeon's protracted life history but also by limitations on spawning and foraging habitat (Sulak and Clugston 2007, USFWS 2016).

## The Apalachicola River

The Apalachicola River is the largest river in Florida and its watershed, the Apalachicola-Chattahoochee-Flint (ACF) River basin, drains nearly 30,000 square kilometers of agricultural, municipal, and forest lands. With its headwaters in the Appalachian Mountain and flowing over 600 km to the Gulf of Mexico, the basin is known for both its abundant ecological diversity and economic importance to the region (Ruhl 2005, Torak and Painter 2006). Despite once supporting over 35 % of the entire Gulf Sturgeon commercial fishery, after nearly 40 years of protection, sturgeon stocks in the Apalachicola River have not rebounded to historic levels (Flowers *et al.* 2009). Modified flow and limited habitat access resulting from the Jim Woodruff Lock and Dam (JWLD) have been identified as primary factors limiting recovery there. (Flowers *et al.* 2020).

## Life History

Gulf Sturgeon mature slowly – development of mature gonads can take up to 10 years for males and up to 12 years in females. Upon reaching maturity, males spawn annually, whereas females may only spawn at 2–3-year intervals (Huff 1975, Fox *et al*. 2000). During their annual river residency, mature Gulf Sturgeon will make spawning runs upriver seeking locations to deposit their adhesive eggs (Chapman and Carr. 1995, Fox *et al.* 2000). Gulf Sturgeon spawning locations in some rivers, including the Apalachicola River, have been identified using adult telemetry and egg collection. (Fox *et al*. 2000, Scollan and Paruka 2008, Kreiser *et al.* 2008 Randall and Sulak 2012). These areas are generally characterized by a porous, limestone hard bottom, sometimes with gravel (Fox *et al*. 2000). In the Apalachicola River, spawning habitat appears to be restricted to areas 20 river kilometers below the JWLD (Scollan and Paruka 2008, Pine *et al.* 2009).

Gulf Sturgeon were historically thought to spawn primarily in the spring, much like Atlantic Sturgeon, (Sulak and Clugston 2007, Pine *et al.* 2006, ASSRT 2007); therefore, research efforts have traditionally focused on these spring spawn events. However, in recent years the Atlantic Sturgeon has been found to also spawn in the fall in several southeastern rivers (Balazik *et al.* 2012, 2017, Smith *et al.* 2014, Farrae *et al.* 2017, White *et al.* 2020). Recent studies have provided increasing evidence that some Gulf Sturgeon populations also spawn in the fall. In the Suwannee River, FL, adults with acoustic tags were detected moving over 150 kilometers upriver to known spawning grounds in September. Further, adults in spawning condition were caught in October on these spawning grounds (Randall and Sulak 2012). Researchers sampling the Choctawhatchee River have collected eggs deposited in October at putative spawning locations previously identified by telemetry during spring spawns (pers. comm., D. Fox, Delaware State University). Finally, in the Apalachicola River, recent genetic analysis of juvenile Gulf Sturgeon has indicated that are two distinct genetic clusters of fish, likely corresponding to populations of spring and fall spawners (pers. comm., B. Kreiser, University of Southern Mississippi).

Newly hatched Gulf Sturgeon use gravel and cobble as refuge while developing into free-swimming larvae (Mason and Clugston 1993, Sulak and Clugston 2007, Flowers *et al.* 2009). During this time, they feed on plankton while transitioning from benthic to pelagic riverine habitat. Most mortality occurs during this first year of life (Pine *et al.* 2001; Pine and Martell 2009). Young-of-the-year Gulf Sturgeon appear to disperse widely throughout the river system, likely inhabiting the lower reaches of Gulf Coast rivers by midwinter (Kynard and Parker 2004, Sulak and Clugston 2007,). Juvenile Gulf Sturgeon generally remain in their natal systems during their first few years, potentially due to issues with osmotic regulation (Mason and Clugston 1993, Altinok *et al*. 1998, Kynard and Parker 2004).

Movement studies of fish implanted with acoustic transmitters have been paramount to understanding Gulf Sturgeon migrations and habitat use in coastal, estuarine, and riverine environments (Rogillo *et al.* 2007, Flowers *et al.* 2009, Paruka *et al.* 2011, Randall and Sulak 2012). Gulf Sturgeon have a strong affinity for their natal rivers, though telemetry data show some movement between rivers by sub-adults and adults (Paruka *et al.* 2011, Rudd *et al.* 2014). Adult and juvenile Gulf Sturgeon older than 1 year overwinter in brackish waters or in open, nearshore waters of the Gulf of Mexico during the winter months (Paruka *et al.* 2011). It is during this time that most feeding occurs – diet primarily consists of benthic invertebrates (Mason and Clugston 2003). During the spring, all year classes of Gulf Sturgeon return to their natal rivers, where they inhabit the estuary and river (Stabile *et al.* 1996, Fox *et al.* 2000, Pine *et al.* 2006, Paruka *et al.* 2011). This riverine habitat usage may be due to the presence of a thermal refuge (Hightower *et al.* 2002) or because of flow characteristics that allow sturgeon to expend minimal energy while in trophic dormancy (Chapman and Carr 1995, Gu *et al*. 2001, Sulak and Clugston. 2007). Adults and juveniles spend the summer months aggregated in many of the same areas, especially those characterized by deep holes in the river channel (Parauka *et al*. 2011, Randall and Sulak. 2012). During the summer, Gulf Sturgeon have been caught throughout the

Apalachicola River from the estuary to JWLD but are especially common in the Brothers River tributary (Marbury 2016, Fox *et al*. 2021).

**Population Status**

As with other Acipenserids, Gulf Sturgeon possesses a complex, migratory life history, which can cause difficulty in assessing the status of populations (Nelson *et al*. 2013). Historical estimates using stock reduction analysis indicate that prior to 1900, the Apalachicola River supported up to 18,000 adults. Recent point estimates of adult Gulf Sturgeon abundance in the Apalachicola River vary from 350–1,000 (Pine and Martell 2009, Dula *et al.* 2022). By comparison, the free-flowing Suwannee River, FL, harbors the largest Gulf Sturgeon population, with an estimated abundance of 5,000–10,000 adults (Chapman *et al.* 1997).

In the past, Gulf Sturgeon recruitment estimates were made using back-calculated data from adult surveys and point estimates (Pine *et al.* 2001, Pine and Martell 2009, USFWS and NMFS 2009). This method of population assessment can lead to delays in understanding trends, as events that affect juvenile abundance may take years to affect the adult population (Schueller and Peterson 2010). Gulf Sturgeon populations have been found to be especially sensitive to fluctuations in annual recruitment and juvenile mortality (Pine *et al.* 2001), so understanding juvenile population dynamics seems especially important. The abundance of age-1 juveniles in a population is a quantified measure of this recruitment (Peterson *et al.* 2000, Schueller and Peterson 2010). Estimating the size of the age-1 cohort, and repeating those methods over time, has been used to establish trends in annual recruitment in Atlantic Sturgeon (Schueller and Peterson 2010, Baker *et al.* 2023) and in Gulf sturgeon (Fox *et al.* 2021). Assessments of recruitment can also provide prompt information on the effects of management actions. In the

Apalachicola River, direct recruitment estimates of age-1 Gulf Sturgeon have varied from 28–210 individuals per year since 2013 (Fox *et al.* 2021, Dula *et al.* 2022) Although the Gulf Sturgeon Recovery Plan does specifically provide population size criteria to support delisting, the current carrying capacity of each system has been suggested as a potential benchmark of recovery. (USFWS and GSMFC 1995, Ahrens and Pine 2014, USFWS 2022).

**Flow Regime and Sturgeon Populations**

Acipenserid populations have been shown to be sensitive to flow due to influences on spawning, recruitment, and survival at various life stages. Aside from habitat restrictions caused by dams, quality and quantity of upriver spawning habitat can also be related to dam releases. Increases in spring flow led to an increase in available spawning habitat for White Sturgeon (*Acipenser transmontanus;* Counihan and Chapman 2017, Hatten *et al.* 2018). In Pallid Sturgeon (*Scaphirhynchus albus*), upriver habitat usage (i.e., abundance at specific riverine sites) was strongly correlated with higher discharge rates (Hamel *et al.* 2016). Atlantic Sturgeon populations in the Altamaha River, GA may be sensitive to autumn river discharge, with higher flow potentially increasing the amount of available spawning and nursery habitat (Schueller and Peterson 2010). Beyond immediate effects on spawning events, flow has demonstrated effects on annual sturgeon recruitment. In examining environmental drivers of year class strength of Lake Sturgeon (*Acipenser fulvecens*) in the St. Lawrence River, Canada, Nilo *et al.* (1997) found hydrologic conditions during the months after spawning had the greatest effect on recruitment. River conditions prior to spawning can also affect recruitment - there is a significant relationship between the abundance of age-1 Atlantic Sturgeon and number of Altamaha River rises in the June before they were spawned. The mechanism by which summer flows affect recruitment from a subsequent fall spawn is not understood, but flows may affect adults' ability to migrate to upstream spawning sites; the number of adult spawners may be related to annual recruitment (Baker *et al.* 2023).

For Gulf Sturgeon, fluctuations in total discharge had a measurable effect on location and timing of Gulf Sturgeon movements in the Pascagoula River, MS (Peterson *et al*. 2015). Flow rate has also been suggested to have influence on Gulf Sturgeon spawning success in the Suwanee River (Randall and Sulak 2007, Flowers *et al*. 2009). Flowers *et al*. (2009) proposed that increased flow during critical times of year may improve Gulf Sturgeon spawning and juvenile development.

In the Apalachicola River, construction of the JWLD in 1957 restricted Gulf Sturgeon from accessing the upper portion of their riverine habitat. Today, Gulf Sturgeon can access only the lower 170 river kilometers of the river, which comprises only 22 % of their historic habitat (Marbury *et al.* 2021). In addition to the effects on upriver habitat, dam construction and channelization has had far-reaching effects on the lower river (Light *et al*. 1998, Joshi 2019). Prior to the JWLD, high discharge variability and subsequent inundation of surrounding floodplains occurred much more often. (Light *et. al*.1998, 2006, USFWS 2016). Floodplain inundation from higher flows and the resulting increase in forage base may create conditions that allow for better development of larval fish species (Livingston 1997, Freeman *et al.* 2001, Light *et al*. 1998) This has already been proposed as a possible mechanism for improved recruitment and juvenile survival rates in the Apalachicola River (USFWS 2016). Although mean annual discharge has increased post-dam construction, regulation of this flow and subsequent disruption of ecological processes may be a previously unidentified factor affecting variability in the number of yearly recruits of Gulf Sturgeon.

Flows of 420–570 $m^3/s$ at the JWLD have been found to allow for maximization of available spawning habitat, potentially increasing larval survival rates and subsequent recruitment. (Flowers *et al*. 2009, 2020). Because the JWLD is a hydroelectric dam, operations include hydropeaking – a method of generating power by quickly changing reservoir elevation and subsequent discharge. These operations can cause significant visible changes in the reaches of the river just below the dam, where flow can vary from 190–510 $m^3/s$ in a matter of hours. Hydropeaking occurs regularly in the summer months in the Apalachicola River (Torak and Painter 2006, USFWS 2016). Acute high flow events from activities at the JWLD could have a negative effect on recruitment by pushing larvae or young juveniles downstream of ideal habitats (Sulak and Clugston 2007, USFWS 2016).

Slow growth and low survival of larval sturgeon may affect recruitment during droughts more than low spawning success (GSMFC and USFWS 1995, Flowers *et al.* 2009). Drought conditions often coincide with higher river temperatures. Gulf Sturgeon eggs and larvae in laboratory conditions experience significant mortality above 25 °C (Chapman and Carr 1995), which has dire implications for Gulf sturgeon recruitment as climate change continues to warm the waters in Gulf of Mexico Rivers. Gulf Sturgeon hatching in September or October may be at even greater risk, as river temperatures occasionally exceed 30 °C at this time. In the Apalachicola River, flow from JWLD is lowest in late summer when discharge can be as low as 142 $m^3/s$ (Torak and Painter 2006). If sustained low-flow events occur more regularly, risk of extirpation from the system could increase (Sulak *et al.* 2012, Flowers *et al*. 2009, 2020). Although management of Apalachicola River discharge is important to Gulf Sturgeon, water usage in the region is a contentious issue; the three states in which the ACF basin is contained have had high-profile legal battles over the right to its waters (Ruhl 2005, Torak and Painter 2006, Leitman *et al.*, 2016).

Facilitating spawning and subsequent recruitment to the juvenile population in the Apalachicola River is a primary goal for managers concerned with restoration of Gulf Sturgeon in the system (USFWS 2016, 2022). Currently, operations at JWLD allow for increased flows in March and April to potentially improve conditions for the spring spawning event. However, discharge rates and timing could be affecting life history stages and processes outside of this seasonal window. Therefore, the objectives of this study were to:

1. Increase our long-term data set by continuing to estimate annual recruitment of Gulf Sturgeon in the Apalachicola River.
2. With data retrieved from the US Geological Survey (USGS) stream gauges below the JWLD, identify flow regime metrics that could be influencing the observed variation in annual recruitment over the last 10 years.

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CHAPTER 2

# RECRUITMENT OF AGE-ONE GULF STURGEON IN THE APALACHICOLA RIVER, FLORIDA

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**Abstract**

The Gulf Sturgeon (*Acipenser oxyrinchus desotoi*) is a threatened anadromous fish that historically occurred across the northern Gulf of Mexico from the Mississippi River to Tampa Bay. Overfishing and habitat destruction led to population declines and extirpation from some rivers; the species now occurs in just seven systems, including the Apalachicola River in Florida. There is evidence that the Apalachicola River once harbored a robust population of Gulf Sturgeon. University of Georgia researchers have estimated recruitment (i.e., age-1 abundance) in that system using mark-recapture sampling and Huggins closed-capture models from 2013–2020. The objective of this study was to quantify recruitment in 2021–2022 using the same methods. We found that in 2021 annual recruitment was 139 individuals (95% CI: 100–209), and in 2022 recruitment was 161 individuals (136–197). These estimates are within the range of annual recruitment found in previous studies. Since 2018, recruitment appears to have been increasing steadily. Monitoring annual recruitment provides valuable insight into population trends for managers hoping to improve the recovery of this imperiled species.

## Introduction

Gulf Sturgeon (*Acipenser oxyrinchus desoti*, Acipenseridae) is an anadromous ray-fined fish that occurs in the Gulf of Mexico (GOM). These fish share morphological and life history traits with the Atlantic Sturgeon (*A. o. oxyrinchus*), of which it is a subspecies (Huff 1975). Although Gulf Sturgeon once were abundant across the northern Gulf of Mexico from the Mississippi River to Tampa Bay, habitat destruction, overfishing, and acute high mortality events have resulted in a reduced range. Extant populations can be found in only seven rivers (USFWS and NMFS 2009). Gulf Sturgeon were listed as threatened under the Endangered Species Act in 1991, which halted the fishery and provided some coastal habitat protections (USFWS and NOAA 1991).

Compared to many other fish taxa, Acipenserid populations have a protracted and complex life cycle (Nelson *et al*. 2013). For Gulf Sturgeon, development of mature gonads can take up to 12 years. Upon reaching maturity, adult males spawn annually, whereas females spawn at 2- to 3-year intervals (Huff 1975, Fox *et al*. 2000). Mature Gulf Sturgeon will make spawning runs to upriver locations with gravel and hard bottom where they deposit adhesive eggs (Fox *et al.* 2000). Newly hatched Gulf Sturgeon use the gravel and cobble as refuge while developing into free-swimming larvae (Mason and Clugston 1993, Flowers *et al.* 2009). During this time, they feed on plankton while transitioning from benthic to pelagic riverine habitat. Young-of-the-year Gulf Sturgeon appear to disperse widely throughout the river system, likely inhabiting the lower reaches of their natal rivers by midwinter (Kynard and Parker 2004). Young Gulf Sturgeon are thought to remain in freshwater during their first year of life, potentially due to issues with osmotic regulation (Mason and Clugston 2003). This first year of life is when most mortality occurs. (Pine *et al.* 2001; Pine and Martell 2009).  Adult and juvenile Gulf Sturgeon older than 1 year overwinter in brackish waters or in open, nearshore waters of the Gulf of Mexico during the winter months (Paruka *et al.* 2011). Most feeding occurs during this time – diet for all ages primarily consists of benthic marine invertebrates (Mason and Clugston 2003). Gulf Sturgeon have a strong affinity for their natal rivers; and during the spring all year classes return to their natal river or estuary (Chapman and Carr 1995, Stabile *et al.* 1996, Fox *et al.* 2000, Pine *et al.* 2006, Paruka *et al.* 2011). Although natal river fidelity is high, telemetry data does indicate that there is limited between-river movement by some sub-adults and adults (Paruka *et al.* 2011, Rudd *et al.* 2014).

*Apalachicola River Gulf Sturgeon.* — The Apalachicola River is formed by the confluence of the Flint and Chattahoochee rivers in what is now Lake Seminole, which was created by the construction of the Jim Woodruff lock and dam (JWLD) in 1957 by the United States Army Core of Engineers (Figure 2.1). From the dam, the river flows 260 km to the Gulf of Mexico. The Apalachicola River once harbored a robust population of Gulf Sturgeon, with highly productive commercial fisheries lasting into the 20th century (Huff 1975). Population estimates from historical records and a stock reduction analysis indicate that prior to 1900 the Apalachicola River supported as many as 18,000 adults (Ahrens and Pine 2014). Recent point estimates of adult Gulf Sturgeon abundance in the Apalachicola River vary from 350–1,200 individuals (Pine and Martell 2009, Dula *et al.* 2022). By comparison, the free-flowing Suwannee River harbors the largest Gulf Sturgeon population, an estimated 5,000–10,000 adults (Chapman and Carr 1995, USFWS and NMFS 2009).

*Monitoring Gulf Sturgeon Populations*. — Fish populations are difficult to count, and juvenile Gulf Sturgeon are no exception. In the large, interconnected riverine systems they inhabit, it is generally impossible to capture and count every individual. However, researchers have long been developing methods of estimating the abundance of fish and wildlife populations. One of the most frequently used techniques is capture-mark-recapture (CMR). By capturing, marking, and later recapturing a subset of individuals from a population, accurate estimates of abundance can be calculated from the recapture rates of marked individuals. The Lincoln-Petersen model (Petersen 1896; Lincoln 1930) is one of the earliest CMR methods, and is represented by the equation:

$$N = \frac{(n_1 + 1)(n_2 + 1) - 1}{(m_2 + 1)}$$

where:

$N$ is the estimate of total population size,

$n_1$ is the number of marked animals released into the population,

$n_2$ is the total number of animals in the second sample, and

$m_2$ is the number of marked animals in the second sample.

Modifications to this model by Schnabel (1938) and Chapman (1951) help reduce biases that can occur when assessing smaller populations with repeatedly recaptured individuals. Importantly, these CMR models operate on the premise that a population is closed, i.e., that there are no births, deaths, or individual migrations into or out of the study site. Other important assumptions of closed population models are that marking tags are retained, individuals are mixed randomly amongst the population, and therefore have the same probability of being captured. In the past, Gulf Sturgeon recruitment to age 1 was estimated using back-calculated data from adult surveys

(Pine *et al.* 2001, USFWS and NMFS 2009). This method of assessment can result in delays in understanding trends, as events that affect juvenile abundance may take years to affect the adult population (Zehfuss *et al.* 1999, Schueller and Peterson 2010). By directly estimating recruitment (i.e., the abundance of age-1 Gulf Sturgeon) through CMR studies on juveniles, researchers have been able to investigate trends in recruitment of Atlantic Sturgeon (Schueller and Peterson 2010, Baker *et al.* 2023).

Because age-1 Gulf Sturgeon tend to remain in their natal rivers during their summer residency (Marbury 2016, Hancock 2019, Fox et al. 2021), they can be considered a closed population. In CMR, capture probability is the probability of a detecting an individual of the population being assessed. In this study, capture probability may not be uniform for all individuals across an entire summer sampling period (e.g., it might vary by age, or sampling week). Early CMR models do not include a way to model capture probability. Huggins models (Huggins, 1991) were developed to allow for heterogenous capture probabilities that can vary with previous capture history and with individual covariates. These methods have been used successfully to assess Gulf Sturgeon age-1 abundance in the Apalachicola River (Fox *et al.* 2021), where point estimates of recruitment varied between 28 and 210 individuals annually from 2013 to 2018.

Gulf Sturgeon populations have been found to be especially sensitive to fluctuations in annual recruitment and juvenile mortality (Pine *et al.* 2001). By using CMR studies to directly measure recruitment, researchers and managers can monitor these fluctuations; this information can then provide insights into future population trends (Peterson *et al.* 2000, Schueller and Peterson 2010). Recruitment estimates can also provide prompt information on the effects of any management actions that are undertaken to enhance recruitment. Tracking population trends within the young-of-year and juvenile age classes is pivotal to assessing the recovery of Gulf Sturgeon (Flowers *et al*. 2020, Fox *et al.* 2021). In collaboration with the USFWS, the University of Georgia collected 8 years of juvenile Gulf Sturgeon data in the Apalachicola River from 2013–2020. The objective of this study was to continue estimation of age-1 recruitment for 2021–2022. In addition to providing recruitment information that is immediately relevant to resource managers in this system, these findings can be used to identify and investigate environmental drivers of the observed variation in annual recruitment; that analysis will be discussed in chapter 3 of this thesis.

**Methods**

*Study Site.* — Previous sampling has identified an important Gulf Sturgeon aggregation site in the Brothers River (Figure 2.1), a tributary of the lower main stem of the Apalachicola River (Marbury 2016, Hancock 2019, Fox *et al.* 2021). Both juveniles and adults use this area heavily, and in the summer sampling and telemetry data indicates little outmigration by young juveniles. As in those previous studies, most of the sites sampled in this study were located within the Brothers River, although we also periodically sampled in the main stem of the Apalachicola River in search of other locations juvenile may be congregating.

*Sturgeon capture*. — Sturgeon were collected from May through August in 2021–2022 using the same methods described in Fox *et al*. (2021). Sampling was performed using anchored gill nets consisting of three 15-meter panels of 7.6-, 8.9-, and 10.2-cm (stretch-measured) monofilament mesh. These net specifications have proven successful in past juvenile studies in this system (Marbury 2016, Fox *et al*., 2021). Prior to setting nets, dissolved oxygen (mg/l) and temperature

(°C) were measured at each site using a Yellow Springs Instruments Pro 2030 water quality meter. Nets were set for intervals of 30–120 minutes depending on water temperature, oxygen, flow, and weather conditions. Upon capture, sturgeon were placed in floating net pens until all nets had been retrieved. Total length (TL), fork length (FL), and weight were recorded for each individual fish. All sturgeon were scanned for passive integrated transponder (PIT) and floy tags. If previously unmarked, a PIT tag was inserted under the scute nearest the dorsal fin. An anal fin clip of approximately 1 $cm^2$ was taken from each fish and stored in ethanol for genetic analysis by research partners. Finally, the second marginal fin ray was removed from fish under 650 mm FL (presumed to be <2 years old; Moran 2018) for age analysis by research partners. The sturgeon were then immediately released back into the river at the site of capture.

*Telemetry*. — A subset of the juvenile Gulf Sturgeon captured were implanted with acoustic transmitters to provide telemetry data to address the assumption of closure within the study site. A subset of juveniles (FL 350–650mm) were implanted with V7 and V9 transmitters (Innovasea, Bedford, Nova Scotia) during the summers of 2021 (n = 29) and 2022 (n = 51). For this procedure, each sturgeon was placed ventral side up onto a surgical v-board and held in place while a pump continuously irrigated its gills. After disinfecting surgery equipment and the transmitter with 70% isopropyl alcohol, a 2-cm incision was made on the lower abdomen using a surgical scalpel, and the tag was inserted. The incision was closed using a 3/0 Monocryl suture with a single interrupted pattern (Boone *et al.* 2013). Once the fish had recovered, it was released back into the system. Since 2013, an array of acoustic receivers (Innovasea VR2W) has been deployed throughout the lower Apalachicola River and its estuary, including all distributary mouths to the Gulf of Mexico (Figure 2.1). Although data on closure proved useful to this study, most of the telemetry data analysis is reserved for a future study.

*Abundance Estimates*. — We assigned each Gulf Sturgeon an age (1, 2, or 3+) based on previous age and length work in the Apalachicola River (Baremore and Rosati 2014, Fox *et al*. 2021). Age-1 fish had fork lengths of 370–530 mm, age-2 fish were 531–710 mm, and any fish >710 mm was considered to be age 3+. Once age assignments were made, capture histories were created for each individual. To allow for adequate mixing of individuals among sample sites, we considered each calendar week to be a capture period. We estimated the abundance of each age-1 cohort using Huggins closed capture models (Huggins 1991) within the RMark package in Program R (R Core team 2022, as described by Fox *et al*. (2021). The accuracy of these models relies heavily on population closure, so in addition to our telemetry data, we used the program CloseTest, version 3 (Otis *et al.* 1978, Stanley and Burnham, 1999) to help confirm this assumption. We created a set of five candidate models that allowed capture probability to vary in different ways. The constant model ($M_0$), assumed a constant capture probability. The remainder of candidate models allowed for capture probability to vary with sampling occasion ($M_t$), age class ($M_a$), and the additive and the interactive effects of those factors ($M_{t+a}$ and $M_{t*a}$). Akaike's information criterion (AIC; Akaike 1973) was corrected to $AIC_c$ (Otis *et al.* 1978) to account for small sample size and then used to rank the models so we could select the top model for each year.

## Results

*Effort and catch*. — A total of 684 nets were set during sampling trips in May, June, and July of 2021 and 2022, for a total effort of 660 net-hours. The average net soak time for the two summers was 58 minutes. During this study, a total of 576 Gulf Sturgeon were captured, including 144 recaptures (Table 2.1). Gulf Sturgeon captures per net hour (CPUE) varied from 0.43 fish/hour in 2021 to 1.47 fish/hour in 2022. The total number of individual age-1 juveniles captured was 186, and there were 98 recaptures of those fish. The pattern of modal distributions in the length-frequency histograms (Figure 2.2) indicate that all the Gulf Sturgeon we classified as age-1 based on their length are in fact members of a single age-1 cohort.

*Telemetry*. — During sampling for the CMR study, 80 juvenile Gulf Sturgeon (FL 321–578mm) were implanted with acoustic transmitters. Telemetry data were downloaded from all receivers in the system three times during each sampling year. There were over 200,000 total detections recorded on acoustic receivers in the Brothers River alone. Detection data indicated that none of the acoustically tagged juveniles in 2021 ($n = 29$) left the Brothers River during the 2021 sampling period. In 2022 there were multiple instances when telemetered juveniles (6 of 51, 12%) were detected entering the lower Apalachicola River or St. Marks River (Figure 2.1). One of these juveniles was not detected again during the study, but the other five were detected again in the Brothers River within weeks of the initial detections outside of it. These individuals were not detected in the lower distributaries near Apalachicola Bay, indicating they remained near the Brothers River during the sampling period. No juveniles were recorded on any of the upriver receivers near the JWLD during either sampling season. CloseTest software results indicated that the age-one population did not experience significant immigration or emigration in 2021 (p

= 0.22) and in 2022 (p = 0.82). Combined, these results suggest that our sampling site was largely closed during the sampling period.

*Abundance Estimates*. — In both 2021 and 2022, the top model for estimating recruitment based on relative weight was the $M_{t+a}$ model (additive effect of time and age; Table 2.3). In both years, this model held over 90% of the relative weight. In 2021, annual recruitment was 139 individuals (95% confidence interval: 100–209), and in 2022 recruitment was 161 individuals (95% CI: 136–197).

**Discussion**

The results of this study complete 10 years of Gulf Sturgeon recruitment assessments in the Apalachicola River. Point estimates of recruitment in 2021 and 2022 were similar to those reported by Fox *et al*. (2021) and Dula *et al*. (2022), but greater than in all but one year of those studies (Figure 2.3). When placed in the context of those studies, our results seem to indicate a trend of increasing recruitment in recent years – each of the last 4 years has seen more recruits than in 2015–2018.

Effort and CPUE varied in 2021 and 2022 (Table 2.1) due to the different weather conditions during sampling each year. High river flows after large rain events in the watershed limited netting opportunities in 2021 – at high flows, anchored gill nets do not effectively sample juvenile sturgeon (Fox *et al*. 2021). Conversely, relatively low flows in 2022 likely allowed for more efficient and effective sampling. Additionally, due to the Gulf Sturgeon's status as threatened, sampling is limited by guidelines for netting stipulated by USFWS, which were adapted from Kahn and Mohead (2010). In 2022, river temperatures exceeded those guidelines for much of the month of July, ending the netting season earlier than in 2021. Despite the differences in total CPUE between 2021 and 2022, our AIC analysis indicated that time and age, rather than capture efficiency, were the main factors affecting detection probability in both years.

The Huggins closed population models we used in this study allow for variability in capture probability, but the accuracy of the model estimates relies heavily on the assumption of a closed population. Our telemetry data support this assumption. Few or no fish were detected outside of the Brothers River sampling area during our sampling season and most of the fish that did leave in 2022 returned after a short time. These results are comparable to Hancock (2019), who found that just 1 of 37 tagged age-1 individuals (2.7%) moved out of the Brothers River during the summers of 2017 and 2018. These telemetry results, and the results of the CloseTest software indicate that our CMR analysis method was appropriate.

Resource managers suggest that when compared to the other systems Gulf Sturgeon inhabit, the Apalachicola River hosts a relatively robust population, second only to the Suwanee River (USFWS and GSMFC 1995, Pine and Martell 2009.) Historically, Pine and Martell (2009) used an age-structured CMR model that estimated recruitment in the Apalachicola as varying between 0–200 individuals annually from 1977 to the early 2000s. Although there are not yet estimates of Gulf Sturgeon recruitment to age-1 outside of the Apalachicola River, work on estimating Gulf Sturgeon age-1 recruitment trends across the Gulf of Mexico is currently underway (USFWS 2022). We cannot currently compare recruitment among Gulf Sturgeon populations, but we can quantitatively compare our results to some southern Atlantic Sturgeon populations with recruitment estimates based on similar methods as in this study. Baker *et al.* (2023) derived point estimates of annual recruitment of Atlantic Sturgeon in the Altamaha River, GA from 2008–2020 that varied from a few hundred to over 3,500 individuals. The Altamaha

River population of Atlantic Sturgeon is considered by researchers to be the largest and healthiest in the southeast (ASSRT 2007). Compared to Altamaha River sturgeon recruitment, the Apalachicola River produces very few sturgeon – however, the undammed nature of the Altamaha River may explain why it consistently produces large numbers of age-1 juveniles. Like the Apalachicola River, the Savannah River in Georgia and South Carolina is dammed, preventing sturgeon from accessing much of their historic spawning habitat and restricting spawning to just a few sites immediately below the dam. The Savanah River is also thought to host a relatively robust population of Atlantic Sturgeon (ASSRT 2007); annual recruitment there varied between 500–1000 individuals from 2013–2017 (Baker *et al*. 2023) –still far more age-1 fish per year than are produced in the Apalachicola River. Our estimates of Gulf Sturgeon recruitment in the Apalachicola River are more similar to Atlantic Sturgeon populations that are thought to be in poor shape (ASSRT 2007), such as the Ogeechee and Satilla rivers in Georgia. Annual recruitment in those systems is <100 individuals per year with no observable recruitment in some years (Farrae *et al.* 2009, Baker *et al.* 2023). Inconsistent recruitment (i.e., not occurring every year) could be an indicator of a small, fragile population. Although the abundance of Gulf Sturgeon recruits in the Apalachicola River is relatively low compared to healthy Atlantic Sturgeon populations, the Apalachicola River does support at least some recruitment of age-1 Gulf Sturgeon every year.

The trend of increasing recruitment of Gulf sturgeon in the Apalachicola River for the last 4 years was unexpected, in part because there was a well-documented mortality event of Gulf Sturgeon in the wake of Hurricane Michael in October 2018 (Dula *et al.* 2022). After the hurricane, multiple metrics indicated a 36–60% decrease in adult abundance compared to pre-storm estimates. Less is known about how the hurricane affected juvenile Gulf Sturgeon in the river at the time. Dula *et al*. (2022) noted that all five acoustically tagged age-1 fish present in the river before the hurricane were never detected afterwards, suggesting a juvenile mortality event may have also occurred. Why and how recruitment has increased post-hurricane is not well understood. Perhaps high flows from the storm changed some aspects of the rivers hydrology in a way that benefited Gulf Sturgeon recruitment. The river flood pulse concept (Junk 1989, Bailey 1997) describes how storm-related floodplain inundation could import more nutrients into a riverine system, thus increasing the forage base for aquatic species. In the Apalachicola River system, the effects of this mechanism on fish assemblages and abundance were investigated by Dutterer *et al.* (2013), who found evidence of increased recruitment of Spotted Suckers (*Minytrema melanops)* and Largemouth Bass (*Micropterus salmoides)* following increased spring/summer floodplain inundation. These same elements may be benefiting young Gulf Sturgeon in recent years where the floodplain has been inundated for significant periods of time. Finally, another possible explanation for why this mortality event had little impact on the following year's recruitment is that the reduced adult spawning stock was still able to produce enough recruits to fill the river's capacity.  A single female Gulf Sturgeon has the potential to produce over 580,000 eggs during a single spawn (Parauka *et al.* 2011, Sulak *et al.* 2016), so just a few spawning adults could easily result in ~150 offspring. Genetic samples from all sturgeon captured in this system are currently being analyzed by the University of Southern Mississippi, and insight from those analyses could help answer questions about juvenile siblingship and effective number of breeders.

Dula *et al*. (2022) proposed that the increasing number of new recruits since 2018 may have originated from an increased prevalence of fall-spawned juveniles, facilitated by the effects of Hurricane Michael. However, the relative contribution of the fall spawn to total annual recruitment has not yet been determined. Based on the genetic assignments of some fish collected during this study, the size class we considered to be age 1 (370–530 mm FL) consisted primarily of spring-spawned individuals (pers. comm., B. Krieser, USM). During our summer sampling period, young-of-year fish spawned in the previous fall were likely too small (<350 mm FL) to be effectively captured by our sampling gear. Additionally, most fish spawned in the fall 18 months before our summer sampling season typically exceeded the upper end of our age-1 size range. In the future, we hope that additional research will be able to incorporate the emerging genetics results so that the spring- and fall-spawned cohorts can be quantified separately, providing further insight on seasonal recruitment population dynamics in the Apalachicola River.

Facilitation of spawning and subsequent recruitment to the juvenile population in the is a primary goal for managers concerned with restoration of Gulf Sturgeon in every river where they occur (USFWS 2016, pers. comm., A. Kaeser, USFWS). Annual recruitment over the last decade remains low compared to healthy Atlantic Sturgeon populations, but age-1 Gulf Sturgeon are being produced every year in the Apalachicola River. Our results suggest that annual recruitment in recent years has increased since Hurricane Michael, but additional years of recruitment monitoring will help confirm this trend. Additionally, the relatively long-term nature of this set of recruitment data provides an opportunity to examine how environmental conditions may affect annual recruitment; chapter 3 of this thesis will address that analysis. If managers can take actions to help facilitate recruitment, such as improving or supplementing spawning habitat (Flowers 2009, USFWS 2016), the baseline recruitment data from this and previous studies will allow effective, quantitative assessment of how those efforts affect recruitment. Adaptive management that incorporates timely assessments of population responses is key to Gulf

Sturgeon recovery, and long-term studies like this one can provide empirical evidence of that recovery.

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**Table 2.1:** Effort, catch, and recapture data for sampling of Gulf sturgeon (*Acipenser oxyrinchus desotoi*) using monofilament gill nets (50 x 3 m) in the Apalachicola River, Florida, during May–August in 2021 and 2022. Nets mesh (stretch) was 7.6-, 8.9-, and 10.2- cm. The total number of Gulf Sturgeon captured includes all ages and recaptures, with some fish recaptured multiple times. Age-1 individuals were determined by FL (370–530mm) at first capture.

| Year | Net sets | Net hours | Total captures | Total recaptures | Age-1 individuals | Age-1 recaptures |
|---|---|---|---|---|---|---|
| 2021 | 369 | 378 | 162 | 39 | 65 | 17 |
| 2022 | 315 | 282 | 414 | 115 | 121 | 81 |

**Table 2.2:** Results of Huggins closed-capture models of annual Gulf Sturgeon recruitment (i.e., the abundance of the age-1 cohort) in the Apalachicola River, Florida in 2021 and 2022. The constant model (M0) assumed a constant capture probability. The other models allowed for capture probability to vary with sampling occasion (Mt), age class (Ma), and the additive and the interactive effects of those factors (Mt+a and Mt*a). Models are ranked using Akaike's information criteria (AIC) modified for small sample size. For each model, we provide the AICc value, ΔAICc, and relative weight (Wr). Only models with Wr > 0 are included in these results. The top model for each year is indicated in bold.

| Year | Model | AICc | Δ AICc | Wr |
|---|---|---|---|---|
| **2021** | **$M_{t+a}$** | **1289.98** | **0.00** | **0.92** |
| | $M_{t*a}$ | 1293.99 | 4.54 | 0.06 |
| | $M_t$ | 1315.15 | 9.72 | 0.02 |
| **2022** | **$M_{t+a}$** | **1838.88** | **0.00** | **0.98** |
| | $M_{t*a}$ | 1856.19 | 7.34 | 0.02 |

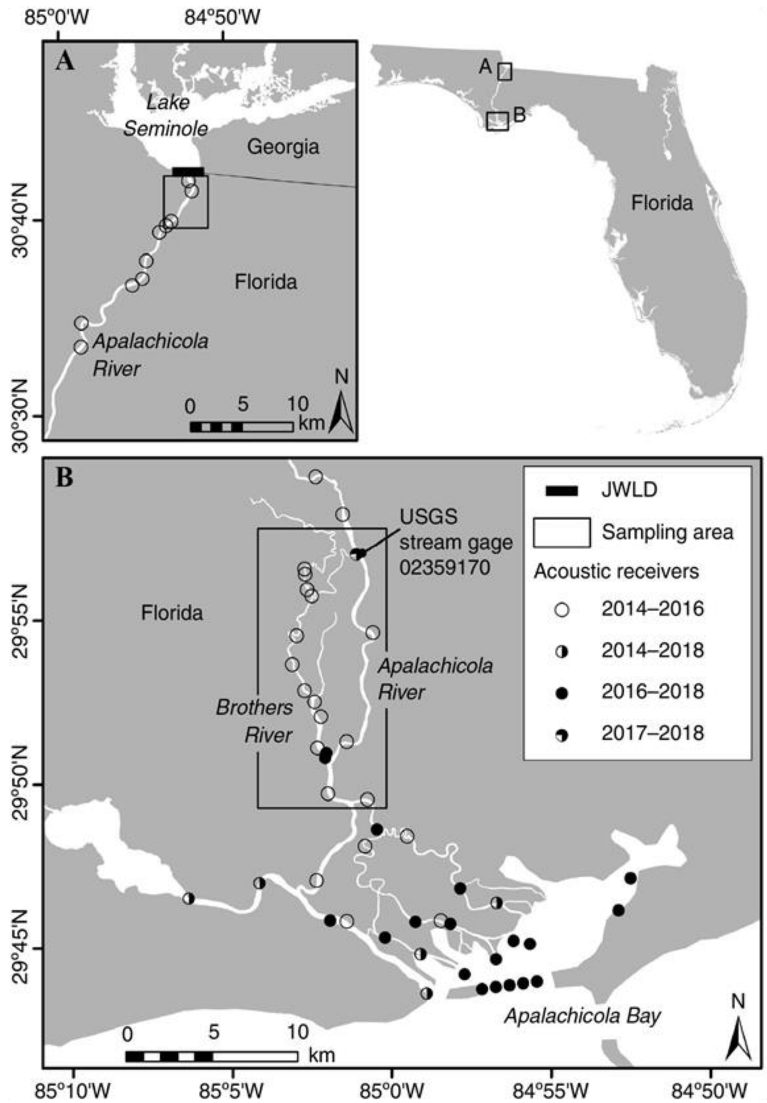


**Figure 2.1:** Study site map (from Fox *et al*. 2021). Maps of the study site in the Apalachicola River in Florida: (**A**) the Apalachicola River downstream of the Jim Woodruff Lock and Dam (JWLD, indicated by a black rectangle) and (**B**) the Brothers River and lower Apalachicola River. Sampling for juvenile Gulf Sturgeon in 2021-2022 occurred within the boxes outlined in black. Circles indicate locations of acoustic receivers within the array installed for this study. In panel B, the location of U.S. Geological Survey (USGS) stream gage 02359170 on the Apalachicola River near Sumatra, Florida, is indicated.

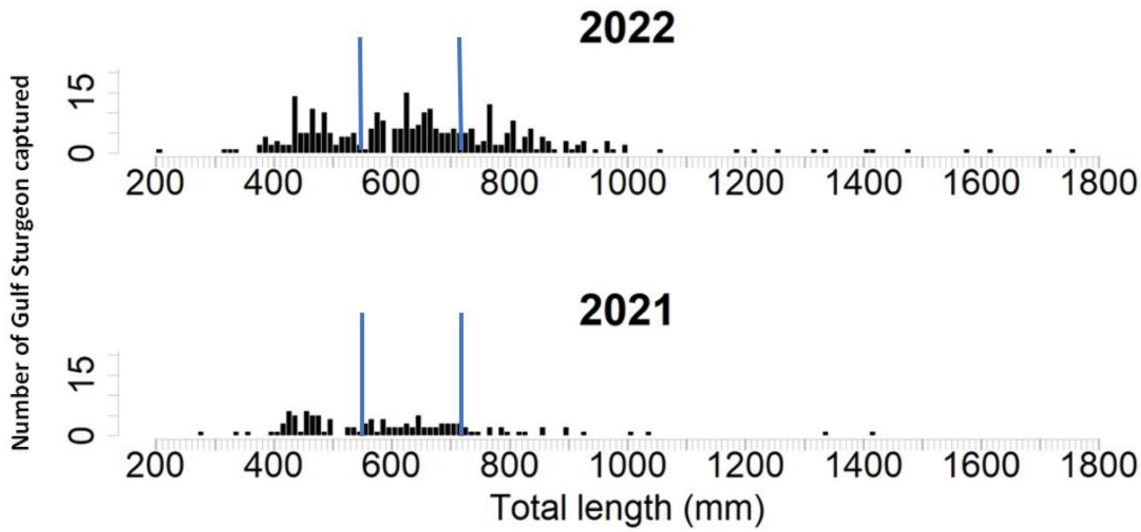


**Figure 2.2.** Length-frequency histograms of Gulf Sturgeon captured in the Apalachicola River system during the summers of 2021 and 2022. Number of Gulf Sturgeon caught, and total length (mm) is represented. Blue lines denote age-1 and age-2 cutoffs.

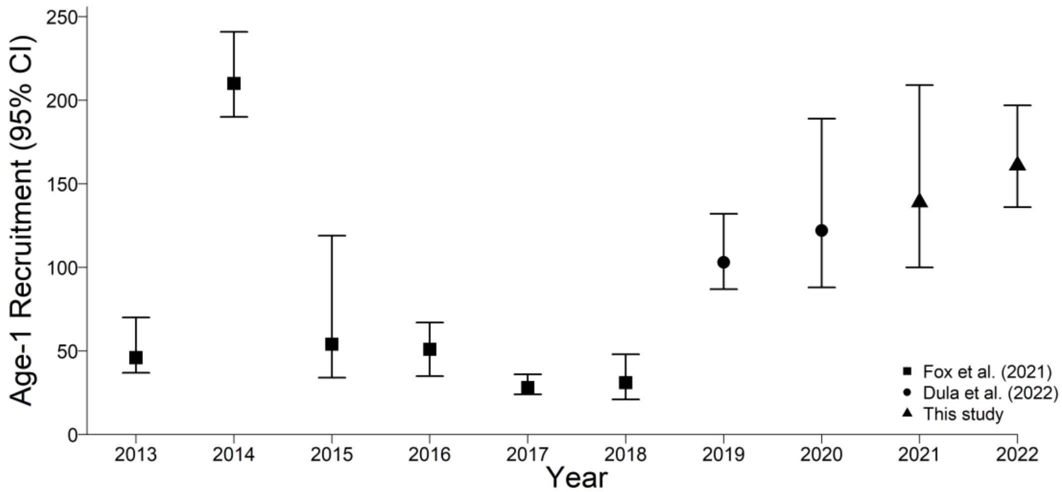


**Figure 2.3.** Age-1 recruitment of Gulf Sturgeon in the Apalachicola River system from 2013–2022 (+/- 95% confidence interval). This study produced results from 2021–2022; previous estimates (2013–2018: Fox *et al*. 2021; 2019–2020: Dula *et al*. 2022) were derived using the same methods.

CHAPTER 3:

# INVESTIGATING THE RELATIONSHIP BETWEEN FLOW REGIME AND GULF STURGEON RECRUITMENT IN THE APALACHICOLA RIVER, FLORIDA

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## Abstract

The Gulf Sturgeon (*Acipenser oxyrinchus desotoi*) is a threatened anadromous fish species that historically occurred across the northern Gulf of Mexico from the Mississippi River to Tampa Bay. Overfishing and habitat destruction led to population declines and extirpation from some rivers; the species now occurs in just seven systems, including the Apalachicola River in Florida. Despite a fishing moratorium implemented in 1984, Gulf Sturgeon stocks have been slow to recover in the Apalachicola River. From 2013–2022, University of Georgia researchers have estimated recruitment (i.e., age-1 abundance) of 22–210 individuals per year in this system. Several hypotheses have been proposed in the literature linking variation in Gulf Sturgeon recruitment to environmental drivers, specifically several metrics related to river discharge. To test these hypotheses, we created a suite of linear regression models that incorporated proposed flow-related drivers, and then used AIC to determine which model(s) best explained the observed variation in annual recruitment. The top model suggested a positive relationship between recruitment and the proportion of days from June–October with at least 10% of the floodplain inundated ($R^2_{adj} = 0.60$). This relationship was then used to predict potential effects on recruitment success under drought, median, and maximum observed floodplain inundation conditions during June–October. Because flow in the Apalachicola River is controlled by Jim Woodruff Lock and Dam, these results have important implications for how flow is managed to improve recruitment of Gulf Sturgeon population in that river.

## Introduction

Gulf Sturgeon (*Acipenser oxyrinchus desotoi*, Acipenseridae) is an anadromous, long-lived, species of ray-finned fish (Huff 1975). Growing to over 2 m in length, it is characterized by a heterocercal caudal fin, five rows of scutes, and an inferior mouth lined with barbels (Bemis and Kynard 1997). Gulf Sturgeon have only minor morphological differences from their sister subspecies Atlantic Sturgeon (*Acipenser o. oxyrinchus,*), but the two subspecies have distinct geographic ranges separated by the Florida Peninsula (Huff 1975). The species was once abundant across the northern Gulf of Mexico from the Mississippi River to Tampa Bay, FL. Current populations have been reduced to remnants across seven Gulf Coast river systems: the Suwannee, Apalachicola, Choctawhatchee, Escambia, Yellow, Pascagoula, and Pearl rivers (USFWS and NMFS 2009). Overfishing and impoundment construction led to population declines and extirpation from some rivers (USFWS and GSMFC 1995). The most severe overfishing occurred in the early 20$^{th}$ century, with fisheries moving westward from Tampa Bay, FL as stocks were depleted (Huff 1975, USFWS and GSMFC 1995). A statewide harvest moratorium was enacted in Florida waters in 1984, and Gulf Sturgeon was listed as threatened under the Endangered Species Act in 1991 (USFWS and NOAA 1991). Despite an end to commercial fishing and some habitat protections afforded by the ESA listing, Gulf Sturgeon stocks have not rebounded to historic levels. Recovery has likely been slowed by the continued habitat limitations caused by channelization, pollution, and – most significantly – dams (Wooly and Crateau 1985, Sulak and Clugston 2007, USFWS and NMFS 2009).

The Apalachicola River is formed by the confluence of the Flint and Chattahoochee rivers at the boundary between Florida, Alabama, and Georgia. These three rivers make up the ACF River Basin, which drains over 48,000 square kilometers of land (Ruhl 2005). Once known as the “breadbasket of the south,” the Apalachicola River exists now as a tightly regulated coastal plain river that flows from the Jim Woodruff Lock and Dam (JWLD) to Apalachicola Bay and the Gulf of Mexico. The dam, which formed Lake Seminole, was constructed at the confluence of the Chattahoochee and Flint rivers in 1957. The lower river basin is characterized by a vast, mostly undeveloped floodplain. This floodplain can span up to 8 kilometers in width in along some sections of the river and regularly experiences substantial flooding (Light *et al.* 1998, Ruhl 2005). Although mean flow in the Apalachicola has increased over the last century, channelization and moderation of flow by the JWLD has caused a reduction in overall river stage and – subsequently – the frequency of floodplain inundation (Light *et al.* 2006). Modified flow and habitat limitations resulting from the JWLD have been suggested to be problematic for Gulf Sturgeon in this river, likely contributing to their lack of recovery (Flowers *et al.* 2020). While the Apalachicola River population is considered by researchers as one of the more robust outside of the Suwanee River, the delayed recovery of this species here coincides temporally with the continued and increasing anthropogenic influences on the Apalachicola River’s flow regime.

Like other Acipenserids, the Gulf Sturgeon has a complex and protracted life history. Female Gulf Sturgeon may take 12 years to mature, and then may only spawn once every few years (Huff 1975). Each year, in March and April, all age-1+ life stages of Gulf Sturgeon return from the Gulf of Mexico to their natal rivers, with spawning adults eventually traveling far upriver to spawn. Spawning habitats are generally characterized by large areas of porous limestone. In the Apalachicola River these sites, which have been identified by egg collection mats, side scan sonar, and acoustic telemetry, are primarily within 20 km of the JWLD (Flowers 2009, Paruka *et al*. 2011). The amount of spawning habitat available in the Apalachicola River is determined by river discharge (USFWS 2016), which is regulated by the JWLD. When river discharges drop below 127 $m^3$/s, spawning habitat is reduced, with increases in discharge up to 622 $m^3$/s maximizing the amount of available habitat (Flowers *et al.* 2009). Based on these findings, managers in this system already prescribe modifications to the flow regime in the spring months to increase spawning habitat and theoretically improve conditions for spawning Gulf Sturgeon (USFWS 2016).

After spawning occurs, egg and larval stage Gulf Sturgeon may be especially vulnerable to environmental variables as most mortality occurs during the first year of life (Pine *et al.* 2001; Pine and Martell 2009, Rudd *et al.* 2014). Eggs and freshly hatched larvae remain must remain in the substrate, and large, acute changes in discharge due to hydroelectric related operations at the JWLD may displace these early life stages, causing increased mortality (Mason and Clugston 1993, USFWS 2016). Following hatching and subsequent yolk sack absorption, larvae feed on plankton while transitioning from benthic to pelagic riverine habitat (Mason and Clugston 1993, Flowers *et al.* 2009). Trawl surveys in the Suwanee River have found young juveniles of (<100 mm FL) at a varying range of river kilometers (33–139), suggesting a wide dispersal (Sulak and Clugston 1998). As they develop further, the young Gulf Sturgeon eventually utilize estuarine habitats for benthic forage. Juveniles presumed to be 10–12 months old have been recorded moving downstream into estuarine feeding grounds between January and February. Laboratory studies have indicated that Gulf Sturgeon <55 days old are intolerant of salinities above 12 ppt (Kynard and Parker 2004). Therefore, it has been suggested that river discharge during the winter months may also determine access to this important forage habit, ultimately affecting recruitment to the age 1 cohort (Sulak and Clugston 1998, Randall and Sulak 2007, USFWS 2016).

Nutrient inputs and resulting ecological effects from the periodic inundation of floodplain areas have complex effects on the biota in and around coastal plain rivers (Junk *et al*. 1989, Poff *et al.* 1997, Benke *et al*. 2000). When the Apalachicola River floodplain is inundated in the summer months, it may provide an increased nutrient source for benthic fauna, which are in turn eaten by juvenile Gulf Sturgeon (Junk *et al.* 1989, Livingston 1997, USFWS 2016). Hydrologists working with the USFWS have found a decline in the amount and frequency of floodplain inundation over the last few decades (Light *et al*., 1998, 2006. This "dryer forest" and resulting loss of connectivity is likely contributing to a reduction in abundance and diversity of aquatic biotic assemblages in the system (Junk *et al*. 1989, Light *et al.* 2006, Schueller and Peterson. 2010). A positive relationship between discharge levels that achieve floodplain inundation and Largemouth Bass *(Micropteres salmoides)* year class strength has been demonstrated in the Apalachicola River (Bonvechio and Allen 2004, Dutterer *et al.* 2012), and a similar relationship has been proposed for Gulf Sturgeon (USFWS 2016). Although Gulf Sturgeon have never been captured or recorded in the Apalachicola River floodplain, it potentially provides critical support for young juveniles.

The late age of maturity, complex life history, and migratory nature of Gulf Sturgeon can extend the time frame for population recovery and make monitoring that recovery difficult (USFWS 2016, Flowers *et al*. 2020). Recruitment population trends within the young-of-year and juvenile age classes are an important metric when assessing recovery in both sturgeons (Schueller and Peterson 2010, Flowers *et al*. 2020). Recent work on the Apalachicola River has focused on estimating recruitment (i.e., abundance of the age-1 cohort) to observe trends in Gulf Sturgeon recruitment (Fox *et al*. 2021). From 2013–2022, point estimates of recruitment in this system have varied from 28–210 (Fox *et al*. 2021, Dula *et al.* 2022, Chapter 2 of this thesis). Quantifying annual recruitment provides managers with relevant and timely feedback on population trends and can indicate potential effects of any management actions.

The drivers behind the variability of Gulf Sturgeon recruitment are not well understood, but variation in environmental characteristics – such as flow – may be explanatory. Therefore, we formulated four distinct hypotheses (Table 3.1) that propose to explain how biologically relevant aspects of the Apalachicola River's flow regime may affect Gulf Sturgeon recruitment. Those hypotheses and their effects on recruitment are summarized here:

1. Spawning habitat hypothesis: greater availability of spawning habitat during spawning allows for a more productive spawn, resulting in increased recruitment of age-1 Gulf Sturgeon (Pine *et al.* 2006, USFWS 2008, Flowers *et al.* 2009).
2. Hydropeaking hypothesis: increased frequency of changes in river stage (such as those caused by hydropeaking operations at JWLD) in March–May disrupt the benthic early life history stages of Gulf Sturgeon and/or the benthic invertebrates on which they forage, decreasing survival. Thus, fewer fish recruit to age 1 (USFWS 2016).
3. Floodplain inundation hypothesis: increased floodplain inundation in June–October benefits invertebrate populations. This increases the forage base for larval and juvenile Gulf Sturgeon, resulting in greater early life stage survival and increased number of age-1 recruits (USFWS 2016).
4. Winter foraging hypothesis: increased river flows during the November–February decrease salinity in the estuary. This allows young juveniles (which have low salinity tolerance) better access to estuarine feeding grounds, increasing the number that survive to recruit to the population at age-1 (Randall and Sulak 2007, Sulak and Clugston 1998, USFWS 2016).

The primary objective of this study was to quantitatively test those hypothesized relationships using a multiple linear regression analysis. As a secondary objective, we used the top model from the regression analysis to predict Gulf Sturgeon recruitment under low-, median-, and high-flow scenarios.

**Methods**

*Study Site*. — The Brothers River (Figure 3.2), a coastal plain tributary of the Apalachicola River, has been identified an important Gulf Sturgeon aggregation site (Marbury 2016, Fox *et al*. 2021). Both juveniles and adults use this area heavily. Most of the sampling sites for this and previous studies were located within the Brothers River, however sampling was periodically performed in the main stem of the Apalachicola River as well, near the estuary and upriver at the JWLD.

*Sturgeon capture*. — This study used data previously collected in 2013–2020 by Fox *et al.* (2021) and Dula *et al*. (2022), as well as new data collected in 2021–2022 (Chapter 2 of this thesis); collection methods for all years were the same.  Sampling was performed using bottom anchored gill nets consisting of three 15-meter panels of 7.6-, 8.9-, and 10.2-cm stretch measured monofilament mesh. Nets were set for intervals of 30–120 minutes depending on water temperature, oxygen, flow, and weather conditions. Upon capture, fish were placed in floating net pens until all nets were retrieved. Fork length (FL) and weight were recorded for each individual. All sturgeon were then scanned for passive integrated transponder (PIT) and floy tags. If previously unmarked, a PIT tag was inserted under the scute nearest the dorsal fin. An anal fin clip of approximately 1 $cm^2$ was taken and stored in ethanol for future genetic analysis by researchers at the University of Southern Mississippi. Each captured fish was assigned an age based on its length (Moran 2018, Fox *et al.* 2021). The second marginal fin ray was removed from fish presumed (based on length) to be <2 years old for future age analysis by US Fish and Wildlife Service research partners. Once data had been collected, the sturgeon were immediately released back into the river.

*Recruitment Estimates* — Estimates of annual recruitment (i.e., age-1 abundance) were obtained from previous studies (Fox *et al.* 2021 for 2013–2018, Dula *et al.* 2022 for 2019–2020) and calculated using the same methods for 2021–2022 catch data (Chapter 2 of this thesis). We used the Rmark package (Laake 2013) in Program R (R Core Team, 2021) to run a suite of Huggins closed-capture models (Huggins 1991). These models either held capture probability constant or allowed it to vary with sampling occasion, age class, or the additive or interactive effects of those factors age and time. We then used corrected Akaike Information Criterion (AICc) (Akaike 1973, Otis *et al*. 1978) to rank the models and selected the top model (i.e., the model that carried the most weight) to produce the recruitment estimate for each year.

*Environmental data.* — Discharge data was obtained from the United States Geological Service (USGS) gauge at Chattahoochee, Florida (USGS 02358000, river kilometer 170) on the Apalachicola River, which has been recording continuously since 1988. From these discharge data we then quantified the environmental variables used in the regression analysis (Table 3.3).

1. For the spawning habitat hypothesis, we calculated the cumulative acres of spawning habitat inundated from March–May (CASH) using a relationship between mean daily discharge and the amount of spawning habitat inundated

developed by the USFWS (2008, 2016) using a method similar to the work published in Flowers *et al.* (2009).

2. For the hydropeaking hypothesis, we counted the total number of acute rises in discharge greater than 100 $m^3/s$ over < 60 minutes that occurred in March and April (TRIS). This metric was based on the biological opinion for the ACF water control manual USWFWS (2016), which describes hydropeaking conditions and potential effects on Gulf Sturgeon.
3. For the floodplain inundation hypothesis, we counted the proportion of days in June–October that had ≥10% floodplain inundation (PDFI). This calculation was based on the work of Light *et al*. (1998), who found that mean daily discharges of > 460 $m^3/s$ from the JWLD led to a biologically relevant amount of inundation: approximately 10% of the total available floodplain.
4. For the winter foraging hypothesis, we calculated the cumulative total of daily discharge in ($m^3/s$) from November–February (CDIS).

*Multiple Regression Analysis.* — We used the ggplot2 package (Wickham 2016) in Program R (R Core Team 2022) to perform a multiple linear regression analysis that quantified the effects of four, temporally-defined flow regime variables (CDIS, TRIS, CASH, and PDFI) on annual recruitment. To normalize the response variable, we natural log transformed the recruitment estimates from each year. We created a candidate set of models including one for each temporally defined flow variable and a global model that combined all flow variables and used corrected Akaike Information Criterion (AICc) (Akaike 1973, Otis *et al*. 1978) to rank the candidate models by relative weight and select the top model. We also examined model likelihood and statistical significance ($\alpha = 0.05$) (Table 3.3).

We used the results of our top model to predict expected recruitment under three different hydrologic conditions- drought, median flow, and flood. To achieve this, we constructed three linear regression models based on the top hypothesis relating flow to recruitment (as selected in the previous paragraph), and provided the flow metrics for drought, median, and flood flows. We then used the models to estimate recruitment in each flow scenario.

**Results**

*Sturgeon Data*. — This analysis includes data from 3600 nets set in the Apalachicola River from 2013–2022 (Fox *et al*. 2021, Dula *et al*. 2022, and Chapter 2 of this thesis). During that period, 3221 Gulf sturgeon were captured, including 558 unique age-1 juveniles. Point estimates of annual age-1 recruitment varied from a low of 28 in 2017 to a high of 210 in 2014 (Table 3.2, Fox *et al.* 2022, Chapter 2). There appeared to be a trend of increasing annual recruitment that began in 2018.

*Multiple Regression Analysis.* — Of the 4 discharge-related variables we examined, only one showed a substantial relationship to annual recruitment. There was a relatively strong positive relationship between PDFI and annual recruitment over our 10-year study period ($R^2_{adj}= 0.60$, $p = 0.005$). The other three discharge variables did not have significant correlations to annual recruitment (CASH: $R^2_{adj} = -0.11$, $p = 0.01$; TRIS: $R^2_{adj} = 0.07$, $p = 0.24$, CDIS: $R^2_{adj} = -0.07$, $p = 0.54$). The global model indicated that the combination of all discharge-related variables did not have a strong relationship with recruitment ($R^2_{adj} =-0.07$, $p = 0.84$). The $AIC_c$ analysis indicated that the floodplain inundation hypothesis was the top model, carrying 97% of the weight (Table 3.3). The hydropeaking hypothesis (weight = 0.1%) was the only other model with a non-zero $AIC_c$ weight.

*Predictions.* — Because AIC analysis indicated that floodplain inundation hypothesis best explained the observed variation in annual recruitment, we used PDFI to predict recruitment under three different flow scenarios. Our drought scenario consisted of a PDFI of zero (no days with ≥10% floodplain inundation during June–October). Under those conditions, our model predicted a point estimate of 45 recruits (95% prediction interval: 15–141) (Figure 3.2). In our median scenario, PDFI was set at 28% (35/123 days with ≥10% floodplain inundation during June–October), the median observed PDFI over the 10-year study period. Under median conditions, our model predicted 99 recruits (95% PI: 21–177). In our flood scenario, PDFI was set at 93% (115/123 days with ≥10% floodplain inundation during June–October), based on the highest observed PDFI during the study period). Under flood conditions, the model predicted 223 recruits (p=95% PI: 63–749) recruits.

**Discussion**

Hypotheses about the environmental drivers of Gulf Sturgeon recruitment have been proposed and repeated in various management documents (e.g., USFWS 2008, 2016) but have never actually been tested. Because researchers have collected ten years of recruitment data for the Apalachicola River Gulf Sturgeon population, we were able to evaluate those hypotheses using real-world recruitment data. Our results indicated that most of the proposed hypotheses were not good at explaining the observed variations in annual recruitment. We did not find a strong relationship between recruitment and acreage of available spawning habitat. Nor did we find that annual recruitment was strongly related to increases in river rises (such as would result from hydropeaking) during early life stages. Finally, we did not find that increased discharge during the winter months was related to increased annual recruitment. Our global model results indicated that the combination of all discharge-related variables was also not linked to recruitment.

*Floodplain Inundation and Recruitment*. — We found that a greater proportion of days with ≥10% floodplain in June–October had a relatively strong positive relationship with age-1 recruitment as measured the following summer. Young Gulf Sturgeon have never been reported using the floodplain, but few studies have looked for this behavior. Floodplain use by sturgeon is not unknown – age-0 Pallid Sturgeon (*Scaphirhynchus albus*) were recorded swimming and feeding in the inundated Missouri River floodplain (Gosch 2021). Regardless of whether Gulf Sturgeon enter the floodplain, floodplain inundation could certainly benefit them. When the USFWS (2016) proposed the floodplain inundation hypothesis to explain variation in recruitment, they suggested that when the floodplain is inundated, it benefits the macroinvertebrate organisms that juvenile sturgeon prey upon, increasing the forage base for the sturgeon.

The quantity and quality of the forage provided by a river is subject to complex mechanisms (Chanton *et al*. 2002, Nunn *et al.* 2012). The riverine continuum concept (Vannote *et al*. 1980) describes how river systems are constantly influenced by streamflow changes due to elevation. These changes create a cascade of biological effects as ecosystems develop and grow around them. The concept and general model were further modified by Bayley (1995) and

Tockner (2000) to account for drastic, manmade changes to river flow, such as dams. Regarding floodplains, Junk *et al.* (1989) introduced the flood pulse concept that describes how varying levels of flow can influence floodplain ecology and resulting inputs into the river. These complex processes have been shown to affect anadromous fish species. For example, different flows and subsequent floodplain inundation levels created significant differences in the quantity and source of nutrients incorporated by Chinook Salmon (*Oncorhynchus tshawytscha*) and Steelhead (*Oncorhynchus mykiss irideus*) populations (Belmore *et al*. 2013). For Gulf Sturgeon, the quantity and quality of nutrients consumed by larvae and young juveniles is also likely influenced to some degree by the amount and type of biological activity in the floodplain.

In the Apalachicola system, floodplain inundation has already been demonstrated to benefit other fish species. These fish will enter and use inundated floodplain for various purposes, including spawning and feeding (Burgess *et al*. 2013), as well as for potential refuge (Gerken and Paukert 2010, Górski *et al.* 2011). Walsh *et al.* (2009) found that larval fish from over 40 taxa occupied Apalachicola River floodplain areas in the spring and summer months. Increased inundation led to larger age-0 growth rates, catch rates, and subsequently increased recruitment of Largemouth Bass, Redear Sunfish (*Lepomis microlophus*), and Spotted Suckers (*Minytrema melanops*) in the system (Dutterer *et al*. 2012). These studies noted that there appeared to be benefits at multiple trophic levels, with larval fish likely also benefiting from the large amounts of plant matter, and subsequent refuge, present in the floodplain (Rozas and Odum 1988.)

During the June–October period that we investigated, spring-spawned juvenile Gulf Sturgeon would be approximately 2–6 months old. Little is known about Gulf Sturgeon in the wild at this life stage, as they spread widely from the spawning area (Sulak and Clugston 1998) and are difficult to capture. When Gulf Sturgeon larvae begin exogenous feeding after approximately 1 week of yolk sack absorption, they have a short time window in which they must be successful or perish. This period of life has been referred to as the "critical period" for Shortnose (*Acipenser brevirostrum*) and Atlantic Sturgeon (Hardy and Litvak 2004) as well as other marine fish species. By 60–90 days after hatching (May–July), Gulf Sturgeon larvae have likely dispersed widely throughout the river, where they feed primarily on benthic invertebrates (Mason and Clugston 1993, Kynard and Parker 2004).

Variation in the time of peak productivity in a river system can affect annual variation in fish recruitment, corresponding with peaks in food source (Cushing 1990). Input from the floodplain in summer and early fall would increase biological productivity in the Apalachicola River while young Gulf Sturgeon are feeding and growing. For Gulf Sturgeon to survive to age 1, they must effectively feed, grow, and escape predation. More abundant food, resulting from floodplain inundation and the associated nutrient input to the river, would help the young fish with the first two of these objectives. Feeding rates were significantly related to growth rates of captive White Sturgeon (*Acipenser transmontanus*) (Deng *et al.* 2003). Beyond survival, poor feeding environments can also have other effects on riverine fish that manifest later in life, including reduced frequency of spawning events or reduced overall fecundity. (McBride *et al.* 2015). By increasing food sources at multiple trophic levels, inundation of the Apalachicola River floodplain during the early life stages of a year class may well benefit the Gulf Sturgeon population for decades, as those fish mature faster and spawn more throughout their lifespan.

*Apalachicola River Gulf Sturgeon Recovery*. — The Apalachicola River's capacity to host a healthy Gulf Sturgeon population is likely limited by habitat disruptions caused by the construction of the JWLD (Flowers *et al*. 2020). Dams affect local flora and fauna composition and can alter ecosystem structure in habitats far above and below the impoundment (Freeman 2003, Rolls *et al.* 2012, 2013, Kennedy 2016). The Suwannee River, which is unimpounded for its entire length of nearly 400 km, harbors the largest Gulf Sturgeon population, with an estimated abundance of 5,000–10,000 individuals (Chapman and Carr 1995, Sulak and Clugston 1998, USFWS and NMFS 2009). After the closure of the fishery, the Suwanee River population grew by an estimated 5% annually from 1986 to 1995 (Pine *et al.* 2001). This is a stark contrast to the Apalachicola River population of Gulf Sturgeon, which were protected from harvest at the same time. In the Apalachicola River, point estimates of the subadult/adult population range from 350–1,000 individuals (Pine and Martell 2009, USFWS and NMFS 2009, Dula *et al.* 2022). The presence of the JWLD on the Apalachicola River may explain much of the difference between these two rivers. The natural streamflow dynamics of the undammed Suwannee River may have helped facility Gulf Sturgeon recovery there, whereas the JWLD continues to impair the Apalachicola Population by both preventing fish from accessing approximately 78% of their potential historic spawning habitat (USWFWS 2008, Flowers *et al.* 2009, Kaeser *et al.* 2013), and by altering hydrologic patterns (Light *et al.* 1998, Torak and Painter 2006). Compared to the historic median, overall discharge rates for the Apalachicola River have been increased in the winter and early spring months, but decreased in the summer and early fall (Light *et al.* 2006). Because floodplain inundation during the summer and fall correlates with stronger annual recruitment, this specific hydrologic change may explain why the Apalachicola River Gulf Sturgeon population is failing to recover, in contrast to the nearby Suwannee River population. Ecosystem-based management actions, which consider both abiotic and biotic factors like river discharge, nutrient enrichment, and resulting productivity (Livingston 1997, Belmore *et al.* 2013), are likely key to recovery efforts for this species.

*Implications of Climate Change for Gulf Sturgeon*. — In the Apalachicola River, floodplain inundation from June through October is a significant factor affecting annual recruitment. Although droughts have long been part of the climate of the Southeastern U.S. for millennia (Carter *et al.* 2018), multi-year droughts could prove detrimental for Gulf Sturgeon in this system. Regardless of how successful a spawn may be, drought conditions during early life stages could be impairing population recovery through reduced juvenile survival, reduced overall fecundity, or changes to the rate of maturity that could have effects on the population for decades afterwards. If low-flow events continue to occur, the risk of extirpation from the system could increase (Randall and Sulak 2007, Flowers *et al.* 2009, 2020). Climate change predictions cite increasing frequency and duration of droughts in the southeast (Walsh *et al.* 2018). These same studies also suggest that despite the increase in droughts, total annual precipitation will increase due to acute high-precipitation events. If such flooding events occur during the summer and early fall, they might prove advantageous for Gulf Sturgeon, potentially helping more young-of-year juveniles survive to age-1.

Climate change is also predicted to increase the intensity of hurricanes in the southeast (Bender *et al*. 2010), accounting for some of the predicted rise in acute precipitation events. When Hurricane Michael hit the Apalachicola River in October 2018, it caused a large mortality event among adult Gulf Sturgeon (Dula *et al*. 2022). The storm's immediate effects on the juvenile population are unclear, but the age-1 cohort in the Apalachicola River has increased in size each year since 2019 (fish that were age-1 in 2019 were most likely spawned in spring 2018, before the hurricane). The fall flooding caused by the storm may help explain why recruitment has been increasing, despite the substantial adult mortality. The increase in primary productivity and subsequent benefits to both abundance and diversity of benthic fauna may be continuing to benefit multiple years of post-storm recruits. Although the potential increase in fall flooding events from more large hurricanes could potentially benefit Gulf Sturgeon recruits, repeated adult mortality events caused by hurricanes also have the potential to cause population collapse (Dula *et al.* 2022).

Beyond droughts and hurricanes, warming water temperatures pose another threat to Gulf Sturgeon. Similar to the results of this study, age-0 White Sturgeon recruitment in the Columbia River, WA was positively correlated with discharge levels in June and July (Counihan and Chapman 2017). However, the results of that study also suggested that high water temperatures during the summer had a negative influence on White Sturgeon Gulf Sturgeon eggs and larvae in laboratory conditions experience significant mortality above 25 °C (Chapman and Carr 1995, Altinok *et al*. 2008). Low river discharge rates correlate with high river temperatures (Gu *et al.* 1998, Sinokrot and Gulliver 2000), and more frequent droughts may increase thermal stress on juvenile sturgeon. Droughts will compound the climate-change related warming of Gulf of Mexico Rivers, posing a serious threat to Gulf sturgeon recruitment. Temperature data were not available for the full length of this study, and we were therefore unable to include temperature in our suite of candidate models. However, the Apalachicola River basin is geologically characterized by limestone karst, with many cool (<16 °C) springs (Torak and Painter 2006) leading to a wide variation in local river temperatures; Gulf Sturgeon in the Choctawhatchee River were found near springs in the summer months, perhaps using them as thermal refuge

(Hightower *et al*. 2002). Although future research should investigate the relationship between recruitment and water temperatures, such an analysis might be confounded by sturgeon behavior.

Natural resource managers are likely to benefit in the future by making decisions in the that consider entire landscapes or watersheds (Nislow *et al*., 2010). Globally, riverine flow regime managers have worked with stakeholders and have found ways to intentionally inundate floodplains in efforts to improve the health of riverine systems (Auerswald *et al.* 2019). However, these actions are only possible if there is excess water available. While climate models do suggest that the southeastern US is likely to experience more prolonged droughts, these same studies also project that total annual precipitation will increase (Walsh *et al.* 2014, Carter *et al.* 2018). The results of this study suggest that the floodplain inundation hypothesis is a viable explanation for the variation in juvenile Gulf Sturgeon recruitment. Increased river discharge and subsequent floodplain inundation during late summer and fall may facilitate strong Gulf Sturgeon recruitment numbers in the Apalachicola River. This information gives managers with a new tool that could promote the recovery of Gulf Sturgeon in this system. Managers in this system could ensure that when appropriate, excess water is released at the JWLD with the intent of inundating this floodplain. The Apalachicola River floodplain is largely undeveloped, with over 450 $km^2$ of bottomland forest (Torak and Painter 2006 Light *et al.* 2006), making this intentional inundation potentially feasible. One logistical problem specific to this system is the low storage capacity of Lake Seminole, which limits the actions that can be taken in a drought. (Torak and Painter 2006, Leitman *et al.* 2016). Regardless, this research supports the fact that managers must consider the dynamic complexities of riverine ecosystems when attempting to facilitate the recovery of this and other imperiled fish species.

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**Table 3.1:** Proposed hypotheses relating Gulf Sturgeon recruitment to environmental drives. For each hypothesis, we provide the proposed time period and the specific environmental variable we analyzed. Environmental variables were calculated based on flow at USGS streamgage 02358000 in Chattahoochee, FL.

| Hypothesis | Source | Proposed mechanism and effect | Time period | Environmental variable |
|---|---|---|---|---|
| 1. Spawning habitat | USFWS (2008) Flowers *et al*. (2009) | Increased availability of spawning habitat during spawn results in increased number of recruits | Mar–Apr | Cumulative acres of spawning habitat inundated (CASH) |
| 2. Hydropeaking | USFWS (2008, 2016) | Increased frequency of changes to river stage during egg/larval periods disrupts early life stages and decreases number of recruits | Mar–May | Total number of rises (TRIS) |
| 3. Floodplain inundation | USFWS (2016) | Increased floodplain inundation during larval/juvenile stages leads to better forage, increasing number of recruits | Jun–Oct | Proportion of days in which at least 10% of the floodplain is inundated (PDFI) |
| 4. Winter Foraging | Randall and Sulak (2007) | Increased river discharge during winter allows greater juvenile access to estuarine feeding grounds, increasing number of recruits | Nov–Feb | Cumulative discharge (CDIS) |

**Table 3.2:** Gulf Sturgeon recruitment (i.e., age-1 abundance) in the Apalachicola River from 2013–2022. Results from 2013–2018 (indicated with a *) are from Fox *et al.* (2021). Results from 2019–2020 (indicated with a +) are from Dula *et al.* (2022).

| **Year** | **Number of recruits** | **95% Confidence interval** |
|---|---|---|
| 2013* | 46 | 37–70 |
| 2014* | 218 | 190–241 |
| 2015* | 54 | 34–119 |
| 2016* | 51 | 35–67 |
| 2017* | 28 | 24–36 |
| 2018* | 31 | 21–48 |
| 2019+ | 117 | 95–157 |
| 2020+ | 122 | 88–189 |
| 2021 | 139 | 99–209 |
| 2022 | 161 | 136–197 |

**Table 3.3:** Results of multiple linear regression analysis used to investigate the relationship between annual recruitment (Rec) of Gulf Sturgeon (log transformed) and flow regime variables (Table 3.1) in the Apalachicola River, FL. The global model related recruitment to an additive combination of all flow variables. For each model, we provide the number of parameters (K) AICc value, delta AICc,, Akaike weight (W), adjusted $R^2$ value, model estimate, and p-value (α = 0.05). The top model is highlighted in bold.

| Model | Parameter est. | K | AICc | ΔAICc | W | $R^2_{adj.}$ | p-value |
|---|---|---|---|---|---|---|---|
| **Rec~ PDFI** | **1.70** | **3** | **19.99** | **0.00** | **0.97** | **0.60** | **0.005** |
| Rec~ TRIS | 0.07 | 3 | 28.46 | 8.46 | 0.01 | 0.07 | 0.235 |
| Rec~ CDIS | 0.00 | 3 | 29.84 | 9.85 | 0.00 | -0.07 | 0.544 |
| Rec~ CASH | 0.00 | 3 | 30.22 | 10.22 | 0.00 | -0.11 | 0.771 |
| Rec~PDFI+TRIS +CDIS+CASH | 0.00 | 6 | 46.69 | 26.70 | 0.00 | -0.22 | 0.842 |

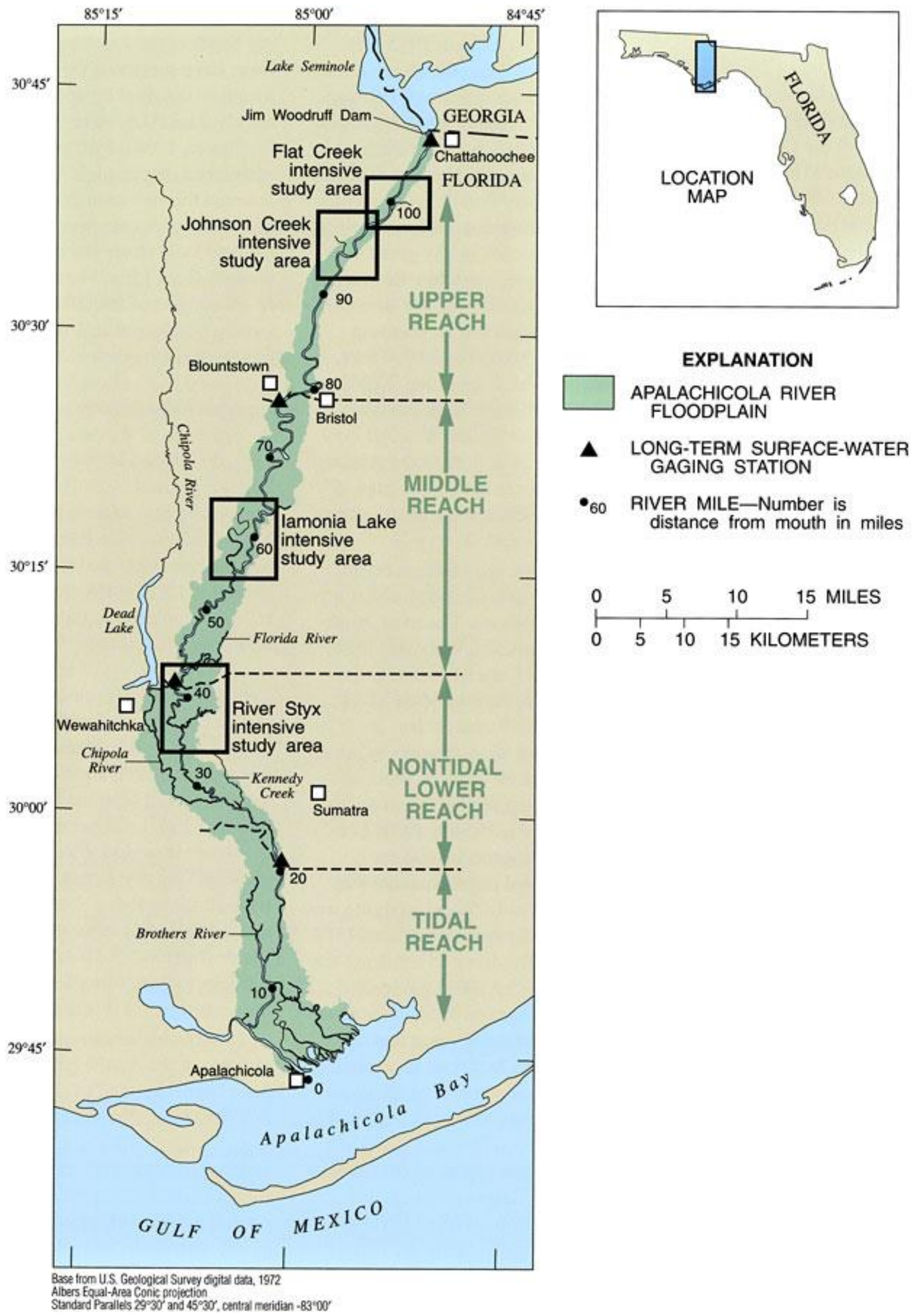


**Figure 3.1:** Map of the Apalachicola River FL, and surrounding floodplain (from Light *et al.* 1998). Floodplain areas highlighted in green. Areas in boxes are study sites from which non-tidal floodplain inundation was observed and quantified. Environmental variables were calculated based on flow at USGS streamgage 02358000 in Chattahoochee, FL.

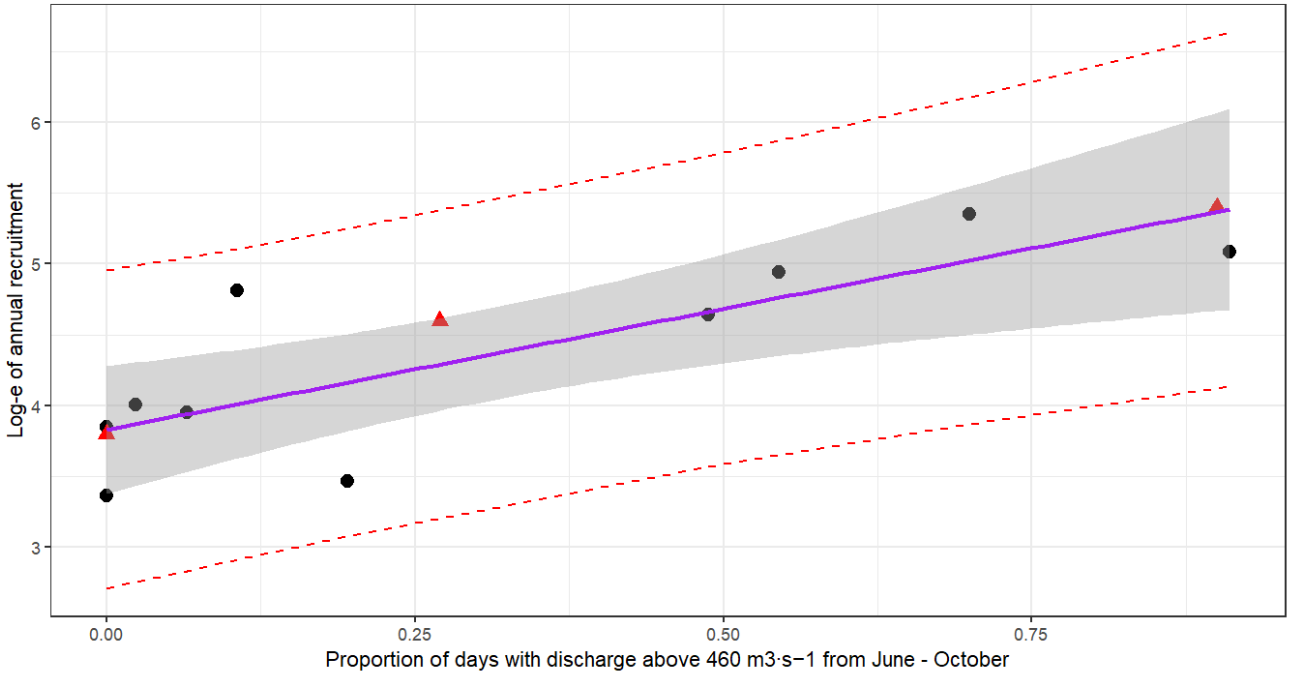


**Figure 3.2:** Relationship between log-transformed point estimates of annual Gulf Sturgeon recruitment in the Apalachicola River (2013–2022) and the proportion of days in June–October with ≥10% floodplain inundation (i.e., discharge ≥460 $m^3/s$). Discharge was measured at the JWLD (USGS streamgage 02358000). Black circles indicate observed estimates of annual recruitment, the purple line indicates the model regression line, and grey shading shows 95% confidence level ($R^2_{adj}$ = 0.599, p = 0.005). Red triangles indicate point estimates of the model predictions for drought (left), median (middle) and flood (right) conditions; model prediction intervals are indicated by dashed red lines.

# CHAPTER 4

# CONCLUSIONS

For managers of Gulf Sturgeon, an overarching goal over recent decades has been to facilitate the establishment of a sustainable population in all seven systems in which Gulf Sturgeon still reside (USFWS and GSMFC 1995, USFWS 2016, 2022). Despite the implementation of a state-wide fishing moratorium in 1984, the recovery of Gulf Sturgeon stocks in the Apalachicola River – and most other rivers – has been slow or non-existent. Assessing recovery is a painstaking exercise, as these fish are slow to mature, highly migratory, and often prove difficult to capture in the field. The use of annual recruitment information to identify trends in recruitment (and potentially trends in the future adult population) provides a consistent benchmark, if not an accurate assessment, of yearly inputs to the population. Young Gulf Sturgeon are easier to catch and handle than the adults, and their tendency to congregate in their natal systems during the first year allows for the use of relatively simple closed population models, as in Chapter 2 of this thesis.

Additionally, the variation in annual recruitment seen over the last 10 years in the Apalachicola River also provides the opportunity to investigate some potential reasons for the slow recovery of Gulf Sturgeon. Various hypotheses in the literature suggested that changes in river discharge patterns at specific times of year may affect the availability or quality of habitats for Gulf Sturgeon larvae and juveniles. Our analysis in Chapter 3 indicates that increased flood plain inundation in summer and fall, which results from increased discharge during that time, was the only study variable that explained variations in annual recruitment. Floodplain inundation is also important for numerous other fishes through mechanisms like increased food supply or refuge from predators.

Across the Gulf Sturgeon's range, there are unique challenges faced by managers in understanding and mitigating the factors affecting Gulf Sturgeon recruitment. Habitat disruptions have been identified as one of the remaining factors limiting recovery (Flowers *et al.* 2020). Stochastic events like hurricanes (Dula *et al*. 2022) or oil spills can have major effects on Gulf Sturgeon recovery as well. Increasing the number of recruits can help rebuild populations and mitigate some of the losses from mortality events. The research in Chapter 3 of this thesis provides some direction for adaptive management to occur in the Apalachicola River. By quantifying the relationship between annual recruitment and river flow, we found that floodplain inundation seems particularly important for achieving large age-1 year classes in the Apalachicola River. Because flow in this river is anthropogenically controlled, it may be possible for managers to enact water management changes that maximize annual recruitment within this population. There may well be other variables that we did not investigate that also affect recruitment – for instance, temperature. Temperature monitoring in the Apalachicola has only been consistent over the past 7 years, but as juvenile monitoring continues, future analyses can include that variable in their models. Continued sampling of juvenile Gulf Sturgeon, population modeling, and hydrologic monitoring are likely key to the successful management of this species across its range. If changes are made to flow or other aspects of Apalachicola River habitat, ongoing juvenile monitoring would reveal any effect on juvenile recruitment the following year. By understanding the environmental drivers affecting recruitment and exploring habitat enhancement opportunities, conservation efforts can be better targeted to promote the recovery and long-term viability of the Gulf Sturgeon in the western Gulf of Mexico.

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