RECRUITMENT AND OVERWINTER HABITAT USE OF JUVENILE GULF STURGEON IN THE APALACHICOLA RIVER, FLORIDA

by

NATHANIEL QUINN HANCOCK

(Under the Direction of DOUGLAS L. PETERSON)

ABSTRACT

The Gulf Sturgeon (*Acipenser oxyrinchus desotoi*) is listed as federally threatened because of historic overfishing and habitat degradation. Although there has been extensive research on subadult and adult Gulf Sturgeon, little is known about early life stages. From 2016 to 2018 I conducted a study designed to provide annual recruitment estimates, investigate the relationship between recruitment and flow regime, and determine the overwinter habitat use of age-1 Gulf Sturgeon. Closed capture-mark-recapture recruitment results were tested against flow using linear regression. Acoustic telemetry was used to provide an estimate of overwinter survival and to describe overwinter habitat use. The results from this study provide a baseline of recruitment and description of overwinter habitat use for age-1 Gulf Sturgeon. These results will better inform managers about the locations vital to survival of age-1 year classes and provide a baseline for measurement of recruitment success.

INDEX WORDS: Gulf Sturgeon, sonic telemetry, capture-mark-recapture, mark recapture, recruitment, abundance, population assessment, habitat use, juvenile

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DEDICATION

I would like to dedicate this thesis to my wife, Heather, for all of her love and support throughout my years at UGA and the writing of this thesis. I would also like to dedicate this thesis to my parents, Todd and Barbara Hancock, for kindling my passion for conservation, fisheries, and the outdoors. Finally, I would like to think everyone else who provided support of any kind during this process. I will always be grateful for everyone's unending motivation and support.

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Chapter 1

Introduction and Literature Review

Sturgeons are an ancient group of cartilaginous fishes that have existed largely unchanged for at least 200 million years (Bemis and Kynard 1997). These large, heavy-bodied, benthic fish are characterized by both a long life span and delayed maturation. Although they lack scales, they feature five rows of bony scutes interspersed with patches of smaller denticles embedded in their skin (Scott and Crossman 1973; Birstein 1993; Bemis and Kynard 1997). Many sturgeon species are anadromous, making them an important link between marine and freshwater ecosystems (Bemis and Kynard 1997, Limburg and Waldman 2009). These same life history traits, however, make sturgeon particularly vulnerable to anthropogenic disturbances such as overharvest and habitat change (Rochard et al. 1990).

The Gulf Sturgeon (*Acipenser oxyrhinchus desotoi*) is a subspecies of the Atlantic Sturgeon (*Acipenser oxyrhincus oxyrhincus* Mitchill 1815), distinguished primarily by its separate geographical range and by several morphological and behavioral differences. In contrast to Atlantic Sturgeon, which are found only on the Atlantic coast of North America, the historic range of Gulf Sturgeon includes all major river systems in the northern Gulf of Mexico, from Tampa Bay, Florida, to the Pearl River on the Mississippi/Louisiana border. Although Gulf Sturgeon closely resemble Atlantic Sturgeon, they have slightly longer heads and pectoral fins, slightly shorter scutes, and a larger spleen (Huff 1975). Gulf Sturgeon are not sexually dimorphic, but females typically grow larger than males. Some individuals reach maximum lengths of greater than 3 meters (Scott and Crossman 1973).

Gulf Sturgeon have an anadromous life cycle that relies on a variety of different habitats depending life stage and season. During the summer months, both adults and juveniles reside in channel habitats of their natal rivers – apparently fasting until temperatures begin to cool in the early fall, at which time they quickly move into the Gulf of Mexico (Gu et al. 2001). Throughout late fall and winter they actively forage in nearshore marine waters until the following spring, at which time they again return to their natal rivers. After entering freshwater, adults will continue their upstream migration until they find suitable spawning habitat – often in the upper reaches of the watershed where they can find moderate flows with clean gravel spawning substrates (Fox et al. 2000; Sulak and Clugston 1998, 1999; Kieffer and Kynard 1996; Folz and Meyers 1985). After spawning, adults disperse back downstream where they remain in deep holes and mainstem channels throughout the summer months (Sulak and Clugston 1999; Wooley and Crateau 1982, 1985). Like many other sturgeon species, Gulf Sturgeon are periodic spawners; females spawn only once every 3-5 years, and males every 2-3 years (Huff 1975).

Although the life history of both adult and subadult Gulf Sturgeon has been fairly well studied, relatively little is known about the behavior of early juveniles. Research shows that after hatching, free embryos remain at the spawning site sheltered under cover such as rocky structures. Larvae then leave the spawning site and begin a 1-step long larva-juvenile migration in which they gradually disperse downstream from the spawning area while remaining in freshwater habitats. Based on records that show larvae holding in the water column, it is possible that drift feeding is used during this migration period. Once the larvae mature to age 10-12 month juveniles they have been recorded moving downstream into the estuary between January and February where they join older juveniles in overwintering habitats. (Kynard and Parker 2004, Sulak and Clugston 1998). Once reaching juvenile stage, Gulf Sturgeon begin using water column habitats less and by 12 months of age are strictly benthic, feeding on a variety of invertebrates including mollusks, crustaceans, amphipods, and annelids. The young juveniles remain in these estuarine habitats throughout the winter months before returning back upstream to freshwater habitats in spring along with other early juvenile age classes (Kynard and Parker 2004, Huff 1975, Mason and Clugston 1993). Little is known about habitat use or biological requirements of age-1 juveniles during this estuarine overwintering period, although research on the Apalachicola River indicates they remain in the river delta throughout the winter months (Marbury and Peterson 2015). Evidence from tagging studies suggests that juveniles continue to overwinter in their natal estuaries until age-5 to -6 before initiating longer winter migrations into nearshore marine habitats as subadults (Sulak and Clugston 1998). After the fish mature at age-7 to -12, winter migrations extend to include both nearshore and offshore marine habitats in the northern Gulf of Mexico (Huff 1975).

Like all sturgeons, the delayed maturation and protracted spawning period of Gulf Sturgeon makes them sensitive to overharvest. During the 20th century, the commercial fishery was initially centered on Tampa Bay, but quickly expanded to the west as eastern populations were depleted (Huff 1975). By 1890 the fishery had reached the Apalachicola River and within a decade, that population had also collapsed. Despite numerous population collapses, largely unregulated fishing continued – albeit at lower levels - until statewide bans were enacted in Alabama (1972), Mississippi (1974), Florida (1984), and Louisiana (1990) (ADCNR 1972, Louisiana Legislature 1990, 1993, Mississippi Legislature 1974, USFWS and GSMFC. 1995). During this period a status review determined that further harvest would likely result in species extinction (Hollowell 1980). As a result, the species was listed as threatened under the Endangered Species Act in 1991(NOAA and USFWS). Once found from the Pearl River in Louisiana to Tampa Bay in Florida, the range of Gulf sturgeon now includes only the Pearl, Pascagoula, Escambia, Blackwater, Yellow, Choctawatchee, Apalachicola, Ochlockonee, and Suwannee Rivers (Huff 1975, Stabile et al. 1996, US Commission of Fish and Fisheries 1902, USFWS and NMFS 2009).

Despite federal protection, Gulf Sturgeon recovery has been hampered by a variety of anthropogenic factors. Although commercial fishing is widely recognized as the most important cause of Gulf Sturgeon decline, pollution, dredging, and construction of dams have severely inhibited recovery of most populations (Zehfuss et al. 1999). To address some of these threats to the recovery process, the USFWS and NMFS drafted the Gulf Sturgeon Recovery Plan in 1995 (USFWS and GSMFC 1995). This plan established several long-term goals to help guide species recovery through a series of discrete and quantifiable research objectives that included (1) targeted annual assessments of age-1 juvenile abundance as a quantified measure of annual recruitment, (2) directed research to determine the habitat requirements of early life stages, and (3) a broad investigation of how various environmental factors affect juvenile survival rates (USFWS and NMFS 2009; USFWS and GSMFC 1995).

The recovery status of Gulf Sturgeon populations varies widely across the range. The healthiest population is found in the Suwanee River, Florida, which contains at least 10,000 individuals (Sulak et al. 2016). The Suwannee River is undammed, allowing sturgeon to access over 400 km of free-flowing habitat. (Sulak and Clugston 1999; Chapman et al. 1997; Carr et al. 1996). In contrast, the Apalachicola River has a much smaller population of only 350 to 1200 individuals (Zehfuss et al. 1999, Sulak et al. 2016). Construction of the Jim Woodruff Lock and Dam (JWLD) in 1947 is widely recognized as a major impediment to the recovery of the population, as it prevents sturgeon from accessing as much as 78% of historical spawning habitat (Flowers et al. 2009; USFWS 2004; Zehfuss et al. 1999, USFWS and GSMFC 1995). Although Gulf Sturgeon still have access to the lower 170 km of the Apalachicola River mainstem, consistently low recruitment in this population suggests that spawning habitats below the dam may not be sufficient to restore the population to its historical abundance (Marbury and Peterson 2015). Quantitative recruitment assessments are completely lacking for many Gulf Sturgeon populations. The Apalachicola River is one of the most studied populations within the range, yet persistent knowledge gaps regarding population dynamics and early life history continue to hinder assessment efforts making it difficult to identify specific restoration actions needed for recovery. For anadromous sturgeons with long generation times, recruitment assessments are of the few effective methods for quantifying population status and trends (Schueller and Peterson 2010). For Gulf Sturgeon, annual recruitment is likely a bottleneck to recovery for many populations because of high mortality during the first year of life (99.6%) (Pine et al. 2001; Pine and Martell 2009). Consequently, quantified estimates of age-1 cohort size provide a critically important assessment of population trends, allowing managers to quickly assess the impacts of specific recovery actions or the potential effects of environmental change (Flowers et al. 2009; Sulak and Clugston 1999; Zehfuss et al. 1999). In 2013, Marbury and Peterson (2015) completed the first direct estimates of Gulf Sturgeon recruitment on the Apalachicola River. Although this study established an important benchmark for annual recruitment in that population, it only spanned 3 years. Because of their protracted life cycle and slow reproductive rate, Gulf Sturgeon populations must be assessed over many consecutive years to accurately determine population trends, and hence, population status.

Little is known about the seasonal habitat requirements of juvenile Gulf Sturgeon, although habitat may be a major impediment species recovery. In the Apalachicola River, Marbury and Peterson (2015) described a pattern of seasonal habitat use in which age-1 juveniles remained in freshwater holding areas during the summer but used estuarine river channels during the winter. Abiotic conditions could drive the habitat selection during early life history; young juveniles have been found to be more sensitive to salinity than older fish (Foster et al. 1994, Kynard and Parker 2004). This salinity barrier hypothesis (Randall & Sulak 2007, Sulak & Clugston 1998) is one of a number of as-yet untested theories about factors driving Gulf Sturgeon population trends. Despite the growing understanding of within-river juvenile movements, there are no published studies that focus on the seasonal transitions of age-1 juveniles between freshwater and estuarine habitats.

The goal of this project was to evaluate seasonal habitat requirements and annual recruitment of juvenile Gulf Sturgeon in the Apalachicola estuary. The specific objectives of this study were to 1) conduct annual age-1 abundance estimates as a quantified measures of recruitment; 2) identify estuarine habitats used by age-1 juveniles during seasonal transitions between fresh and salt water; 3) estimate survival of age-1 juveniles during their estuarine overwintering period. Results from this study will build upon the initial recruitment assessments from Marbury and Peterson (2015) to establish recruitment trends in the Apalachicola River population. This information can be used to evaluate the success of recovery actions, such as streamside rearing, that have been demonstrated as successful for other sturgeon populations (Holtgren et al. 2011) or construction of additional spawning habitat . Evaluation of seasonal habitats used early juvenile life stages will help identify future management activities such as seasonal protection of critical habitats from dredging that can help restore the population.

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Chapter 2

Recruitment of Juvenile Gulf Sturgeon in the Apalachicola River, Florida[1]

[1]Hancock, N.Q., Marbury J.A., Fox A.G., Kaeser, A.J., and D.P. Peterson. To be submitted to *Transactions of the American Fisheries Society*

Abstract

The Gulf Sturgeon (*Acipenser oxyrinchus desotoi*) is listed as federally threatened because of historic overfishing and habitat degradation. The objectives of this study were to estimate annual recruitment of age-1 Gulf Sturgeon in the Apalachicola River, Florida and to evaluate the relationship of river flow and recruitment. Gulf Sturgeon were sampled in the Brothers River, the primary aggregation site of the Apalachicola population, from April to August, 2016-2018. Gill nets made of 7.6, 8.9, 10.2 cm stretch monofilament were anchored in main channel habitats for approximately an hour. Gulf Sturgeon were injected with uniquely numbered PIT tags for use in Huggins closed mark recapture estimates of age-1 abundance. Linear regression was conducted to evaluate the relationship between flow (discharge, high flow duration (HFD)) and recruitment. Annual mark-recapture estimates indicated consistent, low recruitment between 28 to 51 age-1 juveniles during the study. Modelling showed positive relationships between recruitment and increased HFD in individual months (July, August, September) and summer (HFD summed from June to August) (R^2=0.983, 0.983, 0.983, 0.979). Recruitment had a positive relationship with discharge in July and August (R^2=0.941, 0.931). This suggests a relationship between flow and recruitment success, especially in late summer months during larval stage. This study provides the first estimates of the relationship of an environmental variable and direct recruitment of Gulf Sturgeon. Determining the extent of the relationship between flow and recruitment and investigating other environmental variables will allow managers to better predict the response of Gulf Sturgeon populations to environmental change.

Introduction

The Gulf Sturgeon (*Acipenser oxyrinchus desotoi*, Acipenseridae) is an allopatric subspecies of the Atlantic Sturgeon (*Acipenser oxyrhincus oxyrhincus* Mitchill 1815). The species' historic range included all major river systems in the northern Gulf of Mexico, from Tampa Bay, Florida, to the Pearl River in Mississippi and Louisiana (USFWS and NOAA 1991). The Gulf Sturgeon has an anadromous life cycle and exhibits a late age of maturity, protracted spawning intervals, and a long life span (Huff 1975). Gulf Sturgeon were historically overharvested for their caviar and meat and, combined with the construction of dams on many major spawning rivers, suffered major population declines (Huff 1975, Zehfuss et al. 1999). As a result, statewide fishing bans were first enacted in Alabama in 1972 and Mississippi in 1974. In 1980, an US Fish and Wildlife Service status review determined that further harvest would likely result in the species' extinction (Hollowell 1980). Fishing bans were eventually enacted in Florida (1984) and Louisiana (1990) (ADCNR 1972, Louisiana Legislature 1990, 1993, Mississippi Legislature 1974, USFWS and GSMFC. 1995). The species was ultimately listed as threatened under the Endangered Species Act in 1991(USFWS and NOAA). The extant range of Gulf Sturgeon includes the Pearl, Pascagoula, Escambia, Blackwater, Yellow, Choctawhatchee, Apalachicola, Ochlockonee, and Suwannee rivers (Huff 1975, Stabile et al. 1996, USFWS and NMFS 2009).

Currently, the recovery status of individual Gulf Sturgeon populations is not well understood but is believed to vary widely across the range. The largest population occurs in the Suwanee River, Florida, which contains at least 10,000 individuals (Sulak et al. 2016). Although some degree of habitat degradation is present in the Suwannee River, it is unimpounded and provides 400 km of free-flowing habitat for Gulf Sturgeon and other migratory fishes (Carr et al. 1996, Chapman et al. 1997, Sulak and Clugston 1999). In contrast, the Apalachicola River has a much smaller population, estimated to be only 350 to 1200 individuals (Zehfuss et al. 1999, USFWS 2004).

The Apalachicola River contains one of the most studied Gulf Sturgeon populations throughout the range. Although Gulf Sturgeon were once found throughout the entire ACF basin, the construction of the Jim Woodruff Lock and Dam (JWLD) in 1947 blocked their access to the Flint and Chattahoochee Rivers. Recent studies indicate that construction of JWLD eliminated Gulf Sturgeon access to as much as 78% of their historical spawning habitat. Consequently, the dam is currently recognized as the major recovery impediment to the Apalachicola River Gulf Sturgeon (USFWS and GSMFC 1995, Zehfuss et al. 1999, Flowers et al. 2009).

Repeated estimates of adult abundance provide a long-term assessment of large-scale population trends, but are insensitive to annual variation in recruitment because of the protracted life cycle and slow reproductive rate of Gulf Sturgeon. Consequently, adult abundance estimates do not help improve our understanding of how environmental factors affect ongoing recovery efforts (Schueller and Peterson 2010). In contrast, mark-recapture estimates of annual recruitment of age-1 individuals provide a quantitative measure of population status and trends in anadromous sturgeon species (Schueller and Peterson 2010, Bahr and Peterson 2016, Hale et al. 2016). Accurate estimates of annual recruitment are critical for evaluating recovery of Gulf Sturgeon populations because of the insensitivity of adults population estimates to short term changes (Sulak and Clugston 1999, Zehfuss et al. 1999, Flowers et al. 2009). Annual recruitment estimates also allow managers to quickly evaluate recovery actions as well as the effects of unpredicted environmental change. Although annual recruitment assessments have become the standard method for assessing population trends in Atlantic Sturgeon, direct recruitment estimates for Gulf Sturgeon have only been completed on the Apalachicola River (Marbury and Peterson 2015). Although previous studies have attempted to model and back-calculate recruitment based on age structure data (Sulak and Clugston 1999, Randall and Sulak 2007, Pine and Martell 2009), their methods rely on several uncertain assumption and their results provide only a historical depiction of general population trends.

Due to the complexity of the first year of life for Gulf Sturgeon, there are a number of competing hypotheses regarding the primary factors contributing to successful recruitment to age-1. As a result of high mortality of eggs at increased temperatures around 25ºC it has been hypothesized that cooler conditions during and following egg deposition (between late March and late May) may contribute to recruitment (Sulak and Clugston 1999). This effect also apply to 70-80 day juveniles which have shown stress and mortality in lab conditions under a temperature increase from 21 to 23ºC (Kynard and Parker 2004). Flow during egg and larval stage may also be important. During this period eggs and embryos remain in the substrate at the spawning site until they develop to larval stage and begin moving downstream (Sulak and Clugston 1999, Kynard and Parker 2004). It is hypothesized that high flows during this period could reduce retention of larvae in the spawning substrate, disrupt feeding during downstream migration, and possibly push larvae downstream into saline water although little data currently exists to support this hypothesis(USFWS 2016). Furthermore, based on the flood pulse concept it is proposed that increased flow may contribute to increased recruitment through access to floodplain foraging habitats and addition of organic matter and nutrients to the system (Junk et al. 1989). Although Gulf Sturgeon have not been recorded using this floodplain habitat, the stimulation of benthic prey availability as a result of added nutrients in the main channel may increase foraging habitat and recruitment success (Light et al. 1998, USFWS 2016). It has also been speculated that flow during the fall and winter months may influence availability of juvenile foraging habitat by altering the salinity of the estuary where young juveniles reside (Sulak and Clugston 1998, Sulak et al. 2007, Sulak et al. 2016); however, quantitative data are largely lacking. Flowers et al. (2009) found that increases in flow during the spawning period (April-May) were positively related to an increase in available spawning habitat suggesting that sufficient flow during this period to inundate available habitats may be critical for producing strong year classes of juveniles. Considering this it is possible that median flows, sufficient to inundate spawning habitat but not so high as to flush early life stages, may be needed. It is apparent that Gulf Sturgeon recruitment to age-1 can be affected by many factors, including fluctuating environmental conditions such as temperature or flow (Cummins 2018, Fox and Peterson 2018). Furthermore these factors may interact with one another synergistically or antagonistically to alter year class success.

Despite the large number of hypotheses regarding the relationship of environmental factors and recruitment to age-1, little has been done to begin quantifying this relationship and evaluating these hypotheses. Fortunately, the effects that environmental variables have on annual recruitment can be evaluated using modern modelling methods, an approach previously used for Atlantic Sturgeon (Cummins 2018, Fox 2018).

Evaluating whether there is, in fact, a relationship between flow and annual recruitment of Gulf Sturgeon is an important first step toward understanding this potential impediment to species recovery. Although Marbury and Peterson's (2015) recruitment estimates for the Apalachicola River established an important benchmark for annual recruitment in that population, the study spanned only three years. Consequently, the objective of this project was to conduct an additional three consecutive years of mark-recapture recruitment estimates and to use the combined six years of recruitment and river flow data to determine the effects of flow on recruitment class strength.

Methods

Study Site

The Apalachicola-Chattahoochee-Flint (ACF) River basin drains approximately 50,000 square kilometers including forests, agricultural, and urbanized landscapes. The Chattahoochee and Flint Rivers flow from their headwaters in northwest and north-central Georgia south until their confluence at Lake Seminole on the Florida-Georgia boundary. Lake Seminole is impounded by JWLD, below which the Apalachicola River runs unimpounded for approximately 171 km before draining into Apalachicola Bay in the northern Gulf of Mexico. The ACF basin is one of the most biologically diverse drainages in North America, hosting 34 federally threatened and endangered species as well as a number of species of concern, many of which are endemic to the watershed (USFWS 2012). The primary sampling location for this project was the Brothers River, a tributary to the Apalachicola River which now contains the majority of the known juvenile summering habitat within the system (Figure 2.1; Wooley and Crateau 1982, 1985, Marbury and Peterson 2015).

Fish Sampling

Gulf Sturgeon were sampled in the Brothers River tributary of the Apalachicola River and the mainstem Apalachicola River from 2016 to 2018. Sampling was conducted 4-5 days a week from May to August. Fish were captured using bottom-set gill nets anchored in main channel habitats throughout the known juvenile holding areas within the Brothers River tributary. Nets were also deployed throughout the Apalachicola River mainstem to help ensure that other potential juvenile holding areas were evaluated. Each gill net comprised three 50-m panels of 7.6-, 8.9-, and 10.2-cm stretch monofilament mesh. Nets were soaked from 1-2 h during each sampling event depending on environmental conditions. Soak times were reduced during stressful conditions such as high temperature and low dissolved oxygen. Captured sturgeon were removed from the nets and held in floating net pens or an aerated live well until they were processed.

Captured Gulf Sturgeon were measured (FL, TL), weighed, and inspected for passive integrated transponder (PIT) tags with a portable PIT tag reader. All untagged individuals received a unique PIT tag injected beneath the skin immediately below the dorsal fin. An approximately 1-cm section of the second marginal pectoral fin ray also was collected from a subsample of 92 age-1and age-2 sized fish (370-510mm FL) for subsequent age estimation. Fish were then released at their original capture site.

Age of each juvenile in the catch was estimated using length-frequency histograms (LFH) as described by Schueller & Peterson (2010). Age estimates from the LFH were then verified by counting annuli in the second marginal pectoral fin ray by two independent observers (Currier 1951, Baremore & Rosati 2014). Disagreements in counts of annuli between the two observers were resolved by a third observer or the fish was simply removed from the analysis.

Environmental Data

Temperature and salinity data for the Brothers River and the lower Apalachicola River system were also obtained from automated instruments maintained by the United States Fish and Wildlife Service. Flow data were obtained from United States Geological Service stream gauge 02358000 located at Chattahoochee, Florida just below JWLD.

Data Analysis

Once ages had been assigned to all juveniles in the catch, a Huggins closed capture model (Huggins 1989, 1991) was used to estimate the annual abundance of each juvenile cohort. The model was run in Program RMark as described by Marbury and Peterson (2015). Age assignments were determined using length frequency histograms for each year of the study (Schueller and Peterson 2010, Marbury and Peterson 2015). Capture periods of one calendar week were used to allow for mixing of marked and unmarked individuals throughout the sampling period. The closed model assumed no births, deaths, immigration or emigration, and no tag loss during the 8 to 13-week study period. CloseTest (version 3) was used to verify closure in each year of the study as described by Stanley and Burnham (1998).

To adjust mark recapture estimates and eliminate bias associated with natural heterogeneity in capture probability, a candidate set of models was created with variable capture probability based on a number of factors including sampling occasion (M_t), age-class (M_a), and the additive and interactive effects of the same two factors (M_{t+a} and

M_{t*a}). Akaike's information criterion (AIC) (Akaike 1973) corrected for small sampling size (AIC_c) (Hurvich and Tsai 1989) was used to determine the relative likelihood of each of the candidate models. Model averaging was then used to estimate the sizes of both age-1 and age-2 Gulf Sturgeon cohorts.

To evaluate the potential relationship between annual recruitment and flow we used six years' of paired flow and recruitment data for the Apalachicola River, including 2016-2018 estimates from this study and 2013-2015 estimates from Marbury and Peterson (2015). Mean discharge and cumulative number of high flow days (high flow duration; HFD) were determined for each month and each season during the study. Three month intervals associated with season were used to aggregate flow across specific life history stages (Winter (pre-spawn December-February), Spring (spawning March-May), Summer (larval to juvenile stage June-August), and Fall (early prespawn/first outmigration September-November)). Mean discharge was determined by averaging 15 minute-interval discharge measurements by season and by month. HFD was calculated by determining the number of days within a time period (season and month) which exceeded the 75th percentile of mean daily flows based on historic data from October 10th 1987 to August 28th 2018.

A candidate set of 28 linear regression models was constructed to evaluate the relationship between monthly or seasonal flow and annual Gulf sturgeon recruitment to age-1. AIC was then used to determine the relative weight of each of the candidate models (Burnham and Anderson 2002). Models achieving a weight equal to or greater than 12.5% of the highest weighted model were included in the final confidence set

(Royall 1997). The overall fit of each model was then determined by calculating the coefficient of determination (Ott and Longnecker 2010).

Results

A total of 1,058 nets (1105 net-hrs of sampling) were fished throughout the three summers of the study. Sampling duration varied from 8 weeks in 2016 to 13 weeks in 2018 (Table 2.1). Most (87%) of the sampling effort was spent in the Brothers River tributary with 137 hours (13%) distributed through the mainstem of the Apalachicola river. A total of 957 Gulf Sturgeon were captured during the study, including 548 unique individuals. Length-frequency analysis indicated that age-1 fish generally had fork lengths of 370 to 530 mm and age-2 fish had fork lengths from 531 to 710 mm, although there was some year-to-year variation in modal distributions (Figure 2.2). All fin rays (n=48) aged from presumed age-1 fish sampled in 2016-17 agreed with the length-based age assignments. Of the 44 rays taken from age-2 fish taken during the same years, 90% (39/44) agreed with the length-based age assignments. Based on these length-age assignments, 79 unique age-1 and 112 unique age-2 fish were captured during the study. Considering the high accuracy of length-based age assignment methods, fish were categorized based upon length estimates alone for mark-recapture analysis.

Huggins closed-capture recruitment model selection (AIC_c) indicated that the M_{t+a} (additive effect of time and age) model held almost all of the weight in each year of the study (Table 2.2). Model averaged abundance estimates of age-1 cohorts were between 21-51 age-1 individuals per year of (Table 2.3). Age-2 abundance estimates were between 39 and 54 individuals per year (Table 2.4). CloseTest results indicated that both age-1 and age-2 populations were closed to immigration and emigration with the exception of the age 2 cohort sampled in 2016. This sample was likely subject to both additions (p=0.046) and losses (p=0.013) from the age-2 population during the sampling period. Consistency between estimates of age-1 abundance and age-2 abundance in subsequent years support that the majority of the population is being sampled within the Brothers River and there is little immigration or outmigration from the population (Figure 2.3).

Sampling at the JWLD in 2017-2018 resulted in the capture of six age-1 and 15 age-2 individuals. These are the first captures of age-1 individuals outside of the Brothers River holding areas in the Apalachicola River. Three individual fish, including one age-2 fish, were captured both at JWLD and the Brothers River within a field season.

From 2013 to 2018, months with the highest mean HFD generally also had the highest mean discharge. January had the highest mean discharge averaged across the years of the study (32170 CFS, s (standard deviation)= 21360) and the second highest mean HFD (16, s=10) during the study period. October had the lowest mean discharge (8535 CFS, s=2288) and HFD (0, s=0). Annual recruitment of age-1 Gulf Sturgeon was positively related to HFD during September (R^2=0.983, W=0.28), August (R^2=0.983, W=0.28), July (R^2=0.983, W=0.28), and summer (R^2=0.979, W=0.17). Annual recruitment was similarly related to mean discharge during August (R^2=0.941, W=0.58) and July (R^2=0.931, W=0.36)

Discussion

This study, in conjunction with the work of Marbury and Peterson (2015), provides a total of six years of direct age-1 recruitment estimates for Gulf Sturgeon on the Apalachicola River. Mark-recapture results indicated that recruitment across both studies was consistently between 22-54 age-1 individuals annually. In 2014 the cohort estimate of 210 (190-241) recruits suggested an unusually strong year class was produced in the preceding year (Table 2.3). Abundance estimates of age-2 cohorts in each year of this study were similar to corresponding estimates of age-1 cohort estimates from the previous year; this was similar to the results of Marbury and Peterson (2015). Consistency of abundance estimates from age-1 cohorts to age-2 suggest high annual survival and no significant immigration of age-1 fish from other locations within the Apalachicola System. These results further corroborate the findings of Marbury and Peterson (2015) that the Brothers River tributary is the primary summer holding area for age-1 Gulf Sturgeon within the Apalachicola River. Although little work has been done to determine the specific factors regarding selection of holding areas it is believed that holding areas are chosen based on a number of interrelated variables which influence bioenergetics including depth, temperature, and water chemistry (USFWS 2016). It is likely that the deep and slow-flowing nature of the Brothers River, in contrast to the Apalachicola mainstem, makes it an ideal habitat from a bioenergetics standpoint. Future studies should be conducted to determine which factors influence the selection of these habitats within the Brothers River.

Telemetry and CloseTest statistical software were used to justify the assumption of closure for this analysis. The concurrent telemetry study (Hancock, 2019) determined

1 of 37 tagged age-1 individuals (2.7%) may have moved out of the Brothers River. This individual was detected at a receiver gating the Brothers River but may or may not have emigrated as it was detected again at the same receiver 18 days later. However, occasional captures of age-1 and age-2 juveniles outside of the Brothers River in 2017-2018 highlight the importance of regularly sampling outside of the primary holding areas to help ensure the accuracy of annual recruitment estimates. Although the reason for lack of closure in the age-2 population in 2014 is uncertain, it is possible that the large size of the cohort as well as an increased distribution of age-2 individuals rendered sampling efforts insufficient to establish closure. Closure should still be regularly evaluated, especially for age-2+ stages in order to justify the use of a closed-population analysis.

Abundance estimates from this study are consistent with those provided previously by Pine and Martell (2009) who used an age-structured mark-recapture model (ASMR) to estimate annual recruitment in the Apalachicola River to be 0 to 200 individuals under the assumption of a single capture probability. Annual estimates from this study are likely more precise than the model derived estimates from the previous authors, but they fall within each of their previous estimates. Unlike ASMR, however, field derived abundance estimates - like those obtained in this study, provide specific annual recruitment estimates and do not rely on the existence of a substantial historic database (Coggins et al. 2006).

Recent recruitment estimates for the Suwannee River of 500 to 1000 individuals greatly exceed annual recruitment documented for the Apalachicola population in this study; however, the lack of comparable recruitment estimates for other populations precludes any further comparisons of recruitment estimation methodologies (Pine et al.

2001). However, the methods used in this study have been well established in similar studies of Atlantic Sturgeon along the US Atlantic Coast (Cummins 2018, Hale et al 2016, Bahr and Peterson 2016, Schueller and Peterson 2010). The Altamaha River, which hosts one of the most robust Atlantic Sturgeon population in the southern portion of their range, produces 500-2500 age-1 individuals per year (Schueller and Peterson 2010). The Savannah River, which is also considered a healthy population, produces 500-600 annual recruits as documented by Bahr and Peterson (2016) and Cummins (2018). The Satilla, Ogeechee, and St. Marys Rivers have typical annual recruitment of less than 100 individuals per year (Peterson and Fritts 2011, Fritts et al. 2015, Fox and Peterson 2017); these populations are thought highly imperiled and likely limited by poor recruitment. Results of this study suggest that annual recruitment of Gulf Sturgeon in the Apalachicola River is comparable to the most imperiled populations of Atlantic Sturgeon and is currently much lower than the most recent recruitment estimates for the Suwannee River (Pine et al. 2001).

Modeling results from this study suggest that annual recruitment estimates were related to high mean monthly discharge and HFD in late summer and early fall. Similar findings were reported for the Suwannee River by Randall and Sulak (2007) who showed a relationship between annual recruitment and high mean discharge in September and December (Randall and Sulak 2007). These authors proposed a "salinity barrier hypothesis" which speculated that high freshwater inputs in December increase age-0 foraging habitat in the lower estuary during their first winter – a period thought to be critical for age-0 survival (Sulak and Clugston 1998, Sulak et al. 2007, Sulak et al. 2016). Our results, however, are inconsistent with this hypothesis as we saw the highest relationship with flow during summer months when age-0 fish are found in freshwater river habitats and winter flows were not found to be correlated with increased recruitment (Kynard and Parker 2004). Similarly, Flowers et al. (2009) reported a relationship between increases in flow and availability of spawning habitat. The results of this study did not indicate any significant relationship between spawning flows (April-May) and recruitment (Wooley & Crateau 1982, Flowers et al. 2009), Furthermore, the 2014 year class that exhibited the highest recruitment of all years studied (Figure 2.3) was spawned during a period of unusually low flows. This directly contradicts the hypothesis that high flows during spawning are required to produce a large number of recruits. The results of our study are most consistent with the hypotheses based on the floodplain pulse concept stating that increased flow in summer and early fall months may increase availability of forage for early juveniles while they are located in the river prior to outmigration (Light et al. 1998, USFWS 2016). Based on the known relationship of increased flow and decreased temperature it is also possible that decreased temperature during this time leads to increased survival as a result of lower stress and optimal growth. Although high flows during summer months could be important for annual Gulf Sturgeon recruitment, causal mechanisms remain uncertain because many other abiotic environmental variables are also correlated with high summer flows (e.g. temperature, pH, dissolved oxygen) and linear relationships seldom represent the full complexity of synergistic and antagonistic effects present in natural environments.   This uncertainty highlights the need for continued studies of Gulf Sturgeon recruitment, including future investigation of environmental variables that influence annual recruitment.

Recruitment estimates from this study were consistent in all years, except 2014. Consequently, my analysis of flow effects on annual recruitment was limited and did not include a robust data set of widely varying recruitment estimates. For example, in this study, I document several months with zero HFD over several years.   Consequently, the increased HFD recorded in 2014 carried large weights in subsequent modeling results (Table 2.4,2.5). A more robust data set, including wide variation in flows and corresponding recruitment estimates across several years would strengthen similar modeling efforts in future studies.

Despite the limitations of the data set obtained, the annual cohort estimates provided in this study provide an important baseline of Gulf Sturgeon recruitment for the Apalachicola River population. Similar estimates conducted in future years will provide an important quantitative measure of population trend in response to future recovery actions, climate change, or environmental disturbance. Future studies are needed to quantify the relationship between flow, recruitment, and subsequently to identify causal mechanisms underlying this relationship and any other environmental factors affecting Gulf Sturgeon recruitment.

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Tables

Table 2.1. Effort and Catch of juvenile Age 1 and Age 2 Gulf Sturgeon in the Brothers and Apalachicola rivers during the summers of 2016-2018.

			Net	Age 1		Age 2	
Year	Weeks	Nets	Hours	Marked	Recaptured	Marked	Recaptured
2016	8	270	269.78	34	23	33	29
2017	12	291	311.33	24	22	44	18
2018	13	497	524.23	21	9	35	16

Table 2.2. Huggins closed capture models describing capture probability using time and age. Models used to estimate abundance of Age 1 and Age 2 cohorts in each year of sampling from 2016-2018 in the Brothers and Apalachicola rivers. Calculated AICc and ΔAIC values are included as well as model weight (W) and parameter counts (K) for each model.

Year	Capture Probability	AICc	ΔAIC	W	K
2016	Time and Age Interaction	1874.95	0.00	0.97	30
	Time and Age Additive	1882.18	7.23	0.03	12
	Time	1906.96	32.02	0.00	10
	Age	1979.31	104.37	0.00	3
	Constant	2003.69	128.75	0.00	1
2017	Time and Age Additive	695.73	0.00	0.99	10
	Time and Age Interaction	704.55	8.82	0.01	24
	Time	717.23	21.50	0.00	8
	Age	821.78	126.05	0.00	3
	Constant	842.10	146.37	0.00	1
2018	Time and Age Additive	793.71	0.00	0.99	13
	Time and Age Interaction	805.01	11.30	0.00	33
	Time	805.86	12.16	0.00	11
	Age	950.65	156.95	0.00	3
	Constant	962.45	168.75	0.00	1

Table 2.3. Age 1 Huggins closed capture abundance (recruitment) estimates for Gulf Sturgeon caught at Age-1 from the Brothers River, Florida in 2013-2018. Abundance estimates that include individuals captured outside of the Brothers River in 2017 and 2018 are shown in parentheses. Data from 2013 to 2015 (shaded) courtesy of Marbury and Peterson (2015).

Year	Abundance Estimate	95% CI	No. Acoustically Tagged
2013	46	37-70	0
2014	210	190-241	10
2015	54	34-119	10
2016	51	35-67	12
2017	21(28)	20-26(24-36)	20
2018	28(31)	20-54(21-48)	0

Table 2.4. Huggins closed capture abundance estimates for age-2 Gulf Sturgeon from the Brothers River, Florida in 2013-2018. Abundance estimates that including individuals captured outside of the Brothers River in 2017 and 2018 are shown in parentheses. Data from 2013 to 2015 (shaded) courtesy of Marbury and Peterson (2015).

Year	Abundance Estimate	95% CI
2013	20	14-64
2014	138	123-163
2015	202	174-247
2016	39	33-49
2017	54(89)	33-76(51-129)
2018	49(56)	32-90(35-79)

Table 2.5. The top five models using high flow duration to predict recruitment of Age-1 Gulf Sturgeon in the Apalachicola River Florida (2013-2018). Akaike's information criteria, ΔAIC, relative weight (W), and coefficient of determination (r2) are presented for the top 5 models. Models in bold were included in the confidence set.

Predictor	AICc	ΔAIC	W	R^2
September	**60.45**	**0.00**	**0.28**	**0.983**
August	**60.45**	**0.00**	**0.28**	**0.983**
July	**60.45**	**0.00**	**0.28**	**0.983**
Summer	**61.43**	**0.98**	**0.17**	**0.979**
October (Prior to Spawn)	74.73	14.28	0.00	0.000

Table 2.6. The top five models using discharge (m^3/s) to predict recruitment of Age-1 Gulf Sturgeon in the Apalachicola River Florida (2013-2018). Akaike's information criteria, ΔAIC, relative weight (W), and coefficient of determination (r2) are presented for the top 5 models. Models in bold were included in the confidence set.

Predictor	AICc	ΔAIC	W	R^2
August	**67.72**	**0.00**	**0.58**	**0.941**
July	**68.66**	**0.93**	**0.36**	**0.931**
Summer	72.80	5.08	0.05	0.863
September	80.67	12.95	0.00	0.492
Mean Yearly Discharge (Pre-Spawn)	80.83	13.11	0.00	0.478

Figures

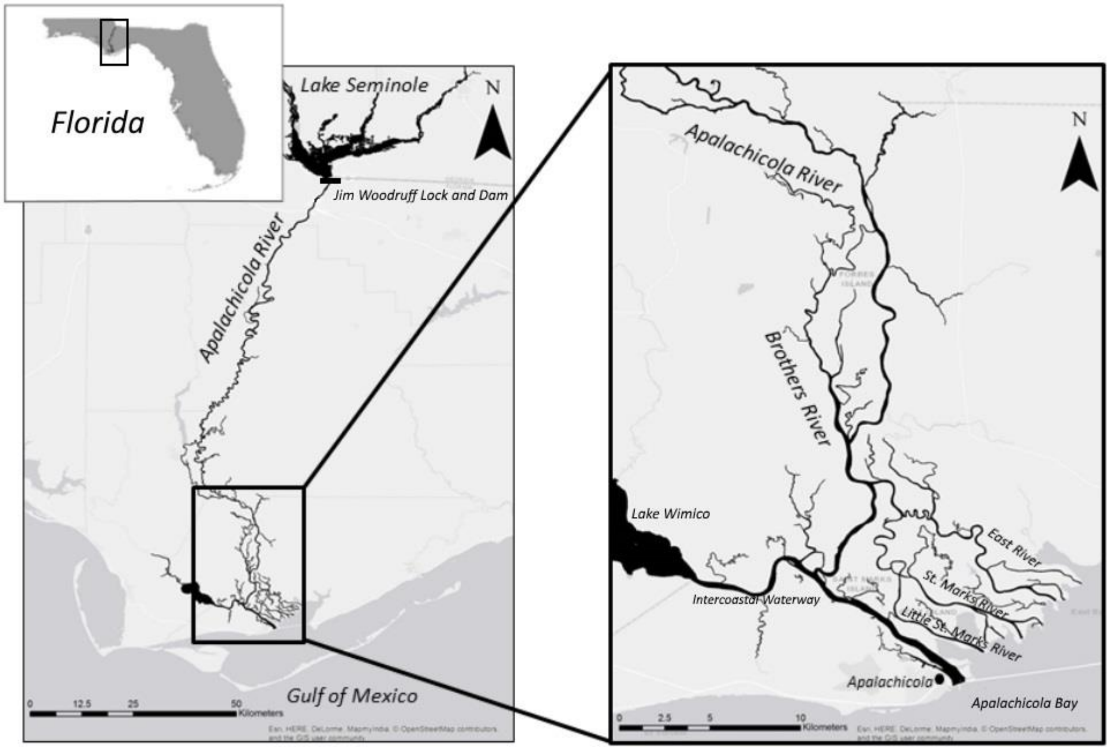

Figure 2.1. Study Site for juvenile Gulf Sturgeon research on the Apalachicola River. Sampling occurred from May to August 2016-2018 primarily in the Brothers River (rectangular inset).

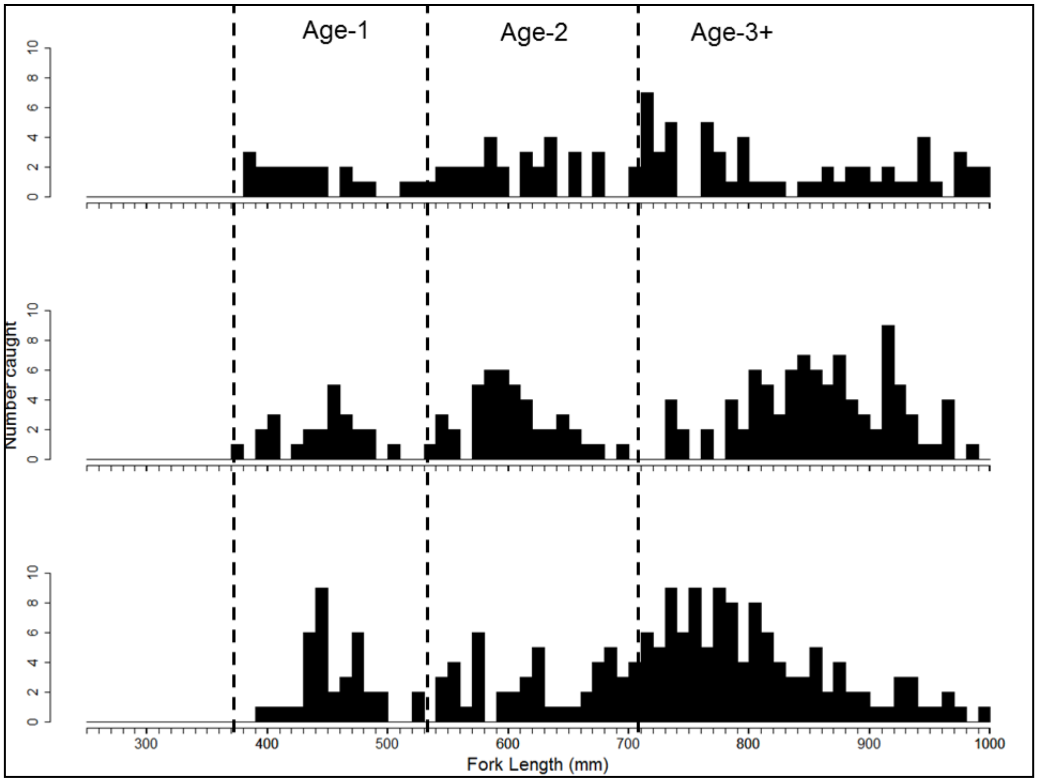

Figure 2.2. Length-frequency histograms of number of individual Gulf Sturgeon in each 10mm fork length bin. Modes are correlated with age classes and verified by fin ray aging. Age-class splits are shown (dashed lines). Sampling occurred from May to August 2016-2018 primarily in the Brothers River, Florida from May to August 2016-2018.

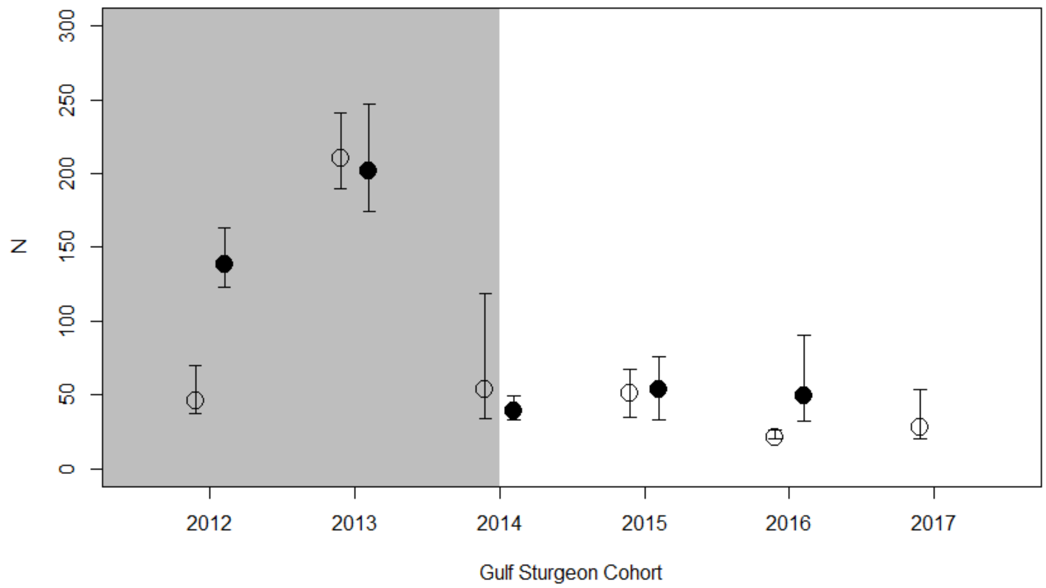

Figure 2.3. Annual abundance estimates of Gulf Sturgeon based on cohort birth year. Age-1 cohort abundance estimates (o) and corresponding estimates of the same cohort at Age-2 (•) are compared to ensure consistency of abundance estimates from one sampling year to the next. Sampling was conducted on the Apalachicola River during the summers of 2013 to 2018. Data from 2013 to 2015 (grey shading) courtesy of Marbury and Peterson (2015).

Chapter 3

Overwinter Habitat Use and Survival of Age-1 Gulf Sturgeon[2]

[2]Hancock, N.Q., Marbury J.A., Fox A.G., Kaeser, A.J., and D.P. Peterson. To be submitted to *Transactions of the American Fisheries Society*

Abstract

The Gulf Sturgeon (*Acipenser oxyrinchus desotoi*) is listed as federally threatened because of historic overfishing and habitat degradation. The objectives of this study were to describe overwinter habitat use of age-1 Gulf Sturgeon and to determine survival during this overwintering period in the Apalachicola River, Florida to help facilitate recovery of the species. Gulf Sturgeon were sampled in the Brothers River, the primary aggregation site of the Apalachicola population, from April to August, 2016-2017. Gill nets made of 7.6, 8.9, 10.2 cm stretch monofilament were anchored in main channel habitats for approximately an hour. Age-1 Gulf Sturgeon were surgically tagged with sonic transmitters. An array of 32 stationary acoustic receivers was used to monitor the movements of tagged fish throughout the lower Apalachicola drainage. Results indicated that age-1 Gulf sturgeon outmigrate from the Brothers River to estuarine habitat in the fall between late September and early November. During the winter, tagged fish primarily used the mainstem of the Apalachicola River near the river mouth but were distributed throughout the lower estuary and distributaries. Tagged fish returned to the Brothers River in spring between March and May. Survival was high with 100% and 87% of successfully tagged fish surviving the overwintering period in 2016 and 2017 respectively.

Introduction

The Gulf Sturgeon (*Acipenser oxyrhinchus desotoi*) is long-lived, benthic fish found in the northern Gulf of Mexico. It has an anadromous life cycle and exhibits several K-selected life history traits such as delayed maturity, protracted spawning interval, and a long life span (Huff 1975). Although it was once found throughout the Gulf of Mexico from Tampa Bay to the Mississippi River, the species has experienced major population declines and range contraction. Historically, most populations were overharvested for both meat and caviar, and the construction of dams on many rivers prevented adult fish from reaching suitable spawning habitat. (Huff 1975, USFWS and NOAA 1991, Zehfuss et al. 1999). This resulted in the species' range shrinking to consist of only nine rivers including the Pearl, Pascagoula, Escambia, Blackwater, Yellow, Choctawatchee, Apalachicola, Ochlockonee, and Suwannee Rivers (Huff 1975, Stabile et al. 1996, USFWS and NMFS 2009). As a result of continued population declines, the species was eventually listed as threatened under the Endangered Species Act in 1991(USFWS and NOAA). The recovery status of Gulf Sturgeon is poorly understood but is believed to vary widely among river systems. The largest population occurs in the Suwanee River, Florida, which contains approximately 10 times as many individuals as other rivers such as the Apalachicola (Zehfuss et al. 1999, USFWS 2004, Sulak et al. 2016).

Although the life histories of adult and juvenile Gulf Sturgeon have been fairly well-studied, relatively little is known about the behavior of age-1 juveniles. Research shows that after hatching free embryos remain at the spawning site sheltered under cover such as rocky structures. Larvae then leave the spawning site and begin a 1-step long larva-juvenile migration in which they gradually disperse downstream from the spawning area while remaining in freshwater habitats. Based on records that show larvae holding in the water column, it is possible that drift feeding is used during this migration period. Once the larvae mature to age 10-12 month juveniles they have been recorded moving downstream into the estuary between January and February where they join older juveniles in overwintering habitats. (Kynard and Parker 2004, Sulak and Clugston 1998). Thereafter, the juveniles are strictly benthic, feeding on a variety of invertebrates including mollusks, crustaceans, amphipods, and annelids. The young juveniles remain in these estuarine habitats throughout the winter months before returning back upstream to freshwater habitats in spring along with other early juvenile age classes (Huff 1975, Mason and Clugston 1993). After hatching, larvae migrate downstream, eventually settling in deep freshwater channels, known as holding areas, where they reside for 2-3 months until they complete their transition to the juvenile stage (Mason and Clugston 1993). Thereafter, the juveniles are strictly benthic, feeding on a variety of invertebrates including mollusks, crustaceans, amphipods, and annelids (Huff 1975). As temperatures begin to decline in the fall, age-0 juveniles are thought to move downstream into brackish water habitats in the lower estuary. The young juveniles remain in these estuarine habitats throughout the winter months before returning back upstream to freshwater habitats in spring at about age-1 (Huff 1975, Mason and Clugston 1993). Little is known about habitat use or biological requirements of juveniles during their estuarine overwintering period, making it difficult to characterize critical habitat or to evaluate important recovery metrics such as annual recruitment and subsequent survival of juvenile year classes.

Limited information about juvenile movement patterns is available from the Suwannee and Apalachicola River systems. Sulak et al. (2009) found that juvenile (approx. 330-900mm FL) Gulf sturgeon in the Suwannee River (n=34) overwintered primarily in mesohaline estuarine habitats in strong association with benthic prey concentrations. The same author found that juveniles in the Apalachicola River (n=4) were detected primarily in the vicinity of the Apalachicola River mouth and did not depart the estuarine zone during the overwintering period (Sulak et al. 2009). Although information about habitat use of different life stages is useful for conservation efforts, previous studies of Atlantic sturgeon (Schueller and Peterson 2010) suggest that juveniles as young as age-2 may have different migratory behaviors from younger age classes. Comparable studies of Gulf sturgeon are lacking; however, these previous studies of a closely related species highlight the importance of considering potential variations in juvenile Gulf sturgeon habitat use during their transition from juvenile to subadult stage life stages.

Marbury and Peterson (2015) completed the first telemetry-based habitat use study on age-1 Gulf Sturgeon. He found that age-1 juveniles (n=17) began their outmigration holding areas in early October. By December all tagged individuals had moved into Apalachicola Bay and did not return to the river until March or early April. Marbury and Peterson also estimated overwinter survival to be at least 89% based on tag returns and recaptures in the Brothers River. This initial study only lasted about 18 months and focused primarily on within-river movements. Data collection was also limited by battery life of sonic transmitters which only lasted ~305 d after they were deployed. Although Marbury and Peterson were successful in determining timing and routes of downstream migration, major questions remain about specific habitat use in the lower estuary and Apalachicola Bay. Consequently, the primary objective of this project was to define the timing and fine-scale juvenile habitat use in the lower Apalachicola estuary and Apalachicola Bay. The secondary objective was to continue overwinter survival estimates from tag returns and recaptures to help inform management strategies.

Methods

Study Site

The Apalachicola River is one of the three major river systems making up the Apalachicola-Chattahoochee-Flint (ACF) basin. The Chattahoochee River flows from its headwaters in the Blue Ridge Mountains through Atlanta and along the Georgia-Alabama border. The Chattahoochee meets the Flint River, which flows out of central Georgia, in Lake Seminole on the Florida-Georgia line. Lake Seminole is impounded by Jim Woodruff Lock and Dam (JWLD). Below the dam, the Apalachicola River runs unimpounded for approximately 171 km before draining into Apalachicola Bay in the northern Gulf of Mexico. The ACF Basin drains approximately 50,000 km^2 and is one of the most biologically diverse drainages in North America. The system hosts 34 federally threatened and endangered species, as well as a number of species of concern, many of which are endemic to the watershed (USFWS 2012). The Brothers River, a tributary to the lower Apalachicola River, was the primary sampling location for this project as it contains the majority of the known juvenile sturgeon habitat within the system (Wooley and Crateau 1982, 1985, Marbury and Peterson 2015) (Figure 3.1).

Fish Sampling

In 2016 and 2017, Gulf Sturgeon were sampled using bottom-set gill nets in the Brothers River tributary of the Apalachicola River and the main stem Apalachicola. Gill nets were constructed from three 50-m panels of 7.6-, 8.9-, and 10.2-cm stretch monofilament mesh. Nets were set 4-5 days weekly from May-August in main channel habitats throughout the known juvenile holding areas (as described by Marbury and Peterson 2015). Nets were also deployed throughout the Apalachicola River mainstem in known adult and subadult holding areas to help ensure that other potential juvenile holding areas were sampled. Once deployed, nets were typically checked every 1-2 h; however they were checked every 30 to 45 minutes when temperatures began approaching 30ºC. As nets were checked, any entangled Gulf sturgeon were quickly removed and placed in a floating net pen or an aerated live well on the research vessel until the entire net had been checked. After all nets had been checked, captured Gulf Sturgeon were inspected for external tags, and then scanned with a portable PIT tag scanner (Avid Powertracker V). If a PIT tag was detected its number was recorded, otherwise a new PIT tag was injected beneath the skin immediately below the dorsal fin. Fin rays were removed from a random subsample of captured fish using methods described by Cuerrier (1951) as well as Marbury and Peterson (2015). All fish were then were measured (FL), weighed, and released at their original capture site. Water quality data including temperature and dissolved oxygen were recorded at each netting location using a YSI Pro 2030 (YSI Incorporated, Yellow Springs, OH).Water temperature data for the lower Apalachicola River system were obtained from automated instruments maintained by the Apalachicola National Estuarine Research Reserve (NOAA 2018).

Age of each fish was estimated using length frequency histogram (LFH) analysis as described for Atlantic sturgeon by Schueller and Peterson (2010). Age estimates from LFH were then verified by aging second marginal pectoral fin rays. (Currier 1951, Baremore and Rosati 2014). Each fin ray was analyzed by two observers. Any disagreements in age estimates were resolved by a third observer or the fish was removed from analysis.

Acoustic Telemetry

During May to October of each sampling year, up to 20 age-1 juveniles (370-550 mm FL) were tagged with acoustic transmitter (model V7, Vemco, Bedford, Nova Scotia) so that their seasonal movement patterns could be monitored. Once captured, these juveniles were transferred from holding pens to a surgical platform mounted on the sampling vessel. Each fish was positioned in lateral recumbency on the surgical platform and a battery-powered pump supplied fresh river water to the fishes' gills throughout the surgical procedure. A 2-3 cm incision was made along the midline of the ventrum using a sterile scalpel through with the sanitized V7 transmitter (~1.6 g) was placed into the body cavity. The incision was then closed with a 2/0 absorbable monocryl suture (Monoswift™ L943) using a single interrupted pattern (Boone et al. 2013; Baremore and Rosati 2011; Marbury and Peterson 2015). Upon recovery, each fish was released at its original capture site. In 2016, transmitters were programmed with a randomly repeating ping rate of 170 to 310 s, which yielded a battery life of approximately 426 days. In 2017, transmitters were programmed with a 120-day activation delay and an increased ping rate (80-160 seconds), which yielded a battery life of ~374 days.

To monitor the movements of acoustically tagged juveniles after their release, an array of 30 stationary acoustic receivers (model VR2W, Vemco) was distributed throughout the Brothers and Apalachicola Rivers, their distributaries, and the East Bay subunit of Apalachicola Bay (Figure 3.2). Most receivers were secured to navigational markers or trees with 5-mm stainless steel cable. Receivers in East Bay open water were anchored on the river bottom using two concrete weights attached by 5-mm stainless steel cable. When possible receivers were attached to Florida Department of Environmental Protection data stations or docks using aluminum U-channel. The entire receiver array was downloaded and maintained every 2 - 3 months throughout the study period. Routine maintenance included replacing batteries thorough cleaning of any biofouling. Supplemental telemetry data were provided through tracking of tagged fish using a portable receiver and hydrophone (model VR-100, Vemco).

Data Analysis

Data from the acoustic receiver array were carefully checked for any potential spurious detections (e.g. simultaneous detections of a single fish at disparate receiver stations). Once the spurious detections had been deleted, raw detection data were converted into detection days (one detection per receiver per day). Median daily, weekly, and monthly river kilometer (rkm) positions of each fish were then calculated. During periods when fish remained stationary between adjacent receivers (when no detections occurred) the position of the fish was assumed based on their last detection. For the purposes of describing seasonal movement patterns, seasons were defined as spring (March-May), summer (June-August), fall (September-October), and winter (November-January).

Results

Sturgeon Tagging and Survival

A total of 1,058 nets (1105 net-hrs of sampling) were fished throughout the two summers of the study. Sampling lasted 8 weeks in 2016 and 12 weeks in 2017 (Table 3.1). Most (87%) of the sampling effort was spent in the Brothers River tributary with 73 hrs (13%) distributed through the mainstem of the Apalachicola river. Length-frequency analysis indicated that age-1 fish generally had fork lengths of 370 to 530 mm, although there was some annual variation in modal distributions (Figure 3.3). All fin rays (n=48) aged from presumed age-1 fish sampled in 2016-17 agreed with the age assignments derived from the annual LFH. Of the 44 fin rays taken from age-2 fish, 90% (39/44) agreed with the LFH assignments. In cases of disagreement fin ray age was used for this study as each fish implanted with a telemetry tag could be quickly aged. Based on these length-age assignments, 58 unique age-1 fish were captured during the study. Fifty-three of these fish (91%) were captured within the Brothers River and 5 were captured just below JWLD.

Thirty-two of the 58 age-1 juveniles captured were tagged with sonic transmitters (Table 3.1, 3.2). Thirty-one of these were captured, tagged, and released within the Brothers River. Tagging success and survival varied between years; three fish (25%) tagged in 2016 and 16 (80%) tagged in 2017 were subsequently detected a total of 17,639 times over the 2 years of the study. Detections of individual fish varied from 21 to 2,845 (mean 928, sd 771) (Table 3.2). All three individuals (100%) tagged in 2016 were detected again in the Brothers River in 2017. In 2017, 14 of the 16 tagged fish (87.5%) were detected or recaptured in the Brothers River in 2018. Across both years of the study, mean overwinter survival rate was 93.75%. During both years of the study, tagged individuals generally remained in the Brothers River during the summer and then moved downriver to habitats near the mouth of the Apalachicola River in the fall (Figures 3.4, 3.5A). During winter months (December-February), they were still detected at the mouth of the Brothers River, but most detections occurred over a wide area dispersed throughout the lower estuary (Figure 3.5B). Spring (March-May) detections followed a similar pattern to those obtained in fall with most detections occurring from the mouth of the Brothers River and in the mainstem of the Apalachicola River between rkm 0-9 (Figure 3.5C). No tagged fish were detected during summer months (June-August)because receivers gated the Brothers River but were not present in the concentrated holding areas where tagged individuals were located. Presence was verified using receivers gating the Brothers River, manual tracking, and recapture events during sampling(Figure 3.5D). The single sturgeon tagged at JWLD behaved in a similar manner to all other tagged fish in that it migrated downstream in fall and moved back upstream in spring; however, its last detection during its upstream migration was in the estuary and it did not reach the mouth of the Brothers River. It was not recaptured or detected returning to the Brothers or Apalachicola Rivers in the spring.

Discussion

Overwinter Survival

Overwinter survival of age-1 Gulf Sturgeon in the Apalachicola River was high during this 2 year study – 87-100% of tagged fish returned to the river in spring. These results were similar to those of Marbury and Peterson (2015), who observed 89%

overwinter survival of tagged juveniles, and to Sulak et al. (2014), who observed 87.8% annual survival for all year classes in the Suwannee River. These results should be viewed as a minimum estimate of survival because tag failure or emigration could have prevented detection of fish returning each year. High survival of age-1 juveniles obtained in this and previous studies suggests that slow population growth of the recovering population in the Apalachicola, is likely a result of some other limiting factor for this population. Because a single female Gulf Sturgeon can produce from 270,000 to >580,000 eggs (Parauka et al 1991, Sulak et al. 2016), healthy populations can be maintained despite low first year survival rates. For example, Pine et al. (2001) estimated that the Suwannee River population could produce 1000 recruits per year with only 5% of adults spawning, 20% annual mortality, and only 0.04% survival of eggs to age-1. In that context, the results of this study suggest the growth of the Apalachicola population is most likely limited by poor survival prior to age-1. Future studies of life stages between egg and age-1 are needed to help identify specific limiting factors; however, other potential bottlenecks such as high adult mortality or low numbers of spawning adults should also be investigated as other possible factors.

*Gulf Sturgeon Moveme*nts

During the two years of this study we observed seasonal movement patterns of age-1 juvenile Gulf sturgeon that were consistent with those reported by Marbury and Peterson (2015). Although we had limited receivers located within the Brothers River, the presence of tagged sturgeon there in the summer was verified through manual tracking, recaptures, and stationary receivers at both ends of the river. Detection data from the both years of the study showed that 24 of 25 (96%) tagged juveniles remained within the

Brothers River during the summer months – a finding that further corroborates the conclusions of Marbury and Peterson (2015) that the juvenile population is essentially confined to this reach of the river system during the summer. The exact reasoning for the aggregation in this reach is unknown however it is believed that holding areas are chosen based on a number of interrelated variables which influence bioenergetics including depth, temperature, and water chemistry (USFWS 2016). Future studies could be conducted using telemetry as well as multiple water quality variables to determine the exact reason for this site selection. Sampling data also showed that age-1 fish are, at least occasionally, present in the mainstem during the summer months, as evidenced by the capture of 5 age-1 juveniles near JWLD in 2017. Because none of these juveniles were detected moving into the Brothers River and no age-1 individuals from the Brothers River were ever captured at JWLD, both sites could represent distinct juvenile holding areas. Although juveniles had not been previously captured outside the Brothers River, the capture of juveniles near JWLD during this study underscores the need for routine sampling outside of known holding areas both in the Apalachicola, as well as in other populations where studies of juvenile Gulf Sturgeon are being conducted. Future telemetry studies of age-2 and older juveniles are also needed to better define seasonal habitat use during the critical but prolonged transitions from juvenile to subadult and adult life stages.

Individuals were detected beginning their outmigration in the early fall with tagged individuals first detected at the mouth of the Brothers River in mid-September in 2016 and mid-October in 2017 (Figure 3.5A). During this season, tagged individuals were detected primarily at the mouth of the Brothers River. They were also detected at the northernmost entry to the distributaries of the Apalachicola River, in the Little St. River, and in the mainstem of the Apalachicola River between rkm 0 and rkm 9 (Figure 3.5A).

During the overwintering period from December to March the tagged fish used a variety of tidally influenced habitats but their movements were concentrated primarily in the mainstem of the Apalachicola River and the southwest section of the northern portion of Apalachicola Bay (aka East Bay) (Figure 3.5B). Ultimately, tagged individuals returned to the Brothers River in March of each year. Although the reasons for this seasonal movement to estuarine habitats is uncertain, Sulak (2009) observed a similar pattern of juvenile habitat use in the Apalachicola system and speculated that high concentrations of benthic invertebrates in the estuary may provide a seasonally abundant food source for early juveniles.

Our results show that age-1 Gulf Sturgeon do not move into estuarine habitats until November at the earliest. Considering that age-0 juveniles are more sensitive to increased salinity it is likely that they would not outmigrate until November or later. This is consistent with previous studies investigating timing of age-0 movements (Kynard and Parker 2004) which indicate that age-0 juveniles move into these habitats between January and February. Notably this doesn't line up with the salinity barrier hypothesis that states increased flow in September and December increases foraging habitat in the estuary and thus contributes to increased recruitment (Randall & Sulak 2007, Sulak & Clugston 1998).

During the two years of this study, tagging success varied greatly. Poor recruitment (Ch 2) contributed to difficulty in capturing sufficient numbers of age-1 juveniles during each year of the study. Furthermore, post tagging mortality and/or possibly tag loss severely limited the number of tagged individuals in year 1 of the study. The discrepancy in post tagging survival observed in 2016 and 2017 could have resulted from differences in water temperatures during the tagging periods in each year. In 2016, tags were deployed starting in July, when the average water temperature was 28.08ºC (range=5.6, stdev=1.67). In 2017, most tags were deployed in May, when water temperatures averaged 24.83ºC (range=4.5, stdev=1.43). The stress of capture and surgical implantation of transmitters after prolonged exposure to high water temperatures could have caused mortality in some tagged individuals. Although somewhat speculative, we did observe infections at the suture sites of 3 recaptured in 2016, while in 2017, we observed no infections in any of the 22 recaptured individuals obtained in that year. These observations suggest that the potential for temperature-induced, post-tagging mortality should be an important consideration in future studies of Gulf Sturgeon.

The results of this study provide new information regarding the timing and extent of juveniles Gulf Sturgeon movements in the upper Apalachicola River estuary during the overwintering period. Many of my findings corroborate the results of Marbury and Peterson 2015 who documented high overwinter survival of age-1 juveniles. The combined results of both studies indicate that juvenile survival after age-1 is not likely a significant bottleneck for the population, suggesting that other limiting factors, such as adult mortality, poor survival prior to age-1, or poor spawning success should be investigated.

The predictability of juvenile movements identified during this study may also help to define critical habitats of juvenile Gulf Sturgeon within the Apalachicola River system – a valuable application for developing an effective recovery plan for the population. Telemetry results that showed the importance of the lower estuary during the winter, for example, may help managers restrict estuarine dredging or development projects to summer months when juveniles are not present. The lack of a single holding area for juveniles during the winter also supports targeted sampling of relatively well-defined summer holding areas as the best method for annual recruitment assessments. Telemetry data from this study also highlight the importance of the Brothers River tributary as the primary holding area for age-1 Gulf Sturgeon within the Apalachicola River, but they also indicate the possible existence of other, yet undetected holding areas within the system. More importantly, however, the results of this study highlight the complexity of seasonal habitat use of juvenile Gulf Sturgeon – a finding that has broad application to many other populations throughout the range where specific habitat needs of juveniles have not yet been defined. Completion of comparable studies will be critical in these other systems for future development of river specific recovery strategies for the species.

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Tables

Table 3.1. Effort, catch, and tagging of juvenile Age-1 Gulf Sturgeon in the Apalachicola River system during the summers of 2016-2017.

				Age-1		
Year	Weeks	Nets	Net Hours	Marked	Recaptured	Acoustically Tagged
2016	8	270	269.78	34	23	12
2017	12	291	311.33	24	22	20

Table 3.2. Individual captures and detection data for age-1 juvenile Gulf Sturgeon that were released with sonic transmitters in the Apalachicola Rivers system, 2016 and 2017. Detection days indicate one detection per receiver per day. Sturgeon were captured and released in the Brothers River except the individual marked with "*" which was captured at JWLD.

Fish ID	Tag Number	Capture Date	FL (mm)	Total Detections	Detection Days
GUS01	45625	7/20/2016	440	0	0
GUS02	45626	7/20/2016	420	0	0
GUS03	45612	8/5/2016	472	952	28
GUS04	45607	8/6/2016	458	0	0
GUS05	45608	8/7/2016	430	1107	73
GUS06	45623	9/21/2016	480	0	0
GUS07	45613	9/29/2016	460	0	0
GUS08	45617	9/29/2016	470	0	0
GUS09	45618	9/29/2016	510	0	0
GUS10	45611	10/6/2016	490	0	0
GUS11	45619	10/6/2016	430	0	0
GUS12	45621	10/12/2016	440	776	20
GUS13	64413	5/8/2017	458	21	8
GUS14	64414	5/8/2017	544	214	43
GUS15	64415	5/8/2017	405	617	64
GUS16	64409	5/9/2017	407	0	0
GUS17	64417	5/9/2017	423	1791	24
GUS18	64418	5/9/2017	379	236	16
GUS19	64410	5/10/2017	517	802	33
GUS20	64411	5/11/2017	459	1241	27
GUS21	64419	5/11/2017	460	282	15
GUS22	64412	5/15/2017	432	0	0
GUS23	64420	5/16/2017	441	41	2
GUS24	64405	5/18/2017	453	677	24
GUS25	64416	5/18/2017	488	794	32
GUS26	64406	5/19/2017	466	1151	28
GUS27	64407	5/25/2017	403	0	0
GUS28	64408	5/25/2017	467	0	0
GUS29	45616	6/8/2017	485	2845	62
GUS30	45610	6/9/2017	442	2582	123
GUS31	45614	6/9/2017	433	564	10
GUS32*	45624	7/13/2017	399	946	28

Figures

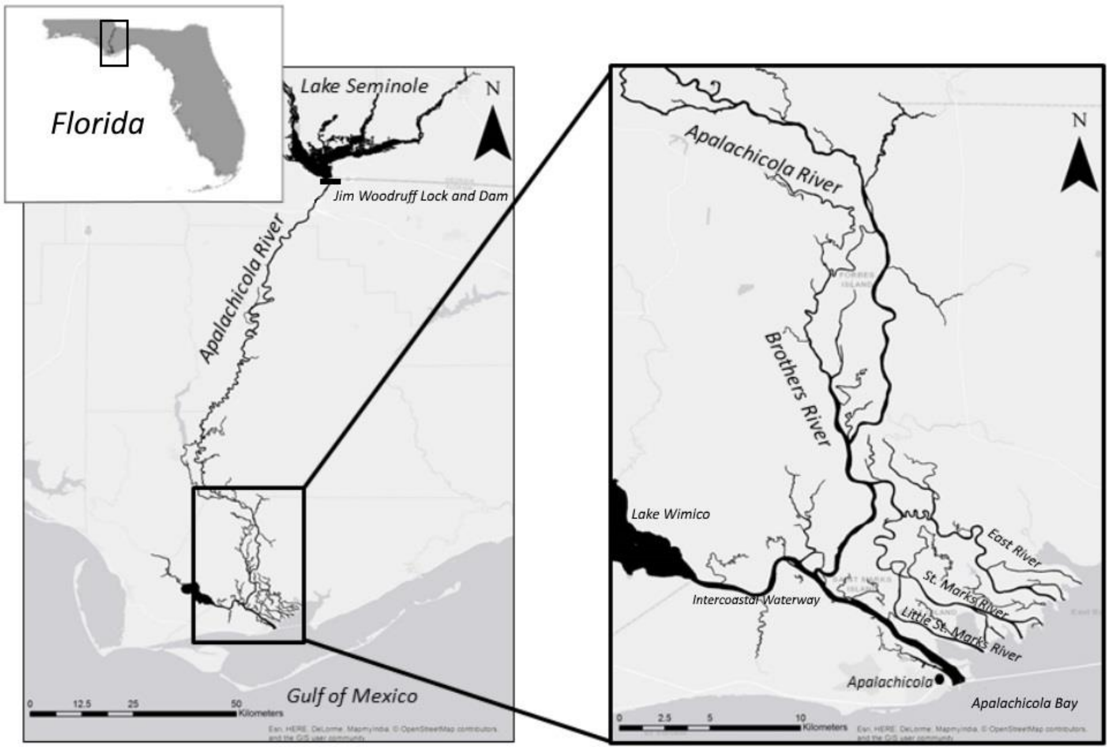

Figure 3.1. Study site for Gulf Sturgeon research on the Apalachicola River, Florida, USA. Sampling occurred from May to August 2016-2017 primarily in the Brothers River (rectangular inset) but also in the 1km reach of the mainstem immediately below Jim Woodruff Lock and Dam as well as other locations in the mainstem where sturgeon had been historically found.

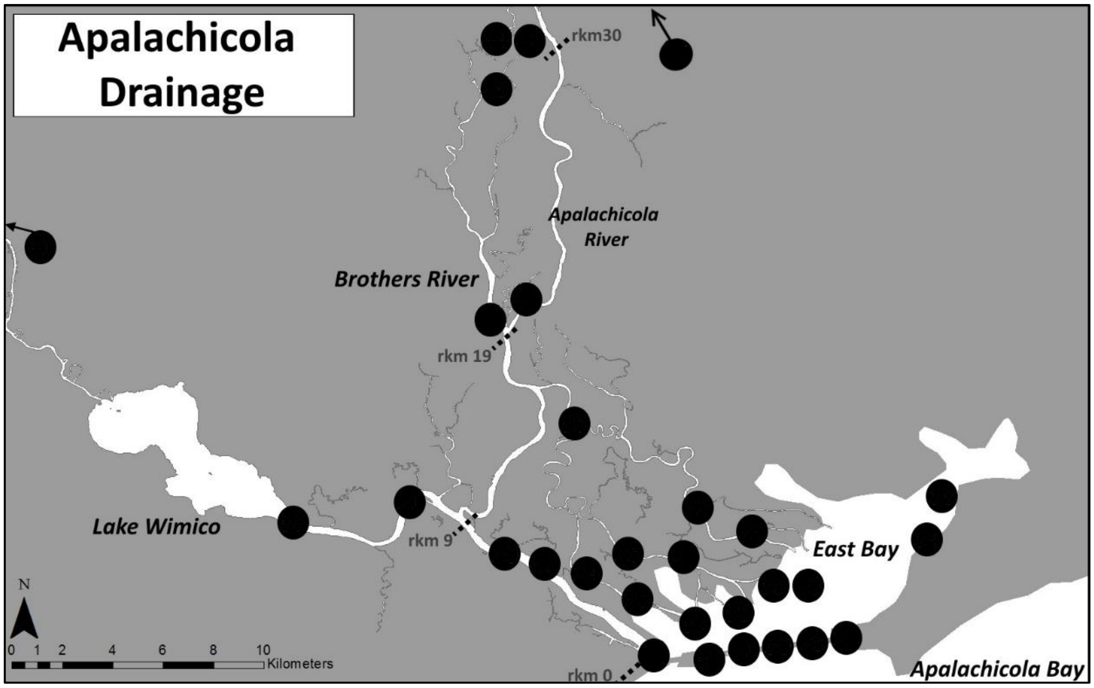

Figure 3.2. Distribution of stationary acoustic receivers in the lower Apalachicola River, Florida, 2016 through 2017. Black circles represent receiver stations.

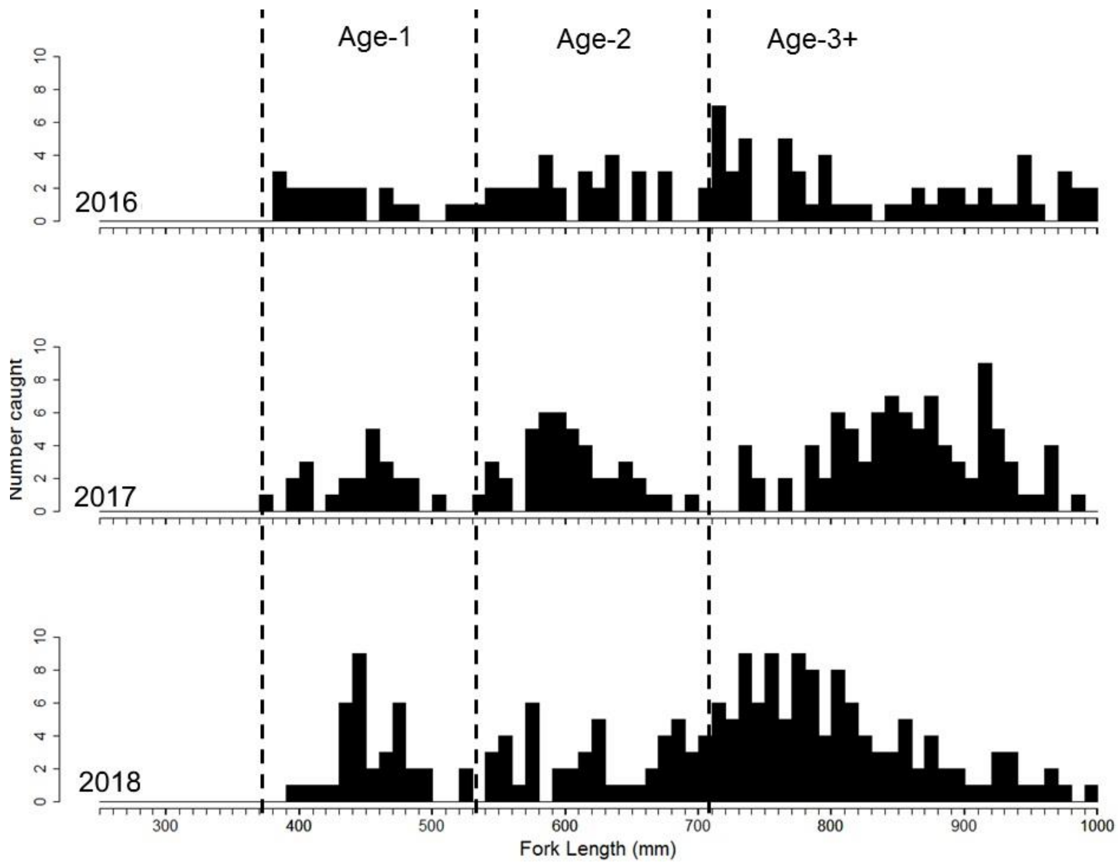

Figure 3.3. Length-frequency histograms of Gulf Sturgeon captured in the Apalachicola River system from May to August, 2016 and 2017. Modes are correlated with age classes and verified by fin ray aging.

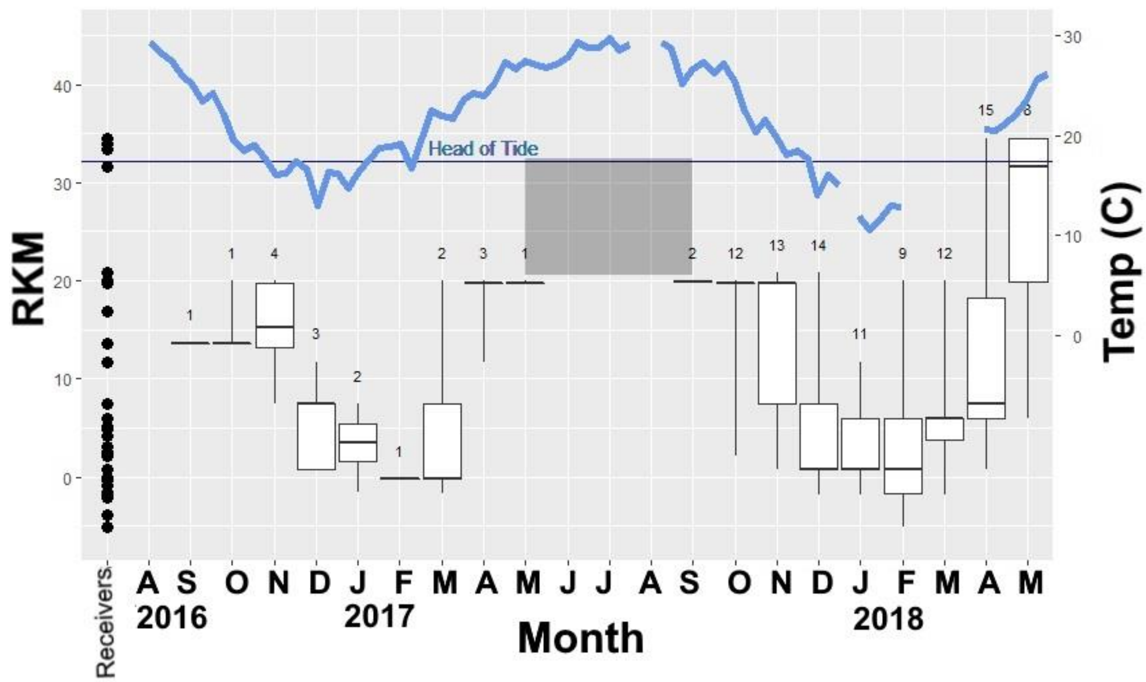

Figure 3.4. Seasonal habitat use of age-1 juvenile Gulf Sturgeon tagged in the Apalachicola River, Florida, August 2016 to May 2018. Boxplot ends represent the 25th and 75th percentile of all tag detections. The median location of total detections is represented by the dark line within each box. Number of individuals detected in each month is shown by the numeral over each box. Dots along the primary y-axis represent RKM location of acoustic receivers. The blue line represents water temperature at RKM 4. Dark dots along the y-axis represent the locations of receivers in the array. Shaded box indicates the interpolated rkm position of age-1 juveniles from May to September 2017 based on manual telemetry, recapture of tagged individuals, and receivers positioned at both ends of the Brothers River tributary. There is no evidence for tagged individuals leaving the Brothers River during this time.

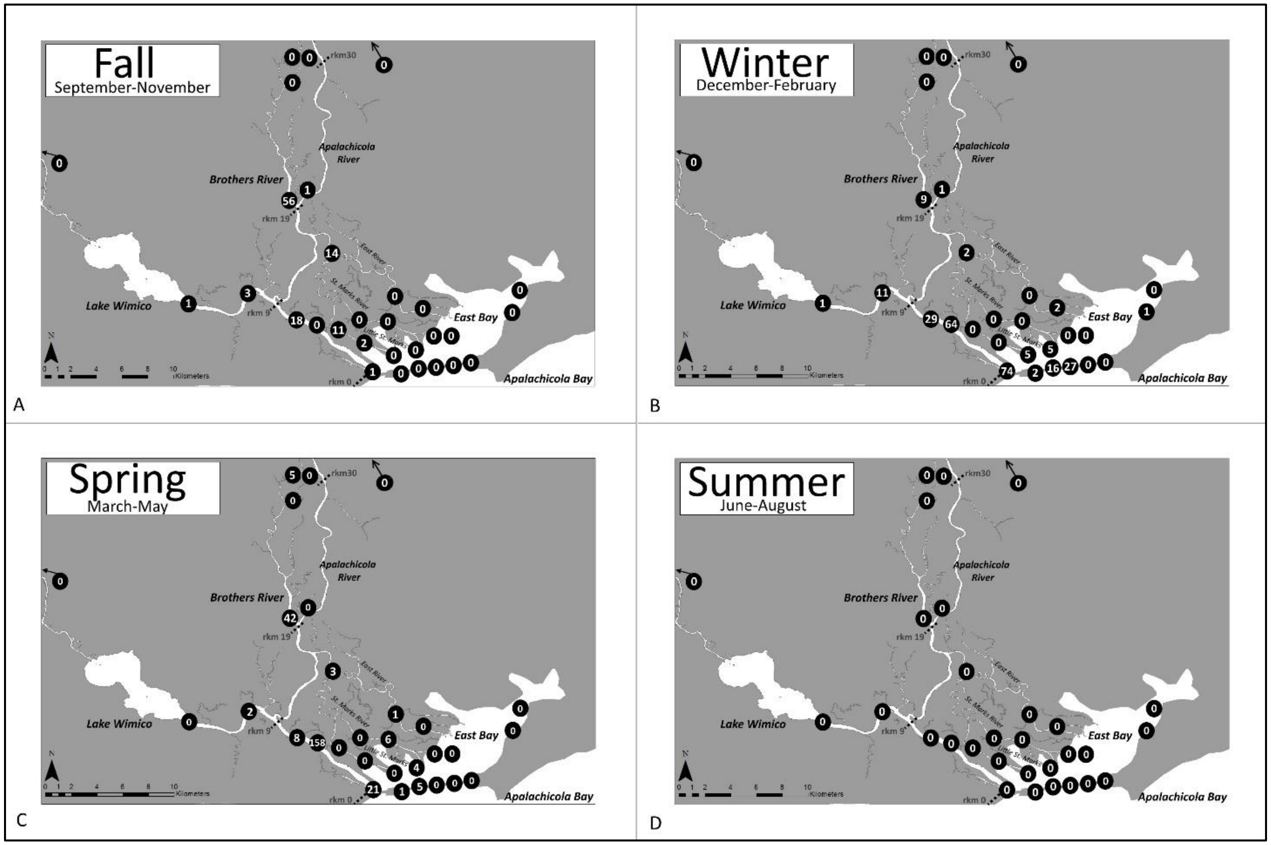

Figure 3.5. Seasonal occupancy of Gulf Sturgeon in the Apalachicola River and Apalachicola Bay, Florida, USA 2016-2018. Each telemetry receiver station is represented by a black circle. Sturgeon detection days (one detection per fish per receiver per day) from 2016-2018 are indicated by the white number on each receiver station. No tagged fish were detected during summer months (June-August)as no receivers were located in the known holding areas

Chapter 4

Conclusions

Although Gulf Sturgeon have been federally listed as threatened for 25 years, little progress towards measurable recovery has been made. Previous studies have provided important information about life history and habitat requirements of adult and subadult Gulf Sturgeon; however, little is known about abundance, behavior, or habitat use of juveniles. Previous studies of Atlantic Sturgeon have demonstrated that annual estimates of age-1 juveniles provides a quantitative measure of annual sturgeon recruitment; however Marbury and Peterson (2015) were the first to apply this approach to a Gulf Sturgeon population. The results presented in Chapter 2 of this study build upon those of the previous authors, and together, provide an important baseline of annual recruitment for the Apalachicola River population that will allow managers to quickly assess the effects of future recovery actions on population trend.

Recent studies by Marbury and Peterson (2015) also attempted to address critical knowledge gaps in juvenile Gulf Sturgeon ecology. During a three year study, these authors studies seasonal movements of age-1 juveniles in the Apalachicola River that provided important new information regarding seasonal habitat use. Despite these important contributions, many critical information gaps remained, especially in regard to fine-scale habitat use of age-1 juveniles and the relationship of recruitment to annual variations in environmental variables. The results presented in Chapter 3 of this study provide the first quantified information regarding fine-scale habitat use and the potential relationship between river flows and annual recruitment for Gulf Sturgeon in the Apalachicola River, FL.

The recruitment results of this study (Chapter 2) were consistent with those of Marbury and Peterson (2015) which showed that the Apalachicola River population is likely limited by poor recruitment. By applying the methods used in both of these studies to other Gulf Sturgeon populations, managers can now establish a regular monitoring program to help quantify and compare current status and future trends of all populations throughout the species' range. Establishing standardized methods for rangewide population assessment is a critical first stem of developing effective recovery plans for the species while evaluating the influences of natural or anthropogenic disturbances to both populations and their habitats.

Considering the low recruitment estimates obtained in this and the previous study by Marbury and Peterson (2015), the modeling results presented in Chapter 2 suggest that late summer flows may be critically important to annual recruitment of the Apalachicola River population. Although these seem to corroborate the "salinity barrier" hypothesis proposed for Suwannee River population (Sulak and Clugston 1998, Sulak et al. 2007, Sulak et al. 2016), future studies are needed to provide empirical data regarding causal mechanisms. Results in this study were strongly influenced by one anomalous year of high recruitment and, consequently, should be further investigated using additional years of recruitment and flow data. By quantifying the relationships between annual recruitment and environmental variables future studies should be able to predict year class success and hence, population response to environment variation. The results presented this study should provide the basis for future analyses of how water quality variables affect juvenile survival and hence, annual recruitment for Gulf Sturgeon in both the Apalachicola as well as other populations range wide.

Based on two years of overwinter telemetry detections (Chapter 3) minimum survival of age-1 and age-2 juvenile Gulf Sturgeon was documented to be 87 to 100%. These findings were also similar to those of Marbury and Peterson (2015) who observed 89% overwinter survival, and to those of Sulak et al. (2014) who observed 87.8% annual survival for all year classes. High survival of age-1 juveniles obtained in this and both of these previous studies suggests that slow recovery of the Apalachicola population, is likely a result of some other limiting factor - probably poor survival of egg/larval stages and/or poor spawning success. Future studies in these areas are needed to identify the specific life stages and habitats where future recovery efforts should be focused.

Telemetry data presented in Chapter 3, built upon the results of Marbury and Peterson (2015). The seasonal migration patterns documented in both studies were virtually identical; age-1 individuals outmigrated to the estuary in fall (September-October) and returned to the river in March. Unlike previous studies however, this study provided new information regarding estuarine habitat use of age-1 juveniles throughout overwintering period. Telemetry data from this portion of the study showed that age-1 juveniles overwintered in a variety of tidally influenced habitats, but most of their time was spent in the mainstem of the lower 10 rkm of the Apalachicola as in the southwestern portion of the East Bay unit of Apalachicola Bay. Although further studies are needed to determine why juvenile Gulf Sturgeon use of these specific areas of the estuary, the predictability of juvenile movements documented in this study will help define critical habitats of for juveniles within Apalachicola system. The timing and predictability of juvenile habitat use documented in this study may also help managers restrict estuarine dredging or development projects to periods when juveniles are not present. Future completion of similar studies on other Gulf Sturgeon populations will be critical for development of population specific recovery plans- particularly in regard to identification of limiting factors and protection of critical habitats. Likewise, the methods used in this study to estimate annual recruitment of the Apalachicola River population provide an important framework for similar assessments of other populations throughout the range. Data obtained through these studies will provide the critically needed groundwork for future assessments of population trends, and subsequently for identifying critical juvenile habitats as well as potential population bottlenecks. Such an approach will ultimately provide the most effective means of developing river specific recovery plans for each Gulf Sturgeon population through the range.

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