

POPULATION DYNAMICS AND MOVEMENTS OF SHORTNOSE STURGEON IN
THE OGEECHEE RIVER, GEORGIA

by

DANIEL JACOB FARRAE

(Under the Direction of DOUGLAS L. PETERSON)

ABSTRACT

The shortnose sturgeon is endangered because of over-harvest, habitat degradation, and a shrinking range. The current status of most populations remains unknown. From 2007 to 2009, I collected mark-recapture, telemetry, and habitat suitability data to assess the population dynamics and movements of shortnose sturgeon in the Ogeechee River, Georgia. Over the three years of my study, abundance, survival, and temporary emigration estimates, combined with documented movement of fish between rivers and poor summer habitat quality in the Ogeechee River, provided clear evidence that Ogeechee River stock of shortnose sturgeon is not a discrete population. I propose that the Altamaha and Ogeechee rivers form a source-sink metapopulation in regards to shortnose sturgeon. The results of this study fulfill many goals of the species' recovery plan. My methods are an effective tool for evaluating population dynamics, movements, and habitat suitability of other shortnose sturgeon populations.

INDEX WORDS: *Acipenser brevirostrum*, mark-recapture, habitat suitability, telemetry, metapopulation

POPULATION DYNAMICS AND MOVEMENTS OF SHORTRNOSE STURGEON IN
THE OGEECHEE RIVER, GEORGIA

by

DANIEL JACOB FARRAE

B.S., Loyola University New Orleans, 2006

A Thesis Submitted to the Graduate Faculty of The University of Georgia in Partial

Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE

ATHENS, GEORGIA

2010

© 2010

Daniel Jacob Farrae

All Rights Reserved

POPULATION DYNAMICS AND MOVEMENTS OF SHORTNOSE STURGEON IN
THE OGEECHEE RIVER, GEORGIA

by

DANIEL JACOB FARRAE

Major Professor: Douglas L. Peterson

Committee: Robert Bringolf
Nathan Nibbelink

Electronic Version Approved:

Maureen Grasso
Dean of the Graduate School
The University of Georgia
May 2010

DEDICATION

I would like to dedicate this to my mother, Julie, and brothers, Nick and Shane, who expressed unreserved interest and support throughout my education. I would also like to dedicate this to the myriad friends and colleagues who helped guide me through the process of graduate school.

ACKNOWLEDGEMENTS

I would like to thank Douglas Peterson for providing an opportunity for me to further my education and professional aspirations. My committee, Robert Bringolf and Nate Nibbelink, has been invaluable during my time at the University of Georgia. Cecil Jennings has provided immeasurable guidance. If not for David Higginbotham, I would be starving and dehydrated, unaware of my surroundings, and without the gear necessary to gather my bearings. A host of fellow graduate students and most of my technicians helped make this thesis possible, and no amount of thanks would do them justice.

I absolutely must acknowledge the Richmond Hill Fish Hatchery, Georgia and the employees there for providing housing for my technicians and me during my 28 months of research. This project was funded by the Georgia Department of Natural Resources and the National Marine Fisheries Service and I owe both of them thanks. I would also like to acknowledge the Strategic Environmental Research and Development Program, specifically Henriette Jager, for providing additional funding, collaboration, and research ideas.

TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENTS	v
LIST OF TABLES	viii
LIST OF FIGURES	ix
CHAPTER	
1 INTRODUCTION AND LITERATURE REVIEW	1
Life History	4
Dissolved Oxygen Limits	7
Water Temperature Limits	9
Salinity Limits.....	10
Current Status and Management.....	12
References.....	16
2 POPULATION DYNAMICS OF SHORTNOSE STURGEON IN THE OGEECHEE RIVER, GEORGIA	24
Abstract	25
Introduction.....	26
Site Description.....	29
Methods.....	30
Results.....	32
Discussion	33

	References.....	38
3	MOVEMENTS OF THE SHORTNOSE STURGEON RELATIVE TO HABITAT QUALITY OF THE OGEECHEE RIVER, GEORGIA	51
	Abstract	52
	Introduction.....	53
	Site Description.....	56
	Methods.....	56
	Results.....	62
	Discussion	63
	References.....	69
4	CONCLUSIONS.....	103
	References.....	106

LIST OF TABLES

	Page
Table 2.1: A summary of catch statistics and catch-per-unit-effort (CPUE; fish per net-hour) of shortnose sturgeon captured from the Ogeechee River from June – August, 2007 – 2009.....	44
Table 2.2: AICc, delta AICc, AICc weights, model likelihood, and number of parameters (K) for the top four closed capture robust design models using covariates of temperature (Temp), dissolved oxygen (DO), and total effort in hours to estimate weekly capture (p) and recapture (c) probabilities of shortnose sturgeon from the Ogeechee River, GA within secondary periods (summers) of 2007 – 2009	45
Table 2.3: Closed capture robust design model-averaged parameter estimates, standard errors (SE), and lower (LCI) and upper (UCI) 95% confidence intervals for survival, temporary emigration off of the study area (γ'') between years, probability of remaining off the study area (γ') between years, and abundance of shortnose sturgeon in the Ogeechee River, GA for 2007 – 2009	46
Table 3.1: A meta-analysis of studies on the physiological tolerances of young-of-year shortnose sturgeon to water temperature (T), dissolved oxygen (DO), and salinity at various ages of days-post-hatch (dph)	76
Table 3.2: A frequency table comparing locations of telemetered sturgeon to habitat quality of Ogeechee and Canoochee river segments (500 m) from January 2008 – September 2009	78

LIST OF FIGURES

	Page
Figure 1.1: Historic range of shortnose sturgeon in North America.....	23
Figure 2.1: A map of the study area on the Ogeechee River, GA.	47
Figure 2.2: Length-frequency histograms of captured shortnose sturgeon from the Ogeechee River, GA during the summers of 2007 – 2009.....	48
Figure 2.3: Annual length-weight relationships of captured shortnose sturgeon from the Ogeechee River, GA during the summers of 2007 – 2009.....	49
Figure 2.4: Trends in shortnose sturgeon abundance estimates (with 95% confidence intervals) in the Ogeechee River, GA.....	50
Figure 3.1: Habitat suitability for shortnose sturgeon in the Ogeechee River in January 2008.....	79
Figure 3.2: Habitat suitability for shortnose sturgeon in the Ogeechee River in February 2008.....	80
Figure 3.3: Habitat suitability for shortnose sturgeon in the Ogeechee River in March 2008.....	81
Figure 3.4: Habitat suitability for shortnose sturgeon in the Ogeechee River in April 2008.....	82
Figure 3.5: Habitat suitability compared to movements of shortnose sturgeon in the Ogeechee River in May 2008	83

Figure 3.6: Habitat suitability compared to movements of shortnose sturgeon in the Ogeechee River in June 2008	84
Figure 3.7: Habitat suitability compared to movements of shortnose sturgeon in the Ogeechee River in July 2008	85
Figure 3.8: Habitat suitability compared to movements of shortnose sturgeon in the Ogeechee River in August 2008	86
Figure 3.9: Habitat suitability compared to movements of shortnose sturgeon in the Ogeechee River in September 2008.....	87
Figure 3.10: Habitat suitability for shortnose sturgeon in the Ogeechee River in October 2008.....	88
Figure 3.11: Habitat suitability compared to movements of shortnose sturgeon in the Ogeechee River in November 2008.....	89
Figure 3.12: Habitat suitability compared to movements of shortnose sturgeon in the Ogeechee River in December 2008	90
Figure 3.13: Habitat suitability compared to movements of shortnose sturgeon in the Ogeechee River in January 2009	91
Figure 3.14: Habitat suitability compared to movements of shortnose sturgeon in the Ogeechee River in February 2009	92
Figure 3.15: Habitat suitability compared to movements of shortnose sturgeon in the Ogeechee River in March 2009	93
Figure 3.16: Habitat suitability compared to movements of shortnose sturgeon in the Ogeechee River in April 2009	94

Figure 3.17: Habitat suitability compared to movements of shortnose sturgeon in the Ogeechee River in May 2009	95
Figure 3.18: Habitat suitability compared to movements of shortnose sturgeon in the Ogeechee River in June 2009	96
Figure 3.19: Habitat suitability compared to movements of shortnose sturgeon in the Ogeechee River in July 2009	97
Figure 3.20: Habitat suitability compared to movements of shortnose sturgeon in the Ogeechee River in August 2009	98
Figure 3.21: Habitat suitability compared to movements of shortnose sturgeon in the Ogeechee River in September 2009.....	99
Figure 3.22: A comparison of habitat suitability and number of sturgeon locations via telemetry per 500 m segment of the mainstem Ogeechee River during July 2008	100
Figure 3.23: A comparison of habitat suitability and number of sturgeon locations via telemetry per 500 m segment of the mainstem Ogeechee River during January 2009....	101
Figure 3.24: A comparison of habitat suitability and number of sturgeon locations via telemetry per 500 m segment of the mainstem Ogeechee River during July 2009	102

CHAPTER 1
INTRODUCTION AND LITERATURE REVIEW¹

¹ Farrae, D. J., R. A. Bahn, and D. L. Peterson *in part to be submitted to*
Reviews in Fish Biology and Fisheries spring 2010

The shortnose sturgeon, *Acipenser brevirostrum*, is one of the most endangered members of the sturgeon family because of depressed population levels and a shrinking range (Bain et al. 2000, Jelks et al. 2008). Shortnose sturgeon are a typical member of the family Acipenseridae: long-lived and late maturing (Vladykov and Greeley 1963). The shortnose sturgeon has been listed as a federally endangered species since 1967 and became a charter member of the Endangered Species Act (ESA) in 1973 (National Marine Fisheries Service (NMFS) 1998). Because of an international range, the shortnose sturgeon is also a species of special concern in Canada and is listed on the International Union for Conservation of Nature and Natural Resources Red List of Threatened Species (Friedland and Kynard 2004). The shortnose sturgeon has a global conservation status rank of G3 (Jelks et al. 2008), indicating that it is a vulnerable species. In Georgia, the species has a conservation status rank of S2 (Freeman et al. 2009), indicating that it is imperiled.

Historically, shortnose sturgeon were distributed among 25 river systems on the Atlantic coast of North America from the Saint John River in New Brunswick, Canada to the St. John's River, Florida (Figure 1.1), although some of these populations have been extirpated during the 20th Century (Vladykov and Greeley 1963, Kynard 1997, NMFS 1998). Based on genetic evidence (Waldman et al. 2002) the mid-Atlantic bight represents a division between northern and southern stocks. Unlike sympatric populations of the anadromous Atlantic sturgeon, *A. oxyrinchus oxyrinchus*, shortnose sturgeon are amphidromous, migrating from coastal rivers to estuarine and marine habitats for reasons other than spawning (Bemis and Kynard

1997). This migratory behavior makes management of shortnose sturgeon populations particularly difficult because the range of habitats they require.

Prior to their listing under the ESA, shortnose sturgeon were commercially exploited for both meat and roe throughout much of the 19th and early 20th centuries (NMFS 1998). Despite the four decades of federal protection, however, most populations have not recovered (Bain et al. 2007). Unfortunately, many remnant populations, such as that in the Ogeechee River, Georgia, are susceptible to a variety of problems including habitat degradation, loss of genetic diversity, and stochastic drift (Wirgin et al. 2005). Long-term recovery of shortnose sturgeon will require a detailed understanding of the specific habitat needs of the species, but understanding basic life history of shortnose sturgeon is a key first step to immediate recovery efforts.

Currently, most shortnose sturgeon populations face multiple threats to recovery. In the Altamaha River, Georgia, for example, shortnose sturgeon are caught incidentally in commercial fisheries targeting American shad, *Alosa sapidissima* (Heidt and Gilbert 1978, Collins et al. 2000, Peterson and Fleming 2008). Bycatch of shortnose sturgeon also has been documented in the Ogeechee River shad fishery, (Weber 1996). Although the total numbers of sturgeon captured may be small, the commercial shad season in Georgia is open from January – March, coinciding with the upstream spawning migrations of shortnose sturgeon. Although new studies of bycatch in these fisheries are now underway (Peterson and Fleming 2008), results of previous studies in South Carolina suggest that mortality of

shortnose sturgeon in commercial shad fisheries is likely suppressing recovery of some populations (NMFS 1998, Collins et al. 2000).

Construction of dams threatens the survival of many sturgeon populations. Dams alter the natural flow and temperature regimes, which could lead to decreased water quality (Jager et al. 2002). However, dams may be most damaging to shortnose sturgeon populations by blocking upstream migration to suitable spawning areas (NMFS 1998).

Life History

Shortnose sturgeon exhibit latitudinal differences in life histories (Kynard 1997), for example shortnose sturgeon grow faster and mature at a younger age in southern populations than they do in northern populations (Heidt and Gilbert 1978, Dadswell 1979). Shortnose sturgeon are estimated to live less than 20 years in the south (Rogers and Weber 1994; Fleming et al. 2003) but nearly 70 years in the north (Dadswell 1979). Shortnose sturgeon mature by 500 – 600 mm total length, which is reached by 2-3 years of age in males and 3-5 years of age in females in southern populations and 5-10 years of age in northern populations (Dadswell 1979, Kynard 1997). Southern shortnose sturgeon spend fewer years between spawning runs than northern populations because of a shorter lifespan in the south (Dadswell 1979, Kynard 1997).

Many life history differences between northern and southern populations of shortnose sturgeon are likely attributable to latitudinal differences in climate. In southern rivers, adults spawn about a month earlier than in northern rivers, as spring water temperatures in this region warm more quickly (Vladykov and Greeley 1963).

Summer is typically the feeding season in the north because water temperatures are more physiologically tolerable than in the south, where summer water temperatures may exceed 30°C. Telemetry studies have shown that southern shortnose sturgeon frequently inhabit brackish and marine habitats during cooler months, becoming increasingly tolerant of salinity as water temperatures decline below 25°C (Collins et al. 2001, Collins et al. 2002). Recent studies by DeVries (2006) show that shortnose sturgeon in the Altamaha River lose weight during the summer months when they are apparently restricted to freshwater riverine habitats. Although further studies are needed to quantify the physiological tolerances of shortnose sturgeon, seasonal movements and changes in condition suggest that southern shortnose sturgeon may use brackish and marine estuarine habitats as primary feeding areas, particularly during the non-summer months (DeVries 2006).

The timing and periodicity of spawning migrations of shortnose sturgeon vary with latitude, although spawning habitat is similar among populations. In southern populations, males typically spawn every 1-2 years; females every 3-5 years (Dadswell 1979). In northern populations adults in spawning condition begin to migrate upriver from late January to mid-February, with spawning occurring when temperatures are between 9–12°C (Hall et al. 1991). Spawning typically occurs in mid-channel areas of river bends over coarse gravel or rock substrates. Current velocities of 52 – 104 cm/sec are necessary to disperse the demersal, adhesive eggs, which hatch after 5-9 days at water temperatures of 12–20°C (Dadswell 1979, Buckley and Kynard 1985, Hall et al. 1991, Kynard 1997).

Upon hatching, shortnose sturgeon are photonegative, seeking cover in the interstitial spaces of the substrate and under benthic debris. During this “pro-larval” stage, they feed exclusively on their yolk-sacs and are largely sedentary. By day 12-14, the yolk-sac is completely absorbed, prompting the metamorphosis into the larval stage (Richmond and Kynard 1995, Kynard 1997, Kynard and Horgan 2002). As true larvae, shortnose sturgeon become photopositive, leaving the substrate and drifting downstream for about two days or until they find freshwater habitats with suitable cover (Richmond and Kynard 1995). During this period, the larvae also begin exogenous feeding as they search for planktonic prey within the water column (Richmond and Kynard 1995, Kynard and Horgan 2002).

The juvenile stage begins around day 40 and lasts from 2-5 years in southern rivers (Gilbert 1989, Richmond and Kynard 1995, Kynard 1997). After their first year in freshwater riverine habitats, juveniles again migrate downstream until they reach brackish estuarine environments that are co-inhabited by adults (Kynard 1997). At this point in their development, the fish are primarily nocturnal; using their barbels and protrusible mouths to seek and capture benthic invertebrates such as oligochaetes, insects, mollusks, and small crustaceans (Vladykov and Greeley 1963). Mud, stones, and wood chips may comprise up to 90% of a juvenile’s stomach content, but these are rarely found in adult stomachs (Dadswell 1979). This difference in stomach contents may indicate inefficiency in juvenile shortnose sturgeon feeding habits or a shift in diet as sturgeon mature. Because preferred habitats of juveniles and adults largely overlap, differences in their diets are not likely a result of differences in prey availability.

After their first year of life, juveniles typically make seasonal movements that are influenced by habitat preferences defined by their physiological tolerances of water temperature and salinity (Ziegeweid et al. 2008b). Because shortnose sturgeon become intolerant of salinity at higher water temperatures, most fish are found in tidal freshwater habitats during the summer months (Hall et al. 1991, DeVries 2006). During this period, they are most commonly found in deep freshwater habitats just above the fresh-saltwater interface of their natal rivers (DeVries 2006, Fleming et al. 2003). During the non-summer months when water temperatures $<22^{\circ}\text{C}$, shortnose sturgeon are more tolerant of salinity and, hence, may be found in brackish or marine habitats in the lower estuary (Hall et al. 1991, DeVries 2006).

Dissolved Oxygen Limits

At stressfully low DO concentrations, fish metabolism decreases until death of the fish occurs; the DO at the point of death is called the threshold concentration (Secor and Niklitschek 2001). The high threshold concentrations in sturgeons are because of a poor oxyregulatory system, low gill ventilation efficiency, and low hemoglobin oxygen affinity (Secor and Niklitschek 2001).

Sturgeons are more sensitive behaviorally and physiologically to low DO levels compared to other fish (Secor and Gunderson 1998, Secor and Niklitschek 2001). Decreased DO during the summer is cited as a limiting factor in sturgeon populations (Secor and Gunderson 1998, Collins et al. 2000). Studies indicate concentrations of $<4.0\text{ mg/L}$ DO are hypoxic in regards to sturgeon species (Secor and Gunderson 1998). Dissolved oxygen levels in this range have been observed in the Ogeechee River in recent studies (D. Peterson unpublished data). In an acute

experiment with shortnose sturgeon, fish 64 days-post-hatch (dph) exhibited 86% mortality at 2.5 mg/L DO; fish >100 dph exhibited less than 20% mortality; mortalities were not observed at DO >3.5 mg/L (Jenkins et al. 1993). Water 25 °C and 2 ppt was lethal to 50% of shortnose sturgeon (LC50) that were 77 dph at 2.7 mg/L; 104 dph at 22 °C and 4 ppt have an LC50 at 2.2 mg/L (Campbell and Goodman 2004). An LC50 occurs at 3.1 mg/L at 30 °C and 2 ppt for 100 dph shortnose sturgeon (Campbell and Goodman 2004). Older young-of-year (YOY) shortnose sturgeon exhibit greater tolerance of low DO (Jenkins et al. 1993, Kynard 1997), but studies on shortnose sturgeon over 365 dph are non-existent. Dissolved oxygen concentrations <2.5 mg/L are a possible explanation for declining or nonexistent populations of shortnose sturgeon.

Interaction of DO and temperature limit survival of southern shortnose sturgeon (Campbell and Goodman 2004). The Q₁₀ law states that for each 10 °C increase in temperature there is a two-fold increase in fish metabolism and therefore oxygen consumption. Additionally, water has a lower capacity for DO at higher water temperatures. The combination of increased oxygen demand and decreased oxygen concentrations creates a two-fold effect for fish. The two-fold effect is exacerbated in sturgeon because of their high DO requirements (Secor and Niklitschek 2001). Temperature and DO have a significant interactive effect on the mortality of sturgeon, especially at times of low DO and high temperatures (Secor and Gunderson 1998). Because of this interaction, YOY shortnose begin to exhibit physiological and behavioral changes to DO ~4.5 mg/L at 22-27 °C and complete intolerance of DO <3.3 mg/L at the same temperatures (Secor and Niklitschek 2001).

Hypoxia can be a limiting factor for shortnose sturgeon at the southern end of their range, where water temperatures alone are often beyond the physiological limits of sturgeon (Ziegeweid et al. 2008a, D. Peterson unpublished data).

Water Temperature Limits

In the southern portion of their range, shortnose sturgeon gather in riverine areas that minimize physiological stress during times of high water temperatures (Flournoy et al. 1992). Shortnose sturgeon in the Altamaha River lose weight during summer months and appear to favor freshwater habitats (DeVries 2006). Weight loss is a possible indication of stress in fish and is the result of limited feeding behavior. Though high water temperatures may threaten sturgeon populations, few studies have been conducted to determine specific lethal temperatures for sturgeon.

Thermal maxima tests of shortnose sturgeon indicate that summer water temperatures in the south may be lethal to YOY sturgeon when refuge is unavailable (Ziegeweid et al. 2008a). Loss of equilibrium and death are considered endpoints; the temperature at loss of equilibrium is called critical thermal maxima (CT_{max}) and temperature at death is called lethal thermal maxima (LT_{max}) (Ziegeweid et al. 2008a). Shortnose sturgeon 64–140 dph acclimated to a higher water temperature are significantly more tolerant of increased temperatures than sturgeon acclimated to lower water temperatures. Individuals acclimated to 19.5 °C have a CT_{max} of 33.7 °C and LT_{max} of 34.8 °C; sturgeon acclimated to 24.1 °C have a CT_{max} of 35.1 °C and LT_{max} of 36.1 °C. Using loss of equilibrium data, Ziegeweid et al. (2008a) estimates the upper limits of safe temperature for shortnose sturgeon to be 28.7–30.1 °C. Young-of-year shortnose sturgeon tolerance of high water temperatures increases

with age and size (Ziegeweid et al. 2008b). For example, mortalities at 30 °C decrease from 100% at 70 dph to 26% at 94 dph and 0% at 112 dph. Young-of-year shortnose sturgeon are 269 times less likely to survive for every 2.4 °C increase in water temperature (Ziegeweid et al. 2008b).

Thermal tolerances in juvenile and adult shortnose sturgeon are unknown. Optimum temperatures, LT_{max} , and CT_{max} are often highest during the earliest life stages and decrease as fish age (Jobling 1994). This trend has not been confirmed experimentally for shortnose sturgeon, but it is possible that thermal tolerances are lower in adults.

Water temperatures at or above the estimated lethal temperature of ~31 °C (Ziegeweid et al. 2008a, Ziegeweid et al. 2008b) are characteristic of rivers in the southern extent of the range of the shortnose sturgeon; examples include the Altamaha (Heidt and Gilbert 1978, DeVries 2006), Savannah (Collins et al. 2002), and Ogeechee rivers, GA (D. Peterson unpublished data). The size structure of the Ogeechee River population of shortnose sturgeon is indicative of persistent recruitment failure (Fleming et al. 2003). Data have not indicated if recruitment failure is because of an inability to successfully reproduce or poor survival during the critical period. Shortnose sturgeon habitat in southern rivers may be limited by availability of cool water refugia (Ziegeweid et al. 2008a) and high water temperatures are a concern for managers (NMFS 1998).

Salinity Limits

Shortnose sturgeon use estuarine portions of rivers during the winter months in the south and move to freshwater as water temperatures increase (Collins et al.

2002). Limited data from fixed locations in Georgia estuaries indicate a significant increase in salinities between 1974 and 1992 in some of the estuaries (Alber and Sheldon 1999). Saltwater encroachment concurrent with increasing water temperatures could limit suitable habitats for shortnose sturgeon (Collins et al. 2002), which are intolerant of saltwater at early life stages (Ziegeweid et al. 2008b).

Young-of-year shortnose sturgeon become more tolerant of increased salinity with increasing size and age if temperature and DO are held constant (Jenkins et al. 1993, Ziegeweid et al. 2008b). Survival among all tested ages of shortnose sturgeon (11–330 dph) is close to 100% at 7 ppt and 21–23°C (Jenkins et al. 1993). However, when the salinity is increased to 9 ppt, sturgeon begin to exhibit a higher mortality rate. Only 330 dph sturgeon survive salinities >15 ppt, but even these fish cannot survive salinities >25 ppt (Jenkins et al. 1993).

Salinity tolerance increases with increasing size and age in YOY shortnose sturgeon. A series of 48-h experiments were used to determine LC50 concentrations of salinity for shortnose sturgeon of three different ages: 66 dph and 56 mm TL, 86 dph and 93 mm TL, and 107 dph and 128 mm TL (Ziegeweid et al. 2008b). The 48-h LC50 values are 14.8, 19.1, and 20.9 ppt for 66, 86, and 107 dph, respectively. Young-of-year shortnose sturgeon are 264 times less likely to survive for every 1.5 ppt increase in water salinity. However, there is a significant interactive effect of temperature and salinity on sturgeon survival. For example, there is 0% mortality for YOY shortnose at 16.4 ppt and 23.1 °C, but 58% mortality for the same size and age fish at 16.4 ppt and 28.6 °C (Ziegeweid et al. 2008b).

Salinity tolerance studies have not been conducted on adult shortnose sturgeon. Until adult salinity tolerances are confirmed, only capture and telemetry data can be used to identify maximum salinity preferences in wild shortnose sturgeon. Water temperatures interact with salinities to affect movements of adult shortnose sturgeon. At water temperatures $>27^{\circ}\text{C}$ in southern rivers, adult shortnose sturgeon remain primarily in fresh water (0–6 ppt), but when water temperatures drop $<27^{\circ}\text{C}$ they move into brackish water (6–20 ppt) and they use estuarine water (20–35 ppt) at water temperatures $<16^{\circ}\text{C}$ (Flournoy et al. 1992, Weber et al. 1998, Collins et al. 2002, DeVries 2006).

Current Status and Management

Presently, shortnose sturgeon are managed on a population basis under the assumption that individual rivers contain unique populations (NMFS 1998). Genetic studies have provided some insight regarding the relationships between neighboring rivers. By estimating gene flow among rivers, researchers can identify genetically discrete populations. Previous studies of haplotype frequencies in shortnose sturgeon show that the Ogeechee River stock is not genetically distinct from the Savannah River or Altamaha River stocks (Wirgin et al. 2005, Wirgin et al. 2009). Movement of hatchery-reared shortnose sturgeon from the Savannah to the Ogeechee (Smith et al. 2002) has led to speculation that the relatively low genetic difference among southern rivers, relative to northern rivers, is because of the movement of stocked sturgeon and is only a recent phenomenon (Wirgin et al. 2009). Conversely, southern shortnose sturgeon may have an inherent propensity for movement between rivers that northern stocks lack (Wirgin et al. 2009). Unfortunately, genetic samples prior to

stocking the Savannah River are unavailable to analyze pre-stocking genetic diversity of sturgeon in southern rivers. Within the southern portion of the range, the Altamaha River sustains the largest population (DeVries 2006). These findings suggest that mixing of southern populations may be related to population density as suggested previously by Kynard (1997). If the Ogeechee and Altamaha rivers support a single genetically discrete unit as suggested by Wirgin et al. (2009), then the two rivers should be managed as a single population. However, results of this genetic analysis must be supported by evidence from population dynamic studies before management options can be evaluated.

Previous studies have attempted to analyze the shortnose sturgeon population in the Ogeechee River. From 1993 – 1995 Weber (1996) obtained a range of population estimates; however the study focused on the identification of spawning habitat. In 1996, the author observed one gravid female making, what appeared to be, a spawning migration but did not find direct evidence of spawning. However, Weber did identify suitable spawning habitat at river kilometer (rkm) 86. Subsequent investigations by Fleming et al. (2003) to identify spawning habitats were not successful. Low juvenile abundance led these authors to conclude that recruitment failure was probably limiting population recovery (Fleming et al. 2003). Both of these previous studies estimated population abundance at <300 individuals, confirming that the Ogeechee population is probably the smallest remaining stock of shortnose sturgeon. These two previous efforts found limited evidence of the Ogeechee River sustaining a genetically unique population of shortnose sturgeon. Despite the consistent presence of adult shortnose sturgeon in the river, there appears

to be a lack of juveniles. A lack of juvenile fish is indicative of either a failure to spawn by adult fish or limited survival of spawned larvae and/or juveniles.

Although several studies have shown that poor water quality may limit first year survival (Secor and Gunderson 1998, Secor and Niklitschek 2001, Ziegeweid et al. 2008a, Ziegeweid et al. 2008b) and recovery of depleted sturgeon populations (Jager et al. 2002), specific limiting factors remain unclear. Fleming et al. (2003) suggest that chronic recruitment failure has hampered recovery of shortnose sturgeon in the Ogeechee River; however, these authors did not evaluate juvenile habitat quality. Prolonged periods of high temperatures and low DO in reservoirs have likely hampered white sturgeon recovery in the Snake River System (Jager et al. 2002). Although environmental tolerances of wild juvenile shortnose sturgeon have not been evaluated, Ziegeweid et al. (2008a) showed that hatchery-reared juveniles become increasingly intolerant of salinity as temperatures exceed 23°C. Because water temperatures at or above the estimated lethal temperature of ~ 30°C (Ziegeweid et al. 2008a) have been documented in coastal Georgia rivers, such as the Altamaha (Heidt and Gilbert 1978, Flournoy et al. 1992, DeVries 2006), Savannah (Collins et al. 2001), and Ogeechee Rivers (D. Peterson unpublished data), poor water quality might be a limiting factor in many southern shortnose sturgeon populations.

Although historical data on shortnose sturgeon populations is scarce, federal protections have helped increase funding for shortnose sturgeon research over the last three decades; however, most studies have focused on northern populations. Effective recovery strategies for southern populations will require focused research and status assessments to provide current information regarding population trends,

habitat quality, and general ecology (Bain et al. 2000). Therefore, the goal of this study was to understand why shortnose sturgeon abundance in the Ogeechee River has not increased, despite 30 years of protection under the ESA. The specific objectives were to:

(1) estimate current abundance and to quantify population dynamics of Ogeechee River shortnose sturgeon; (2) evaluate seasonal habitat use of adult shortnose sturgeon within the tidally influenced portion of the river; and (3) identify potential limiting factors for this population.

Understanding population dynamics and basic life history characteristics of shortnose sturgeon are recognized as essential aspects of recovery plans for the species (NMFS 1998, Bain et al. 2000). Over the past 15 years, the shortnose sturgeon population of the Ogeechee River has been studied intermittently; however, the current status of the stock is unclear because historic population levels are unknown. Furthermore, understanding seasonal habitat use of the adult stock will help management agencies develop a stock-specific restoration strategy.

References

- Alber, M. and J. E. Sheldon. 1999. Trends in salinities and flushing times of Georgia estuaries. pp. 528–531 in K. J. Hatcher, editor. Proceedings of the 1999 Georgia Water Resources Conference. The University of Georgia. Athens, Georgia.
- Bain, M. B., N. Haley, D. L. Peterson, J. R. Waldman, and K. K. Arend. 2000. Harvest and habitats of Atlantic sturgeon *Acipenser oxyrinchus* Mitchill, 1815 in the Hudson River estuary: Lessons for sturgeon conservation. Boletín Instituto Espanol de Oceanografía 16: 43–53.
- Bain, M. B., N. Haley, D. L. Peterson, K. K. Arend, K. E. Mills, and P. J. Sullivan. 2007. Recovery of a US Endangered Fish. PLoS ONE 2(1): e168.
- Bemis, W. E. and B. Kynard. 1997. Sturgeon rivers: an introduction to acipensiform biogeography and life history. Environmental Biology of Fishes 48:167–183.
- Buckley, J. and B. Kynard. 1985. Yearly movements of shortnose sturgeons in the Connecticut River. Transactions of the American Fisheries Society 114:813–820.
- Campbell, J. G. and L. R. Goodman. 2004. Acute sensitivity of juvenile shortnose sturgeon to low dissolved oxygen concentrations. Transactions of the American Fisheries Society 133: 772–776.
- Collins, M. R., S. G. Rogers, T. I. J. Smith, and M. L. Moser. 2000. Primary factors affecting sturgeon populations in the southeastern United States: fishing mortality and degradation of essential habitats. Bulletin of Marine Science 66(3): 917–928.

- Collins, M. R., W. C. Post, and D. C. Russ. 2001. Distribution of shortnose sturgeon in the lower Savannah River. Final Report to the Georgia Ports Authority 21pp.
- Collins, M. R., W. C. Post, D. C. Russ, and T. I. J. Smith. 2002. Habitat use and movements of juvenile shortnose sturgeon in the Savannah River, Georgia-South Carolina. Transactions of the American Fisheries Society 131:975–979.
- Cooke, D. W., S. D. Leach, and J. J. Isley. 2002. Behavior and lack of upstream passage of shortnose sturgeon at a Hydroelectric facility and navigation lock complex. American Fisheries Society Symposium 28: 101–110.
- Dadswell, M. J. 1979. Biology and population characteristics of the shortnose sturgeon, *Acipenser brevirostrum* LeSueur 1818 (Osteichthes: Acipenseridae), in the Saint John River Estuary, New Brunswick, Canada. Canadian Journal of Zoology 57:2186–2210.
- DeVries, R. J. 2006. Population dynamics, movements, and spawning habitat of the shortnose sturgeon, *Acipenser brevirostrum*, in the Altamaha River System, Georgia. M.S. Thesis, University of Georgia, Athens, Georgia.
- Fleming, J. E., T. D. Bryce, and J. P. Kirk. 2003. Age, growth, and status of shortnose sturgeon in the lower Ogeechee River, Georgia. Proceedings of the Annual Conference of the Southeast Association of Fish and Wildlife Agencies 57:80–91.

- Flournoy, P. H., S. G. Rogers, and P. S. Crawford. 1992. Restoration of shortnose sturgeon in the Altamaha River, Georgia. United States Fish and Wildlife Service Project Number AFS-2, Segments One and Two.
- Freeman, B. J., D. J. Farrae, and D. L. Peterson. 2009. Shortnose sturgeon species account. Georgia Department of Natural Resources Wildlife Resources Division. 4pp.
- Friedland, K. D. and B. Kynard. 2004. *Acipenser brevirostrum*. In: IUCN 2007. *2007 IUCN Red List of Threatened Species*. <www.icucnredlist.org> Downloaded on 07 March 2008.
- Gilbert, C. R. 1989. Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (Mid-Atlantic Bight)- Atlantic and shortnose sturgeons. U.S. Fish and Wildlife Service biological Report 82 (11.122).
- Hall, J. W., T. I. J. Smith, and S. D. Lamprecht. 1991. Movements and habitats of shortnose sturgeon, *Acipenser brevirostrum*, in the Savannah River. *Copeia* 3:695–702.
- Heidt, A. R. and R. J. Gilbert. 1978. The shortnose sturgeon in the Altamaha River drainage, Georgia. Pages 54-60 in R.R. Odum and L. Landers, editors. Proceedings of the rare and endangered wildlife symposium. Georgia Department of Natural resources, Game and Fish division, Technical Bulletin WL 4, Athens, Georgia.
- Hosmer, D. W. and S. Lemeshow. 1989. Applied Logistic Regression. Wiley, New York.

- Jager, H. I., W. V. Winkle, J. A. Chandler, K. B. Lepla, P. Bates, and T. D. Counhan. 2002. A simulation study of factors controlling white sturgeon recruitment in the Snake River. *American Fisheries Society Symposium* 28: 12–150.
- Jelks, H. L., S. J. Walsh, N. M. Burkhead, S. Contreras-Balderas, E. Diaz-Pardo, D. A. Hendrickson, J. Lyons, N. E. Mandrak, F. McCormick, J. S. Nelson, S. P. Platania, B. A. Porter, C. B. Renaud, J. J. Schmitter-Soto, E. B. Taylor, and M. L. Warren Jr. 2008. Conservation status of imperiled North American freshwater and diadromous fishes. *Fisheries* 33: 372 – 386.
- Jenkins, W. E., T. I. J. Smith, L. D. Heyward, and D. M. Knott. 1993. Tolerance of shortnose sturgeon, *Acipenser brevirostrum*, juveniles to different salinity and dissolved oxygen concentrations. *Proceedings of the Annual Conference of the Southeast Association of Fish and Wildlife Agencies* 47: 476–484.
- Jobling, M. 1994. *Fish Bioenergetics*. Chapman & Hall, London.
- Kynard, B. 1997. Life History, latitudinal patterns, and status of the shortnose sturgeon, *Acipenser brevirostrum*. *Environmental Biology of Fishes* 48: 319–334.
- Kynard, B. and M. Horgan. 2002. Ontogenetic behavior and migration of Atlantic sturgeon, *Acipenser oxyrinchus*, and shortnose sturgeon, *A. brevirostrum*, with notes on social behavior. *Environmental Biology of Fishes* 63: 137–150.
- National Marine Fisheries Service (NMFS). 1998. Final Recovery Plan for the shortnose sturgeon, *Acipenser brevirostrum*. Prepared by the Shortnose Sturgeon Recovery Team for the National Marine Fisheries Service, Silver Spring, Maryland. 104pp.

- Peterson, D. L. and J. Fleming. 2008. Bycatch in the Altamaha River American shad set-net fishery. Report to NMFS, 6 pp.
- Quattro, J. M., T. W. Greig, D. K. Coykendall, B. W. Bowen, and J. D. Baldwin. 2002. Genetic issues in aquatic species management: the shortnose sturgeon (*Acipenser brevirostrum*) in the southeastern United States. *Conservation Genetics* 3: 155–166.
- Richmond, A. M. and B. Kynard. 1995. Ontogenetic behavior of shortnose sturgeon, *Acipenser brevirostrum*. *Copeia* 1: 172–182.
- Rogers, S. G. and W. Weber. 1994. Movements of shortnose sturgeon in the Altamaha River System, Georgia. Contributions Series No. 57. Coastal Resources Division, Georgia Department of Natural Resources. Brunswick, Georgia.
- Secor, D. H. and T. E. Gunderson. 1998. Effects of hypoxia and temperature on survival, growth, and respiration of juvenile Atlantic sturgeon, *Acipenser oxyrinchus*. *Fisheries Bulletin* 96: 603–613.
- Secor, D. H. and E. J. Niklitschek. 2001. Hypoxia and sturgeons: report to the Chesapeake Bay Program dissolved oxygen team. Technical Report Series No. TS-314-01-CBL; Chesapeake Biological Laboratory, Solomons, Maryland.
- Smith, T. I. J., J. W. McCord, M. R. Collins, and W. C. Post. 2002. Occurrence of stocked shortnose sturgeon *Acipenser brevirostrum* in non-target rivers. *Journal of Applied Ichthyology* 18: 470–474.

- Vladykov, V. D. and J. R. Greeley. 1963. Order Acipenseroidei. Pages 24-60 in V. H. Olsen, editor. Fishes of the western North Atlantic, part III. Memoirs of the Sears Foundation for Marine Research, New Haven, Connecticut. 630 pp.
- Waldman, J. R., C. Grunwald, J. Stabile, and I. Wirgin. 2002. Impacts of life history and biogeography on the genetic stock structure of Atlantic sturgeon *Acipenser oxyrinchus oxyrinchus*, Gulf sturgeon *Acipenser oxyrinchus desotoi*, and shortnose sturgeon *A. brevirostrum*. *Journal of Applied Ichthyology* 18: 509–518.
- Walsh, M. G., M. B. Bain, T. Squiers Jr., J. R. Waldman, and I. Wirgin. 2001. Morphological and genetic variation among shortnose sturgeon *Acipenser brevirostrum* from adjacent and distant rivers. *Estuaries* 24(1): 41–48.
- Weber, W. 1996. Population size and habitat use of shortnose sturgeon, *Acipenser brevirostrum*, in the Ogeechee River System, Georgia. M.S. Thesis, University of Georgia, Athens, Georgia.
- Weber, W., C. A. Jennings, and S. G. Rogers. 1998. Population size and movement patterns of shortnose sturgeon in the Ogeechee River System, Georgia. *Proceedings of the Annual Conference of the Southeast Association of Fish and Wildlife Agencies* 52: 18–28.
- Wirgin, I., C. Grunwald, E. Carlson, J. Stabile, D. L. Peterson, and J. Waldman. 2005. Range-wide population structure of shortnose sturgeon *Acipenser brevirostrum* based on sequence analysis of the mitochondrial DNA control region. *Estuaries* 28(3): 406–421.

Ziegeweid, J. R., C. A. Jennings, and D. L. Peterson. 2008a. Thermal maxima for juvenile shortnose sturgeon acclimated to different temperatures.

Environmental Biology of Fishes 82: 299–307.

Ziegeweid, J. R., C. A. Jennings, D. L. Peterson, and M. C. Black. 2008b. Effects of salinity, temperature, and weight on the survival of young-of-year shortnose sturgeon. *Transactions of the American Fisheries Society* 137:1490–1499.



Figure 1.1. Historic range of shortnose sturgeon in North America (adapted from NMFS 1998).

CHAPTER 2
POPULATION DYNAMICS OF SHORTNOSE STURGEON IN THE
OGEECHEE RIVER, GEORGIA²

²Farrae, D. J. and D. L. Peterson *to be submitted to*

Transactions of the American Fisheries Society spring 2010

Abstract

Shortnose sturgeon, *Acipenser brevirostrum*, are one of the most endangered members of the sturgeon family because of over-exploitation, depressed population levels, and a shrinking range. The lack of historical data on shortnose sturgeon populations has led to an increase in sturgeon research over the last three decades; however, most recent studies focused on northern populations. The primary goal of this study was to determine why the Ogeechee River population is not recovering. Shortnose sturgeon were captured with gill and trammel nets for a mark-recapture analysis using Program MARK. From 1 June – 31 August, 2007 – 2009, we deployed a total of 864 net sets over 660 net-hours and captured 168 individual shortnose sturgeon with 51 total recaptures. Robust design models revealed the best-fitting models incorporated interactions among water temperature, dissolved oxygen, and total effort with capture and recapture probabilities set equal and temporary emigration parameters set to zero or as constant. Abundance estimates (95% CI) were 404 (175 – 633), 264 (126 – 402), and 203 (32 – 446) individual sturgeon for 2007, 2008, and 2009, respectively. Movements of shortnose between the Ogeechee and Altamaha rivers were documented during this study. Over the three years of our study, abundance, survival, and temporary emigration estimates, combined with documented movement of fish between rivers, provided evidence that shortnose sturgeon in the Ogeechee River are not a discrete population. We propose that the Altamaha and Ogeechee rivers may form a source-sink metapopulation in regards to shortnose sturgeon.

Introduction

Shortnose sturgeon, *Acipenser brevirostrum*, are one of the most endangered members of the sturgeon family because of over-exploitation, depressed population levels, and a shrinking range (Bain et al. 2000, Jelks et al. 2008). They are a typical member of the family Acipenseridae: long-lived and late maturing. Originally listed as endangered in 1967, the shortnose sturgeon became a charter member of the Endangered Species Act in 1973 (National Marine Fisheries Service (NMFS) 1998). Outside of the United States, shortnose are listed as a species of concern in Canada and on the International Union for Conservation of Nature and Natural Resources Red List of Threatened Species (Friedland and Kynard 2004). The shortnose sturgeon has a global conservation status rank of G3 (Jelks et al. 2008), indicating that the species is currently considered “vulnerable.”

Historically, shortnose sturgeon were distributed among 25 river systems on the Atlantic coast of North America, from the Saint John River in New Brunswick, Canada, to the St. John’s River, Florida. At present, many of these populations might be extirpated (Vladykov and Greeley 1963, Kynard 1997, NMFS 1998), but targeted status assessments are rare. Based on genetic evidence (Waldman et al. 2002) the mid-Atlantic bight represents a division between northern and southern populations. An amphidromous species, shortnose typically inhabit both fresh and brackish waters of coastal rivers throughout various times of the year (Bemis and Kynard 1997).

Management of shortnose sturgeon populations is complicated not only by their complex life cycle and diverse habitat requirements, but also by latitudinal variation in life history strategies (Kynard 1997). For example, southern sturgeon

typically grow faster and mature younger, than do northern sturgeon (Heidt and Gilbert 1978, Dadswell 1979). This growth difference is illustrated by several previous studies that have reported the maximum age of southern shortnose > 20 years (Rogers and Weber 1994; Fleming et al. 2003), while those in northern rivers may reach nearly 70 years (Dadswell 1979). Regardless of age, shortnose sturgeon typically mature at 500 – 600 mm total length (TL). In the southern portion of their range, this usually occurs by 2-3 years for males and 3-5 years for females. In contrast, the age to maturity in northern rivers is typically 5-10 years (Dadswell 1979, Kynard 1997). Likewise, spawning periodicity is shorter in southern populations, presumably to compensate for their shorter lifespan (Dadswell 1979, Kynard 1997).

Many of the life history differences between northern and southern populations are likely attributable to latitudinal differences in climate. In southern rivers, adults spawn about a month earlier than in northern rivers (Vladykov and Greeley 1963). Telemetry studies have shown that southern shortnose sturgeon frequently inhabit brackish and marine habitats during cooler months and become increasingly tolerant of salinity as water temperatures decline below 25°C (Collins et al. 2001, Collins et al. 2002, DeVries 2006). Altamaha River shortnose sturgeon lose weight during summer months (Flournoy et al. 1992) and appear to prefer freshwater habitats during high water temperatures (DeVries 2006). Although further studies are needed to quantify the physiological tolerances of shortnose sturgeon, seasonal movements and changes in condition suggest that southern shortnose sturgeon may use brackish and marine estuarine habitats as primary feeding areas, particularly during the non-summer months.

Currently, most shortnose sturgeon populations face multiple threats to recovery. In the Altamaha River, Georgia, shortnose sturgeon are caught incidentally in commercial fisheries targeting American shad, *Alosa sapidissima* (Heidt and Gilbert 1978, Collins et al. 2000, Peterson and Fleming 2008). Shortnose sturgeon also have been documented in the bycatch of a similar shad fishery on the Ogeechee River (Weber 1996). The commercial shad season in Georgia is open from January – March, coinciding with the upstream spawning migrations of shortnose sturgeon. Studies of bycatch in these fisheries are currently underway (D. Peterson, personal communication), but previous studies in South Carolina suggest that mortality of shortnose sturgeon in commercial shad fisheries is likely suppressing the recovery of some populations (NMFS 1998, Collins et al. 2000).

The lack of historical data on shortnose sturgeon populations has led to an increase in sturgeon research over the last three decades; however, most recent studies focused on northern populations (e.g., Welsh et al. 2002, Bain et al. 2007, Li et al. 2007, Woodland and Secor 2007, Kynard et al. 2009). Effective recovery strategies for southern shortnose sturgeon populations will require focused research and status assessments to provide current information regarding population trends, habitat quality, and general ecology (Bain et al. 2000). Previous research efforts on the Ogeechee River population have failed to identify conclusive spawning (Weber 1996) or spawning habitat (Fleming et al. 2003). Evidence of low juvenile presence suggests that recruitment failure is limiting recovery of shortnose sturgeon in the Ogeechee River (Fleming et al. 2003). All previous studies have indicated a population of less than 300 shortnose sturgeon in the Ogeechee River (Weber et al.

1998, Fleming et al. 2001), which is small compared to abundances in the neighboring Savannah and Altamaha rivers (NMFS 1998, DeVries 2006).

Despite almost 40 years of protection under the Endangered Species Act, the abundance of shortnose sturgeon in the Ogeechee River has not increased. This study is part of larger efforts to determine why the Ogeechee River population is not recovering. The specific objectives were to estimate current abundance, annual survival, and temporary emigration parameters of Ogeechee River shortnose sturgeon. This study fulfills a primary goal of the NMFS Shortnose Sturgeon Recovery Plan (1998) to monitor abundance and population dynamics of all known populations of shortnose sturgeon.

Site Description

The Ogeechee River is one of the longest free-flowing rivers on the East Coast, containing 425 rkm of unimpounded riverine habitats (Weber 1996). One major tributary, the Canoochee River, drains into the Ogeechee River at rkm 55 (Figure 2.1). The Ogeechee River is classified as a “blackwater” system because of its tannic, nutrient-poor waters (Meyer et al. 1997). Unlike most blackwater rivers, however, the pH of the Ogeechee River is close to neutral throughout most of the year (Meyer et al. 1997). The river originates in central Georgia in the Piedmont Province and flows southeasterly through a mostly undeveloped coastal plain watershed. Tidal amplitudes on the Ogeechee vary from 1.6 to 2.7 m (Weber 1996) and average annual discharge is 115 m³/s (Meyer et al. 1997). Maximum discharge occurs in spring and winter; however, tropical storms frequently cause brief periods of flooding during the summer and fall (Weber 1996, Meyer et al. 1997).

Methods

Sampling locations were selected randomly using a stratified design throughout the lower 70 rkm of the Ogeechee River and the lower 5 rkm of the Canoochee River. Shortnose sturgeon were captured using trammel and gill nets measuring 61 m by 2.5 m. Gill nets were constructed of 10.2, 12.7, and 15.2-cm monofilament mesh (stretch measure); trammel nets were constructed from a 7.6-cm mesh inner panel and two 30.5-cm mesh outer panels. Nets were deployed perpendicular to the current, anchored to the bottom, and set for 25 – 90 min during slack tides. After all nets had been set, water temperature (T; °C) and dissolved oxygen (DO; mg/L) were measured using a YSI[®] 85 multimeter.

As nets were retrieved, captured shortnose sturgeon were placed into a floating net pen, where they were allowed to recover for 10 – 15 min prior to data collection. Each fish was measured (TL; mm), weighed (g), and scanned for a passive integrated transponder (PIT) tag. If a PIT tag was not detected, then one was injected under the fourth dorsal scute. All sturgeon were released in good condition.

Mark-recapture data were analyzed using a closed capture robust design model to estimate abundance, survival, and temporary emigration parameters and to identify covariates affecting capture and recapture probabilities. Individual capture histories were constructed by using each sampling week during the summer as an individual secondary sampling period (recaptures within a week were not counted) within the primary sampling period of the entire summer. Thirteen secondary sampling periods (weeks from June 1 – August 31) within three primary periods (summers from 2007 – 2009) yielded a total of 39 discrete sampling periods.

The population was considered open between primary periods, but closed within secondary periods for model structure. A candidate set of models with combinations of parameters for capture and recapture probabilities were constructed. Capture and recapture probabilities were modeled as constant, time-varying, or as functions of predictor variables from primary or secondary sampling periods, as appropriate. The predictor variables used were total weekly sampling effort in hours, mean weekly T, and mean weekly DO. The same covariates of effort, T, and DO were used for primary periods when capture and recapture probabilities were constant within secondary periods. Combinations of covariates were used in additive and interactive terms, except for temperature and DO because of their physical autocorrelation. All covariates were standardized to a mean of zero and standard deviation of one within the period for which they were used as covariates. Program MARK (program available online: <http://welcome.warnercnr.colostate.edu/~gwhite/mark/mark.htm>) was used to evaluate the relative weight of each model and to obtain parameter estimates.

The relative likelihood of each model was evaluated by an information theoretic approach (Burnham and Anderson 2002), by calculating Akaike's information criterion (Akaike 1973) with an adjustment for small sample size (AICc; Hurvich and Tsai 1989). If model weights were spread among several models, then model-averaged parameter estimates were used to account for uncertainty in model selection and were the basis for all inferences (Burnham and Anderson 2002).

Results

From 1 June – 31 August, 2007 – 2009, we deployed a total of 864 net sets over 660 net-hours and captured 168 individual shortnose sturgeon with 51 total recaptures (Table 2.1). Catch-per-unit-effort (CPUE; fish per net-hour) was 0.37, 0.51, and 0.15 for 2007, 2008, and 2009, respectively. Captured shortnose varied in size from 555 – 1187 mm TL. Juvenile shortnose sturgeon were not captured during the study (Figure 2.2). Length-weight relationships were consistent among all three years (Figure 2.3).

Robust design models revealed the best-fitting models incorporated interactions among T, DO, and total effort with capture and recapture probabilities set equal and temporary emigration parameters set to zero or as constant (Table 2.2). The top four models accounted for over 98% of the relative weight and were used to calculate model-averaged parameter estimates (Table 2.3). Survival estimates between primary periods were 0.737 from 2007 to 2008 and 0.812 from 2008 to 2009. The probability of an individual shortnose sturgeon emigrating out of the study area (γ'') between years was 0.160 while the probability of remaining in the study area ($1 - \gamma''$) between years was 0.840. The probability of a sturgeon remaining outside of the study area (γ') between years was 0.160 and the probability of migrating into the study area ($1 - \gamma'$) between years was 0.840. Other immigration and emigration parameters were logically or statistically confounded and could not be estimated. All estimates of survival and temporary emigration were inaccurate because of large confidence intervals. Abundance estimates (95% CI) were 404 (175 – 633), 264 (126

– 402), and 203 (32 – 446) individual sturgeon for 2007, 2008, and 2009, respectively.

During our study, 10 shortnose sturgeon that were originally tagged in the Altamaha River were recaptured in the Ogeechee River. Additionally, two sturgeon that were originally tagged in the Ogeechee River were recaptured in the Altamaha River (D. Peterson, personal communication). Other shortnose sturgeon movements between the Ogeechee and Altamaha rivers and the Cooper and Edisto rivers, SC have been documented recently (D. Peterson, unpublished data; B. Post, personal communication).

Discussion

The results of our study provide an updated abundance estimate and the first quantitative estimate of population dynamics of shortnose sturgeon in the Ogeechee River, Georgia. The AICc model results indicated that capture and recapture probabilities were best predicted by water temperature, DO, and sampling effort. Covariates such as these should be incorporated in future studies to best predict capture and recapture probabilities. The lack of juveniles in the Ogeechee River population, based on TLs (Figure 2.2), indicates that persistent recruitment failure may be limiting population recovery. Gear selectivity was not responsible for the lack of juveniles because we frequently captured juvenile Atlantic sturgeon, *Acipenser oxyrinchus*, between 200 – 500 mm TL (n=48). Additionally, the same gear captured juvenile shortnose sturgeon in the Altamaha River during a similar study (DeVries 2006). Weight-length relationships from our study (Figure 2.3) are similar to the relationship observed for the Altamaha River stock (DeVries 2006).

Our survival estimates (0.737 – 0.812) are the first attempts at estimating annual shortnose sturgeon survival of which we are aware, but survival estimates appear adequate for sustaining a population of long-lived fish such as shortnose sturgeon (Eberhardt 2002). However, if the Ogeechee River represented a unique population, then persistent recruitment failure should cause decreasing abundance and eventually extirpation. Abundance estimates have remained static over the last 16 years (Figure 2.4), despite federal protection and evidence of recovery in other river systems, such as the Hudson (Bain et al. 2007) and the Altamaha (DeVries 2006). However, a decrease in CPUE in 2009 may indicate some annual variations in capture efficiency or number of sturgeon (Table 2.1). Large annual fluctuations in abundance could simply reflect frequent movements of individuals between the Altamaha and Ogeechee rivers or intermittently successful spawning events. Juvenile shortnose sturgeon have been captured occasionally in the Ogeechee River (J. Fleming, personal communication), which may indicate that spawning may occur intermittently.

Frequent movements between neighboring rivers may be indicative of a metapopulation; this phenomenon has been suggested to occur with shortnose sturgeon in large density-dependent source populations, such as in the Hudson and Altamaha rivers (Kynard 1997, Walsh et al. 2001). Previous genetic analyses of shortnose sturgeon from the Ogeechee and Altamaha rivers suggest that these two systems may, in fact, constitute a single metapopulation (Wirgin et al. 2005, Wirgin et al. 2009), but prior to this study demographic evidence of such a relationship has been lacking. Occasional reproductive events and/or frequent immigration of

sturgeon into the Ogeechee River might be sustaining the population. If most immigrants originate from the Altamaha River, as our field evidence and separate genetic analyses all suggest, then the two rivers fit the definition of a source-sink metapopulation (Pulliam 1988, Figueira and Crowder 2006, Wilberg et al. 2008).

Over the three years of our study, abundance, survival, and temporary emigration estimates and the documented movement of fish between rivers, provided evidence that shortnose sturgeon in the Ogeechee River are not a discrete population. Management of shortnose sturgeon is mostly targeted on a river-by-river basis, under the assumption that one river forms a unique population. Genetic analyses by Wirgin et al. (2005, 2009) have been used to delineate discrete population segments (DPS) of shortnose throughout the range; however, supporting field evidence is scarce. The results of this study provide new evidence of shortnose sturgeon movements between the Ogeechee and Altamaha rivers. In combination with previous genetic analyses, our results suggest that the Ogeechee stock should be classified as a single metapopulation within the greater southeastern portion of the range.

Our research fulfilled one of the goals of the NMFS Shortnose Sturgeon Recovery Plan (1998): determine abundance, age structure, and recruitment for population segments. The Ogeechee River, as an individual population segment, contains an order of magnitude fewer sturgeon than the neighboring Altamaha River (DeVries 2006) and two orders of magnitude fewer fish than the largest known population in the Hudson River (Bain et al. 2007). The Ogeechee stock probably contains few, if any, juvenile shortnose sturgeon and appears to be limited by frequent recruitment failure. However, intermittent spawning may occur when

conditions are ideal. Efforts to quantify spawning habitat (N. Nibbelink, unpublished data) and to identify potential sources of recruitment failure (Chapter 3) are being completed.

Parameter estimates for survival and temporary emigration provided point estimates with wide confidence intervals. Although additional captures would have resulted in better precision, these estimates provide the first quantified evidence of population mixing for this species. For larger populations, such as the Altamaha, Hudson, and Delaware, the robust design may provide the best model for estimating critical population parameters.

The sampling methods and data analyses used in this study should be used to assess shortnose sturgeon populations as part of a long-term, range-wide assessment as prescribed by the NMFS Recovery Plan (1998). Development and application of a standardized assessment protocol will facilitate future comparisons of population dynamics and abundance trends of shortnose sturgeon in other rivers.

Future research efforts on shortnose sturgeon in the Ogeechee River should focus on the monitoring of abundance, recruitment, and emigration trends. Because recruitment and abundance are subject to stochastic and environmental influences, long-term studies are required to make conclusions about population and reproductive status. Concurrent studies on multiple river systems are needed to document movement between coastal rivers and to define DPS's. Identification of migratory routes between the Ogeechee and Altamaha rivers is necessary to properly protect all habitat used by shortnose sturgeon. Other river systems should be analyzed to determine the possibility of source-sink metapopulations and to support genetic

delineation of DPS's. Proper management requires an understanding of population dynamics and the relationship between neighboring populations. Our results provide the basis for proper management of the Ogeechee River shortnose sturgeon.

References

- Akaike, H. 1973. Information theory and an extension of the maximum likelihood principle. Pages 267-281 in B.N. Petrov and F. Casaki, editors. Second international symposium on information theory. Akademiai Kiado, Budapest, Hungary.
- Bain, M. B., N. Haley, D. L. Peterson, J. R. Waldman, and K. K. Arend. 2000. Harvest and habitats of Atlantic sturgeon *Acipenser oxyrinchus* Mitchill, 1815 in the Hudson River estuary: Lessons for sturgeon conservation. Boletin Instituto Espanol de Oceanografia 16: 43–53.
- Bain, M. B., N. Haley, D. L. Peterson, K. K. Arend, K. E. Mills, and P. J. Sullivan. 2007. Recovery of a US Endangered Fish. PLoS ONE 2(1): e168.
- Bemis, W. E. and B. Kynard. 1997. Sturgeon rivers: an introduction to acipensiform biogeography and life history. Environmental Biology of Fishes 48:167–183.
- Burnham, K. P. and D. R. Anderson. 2002. Model selection and multi-model inference: an information-theoretic approach. Springer-Verlag, New York, New York.
- Collins, M. R., S. G. Rogers, T. I. J. Smith, and M. L. Moser. 2000. Primary factors affecting sturgeon populations in the southeastern United States: fishing mortality and degradation of essential habitats. Bulletin of Marine Science 66(3): 917–928.
- Collins, M. R., W. C. Post, and D. C. Russ. 2001. Distribution of shortnose sturgeon in the lower Savannah River. Final Report to the Georgia Ports Authority 21pp.

- Collins, M. R., W. C. Post, D. C. Russ, and T. I. J. Smith. 2002. Habitat use and movements of juvenile shortnose sturgeon in the Savannah River, Georgia-South Carolina. *Transactions of the American Fisheries Society* 131:975–979.
- Dadswell, M. J. 1979. Biology and population characteristics of the shortnose sturgeon, *Acipenser brevirostrum* LeSueur 1818 (Osteichthes: Acipenseridae), in the Saint John River Estuary, New Brunswick, Canada. *Canadian Journal of Zoology* 57: 2186–2210.
- DeVries, R. J. 2006. Population dynamics, movements, and spawning habitat of the shortnose sturgeon, *Acipenser brevirostrum*, in the Altamaha River System, Georgia. M.S. Thesis, University of Georgia, Athens, Georgia.
- Eberhardt, L. L. 2002. A paradigm for population analysis of long-lived vertebrates. *Ecology* 83(10): 2841 – 2854.
- Figueira, W. F. and L. B. Crowder. 2006. Defining patch contribution in source-sink metapopulations: the importance of including dispersal and its relevance to marine systems. *Population Ecology* 48: 215 – 224.
- Fleming, J. E., T. D. Bryce, and J. P. Kirk. 2003. Age, growth, and status of shortnose sturgeon in the lower Ogeechee River, Georgia. *Proceedings of the Annual Conference of the Southeast Association of Fish and Wildlife Agencies* 57:80–91.
- Friedland, K. D. and B. Kynard. 2004. *Acipenser brevirostrum*. In: IUCN 2007. *2007 IUCN Red List of Threatened Species*. <www.icucnredlist.org>
Downloaded on 07 March 2008.

- Heidt, A. R. and R. J. Gilbert. 1978. The shortnose sturgeon in the Altamaha River drainage, Georgia. Pages 54-60 in R.R. Odum and L. Landers, editors. Proceedings of the rare and endangered wildlife symposium. Georgia Department of Natural Resources, Game and Fish division, Technical Bulletin WL 4, Athens, Georgia.
- Hurvich, C.M. and C. Tsai. 1989. Regression and time series model selection in small samples. *Biometrika* 76(2): 297-307.
- Jelks, H. L., S. J. Walsh, N. M. Burkhead, S. Contreras-Balderas, E. Diaz-Pardo, D. A. Hendrickson, J. Lyons, N. E. Mandrak, F. McCormick, J. S. Nelson, S. P. Platania, B. A. Porter, C. B. Renaud, J. J. Schmitter-Soto, E. B. Taylor, and M. L. Warren Jr. 2008. Conservation status of imperiled North American freshwater and diadromous fishes. *Fisheries* 33: 372–386.
- Li, X., M. K. Litvak, and J. E. Hughes Clarke. 2007. Overwinter habitat use of shortnose sturgeon (*Acipenser brevirostrum*): defining critical habitat using a novel underwater video survey and modeling approach. *Canadian Journal of Fisheries and Aquatic Sciences* 64: 1248–1257.
- Kynard, B. 1997. Life History, latitudinal patterns, and status of the shortnose sturgeon, *Acipenser brevirostrum*. *Environmental Biology of Fishes* 48: 319–334.
- Kynard, B., M. Breece, M. Atcheson, M. Kieffer, and M. Mangold. 2009. Life history and status of shortnose sturgeon (*Acipenser brevirostrum*) in the Potomac River. *Journal of Applied Ichthyology* 25(Suppl. 2): 34–38.

- Meyer, J. L., A. C. Benke, R. T. Edwards, J. B. Wallace. 1997. Organic matter dynamics in the Ogeechee River, a blackwater river in Georgia, USA. *Journal of North American Benthological Society* 16(1): 82–87.
- National Marine Fisheries Service (NMFS). 1998. Final Recovery Plan for the shortnose sturgeon, *Acipenser brevirostrum*. Prepared by the Shortnose Sturgeon Recovery Team for the National Marine Fisheries Service, Silver Spring, Maryland. 104pp.
- Peterson, D. L. and J. Fleming. 2008. Bycatch in the Altamaha River American shad set-net fishery. Report to NMFS, 6 pp.
- Pulliam, H. R. 1988. Sources, sinks, and population regulation. *The American Naturalist* 132(5): 652 – 661.
- Rogers, S. G. and W. Weber. 1994. Movements of shortnose sturgeon in the Altamaha River System, Georgia. Contributions Series No. 57. Coastal Resources Division, Georgia Department of Natural Resources. Brunswick, Georgia.
- Vladykov, V. D. and J. R. Greeley. 1963. Order Acipenseroidei. Pages 24-60 in V. H. Olsen, editor. *Fishes of the western North Atlantic, part III*. Memoirs of the Sears Foundation for Marine Research, New Haven, Connecticut. 630 pp.
- Waldman, J. R., C. Grunwald, J. Stabile, and I. Wirgin. 2002. Impacts of life history and biogeography on the genetic stock structure of Atlantic sturgeon *Acipenser oxyrinchus oxyrinchus*, Gulf sturgeon *Acipenser oxyrinchus desotoi*, and shortnose sturgeon *A. brevirostrum*. *Journal of Applied Ichthyology* 18: 509–518.

- Walsh, M. G., M. B. Bain, T. Squiers Jr., J. R. Waldman, and I. Wirgin. 2001. Morphological and genetic variation among shortnose sturgeon *Acipenser brevirostrum* from adjacent and distant rivers. *Estuaries* 24(1): 41–48.
- Weber, W. 1996. Population size and habitat use of shortnose sturgeon, *Acipenser brevirostrum*, in the Ogeechee River System, Georgia. M.S. Thesis, University of Georgia, Athens, Georgia.
- Weber, W., C. A. Jennings, and S. G. Rogers. 1998. Population size and movement patterns of shortnose sturgeon in the Ogeechee River System, Georgia. *Proceedings of the Annual Conference of the Southeast Association of Fish and Wildlife Agencies* 52: 18–28.
- Welsh, S. A., M. F. Mangold, J. E. Skjveland, and A. J. Spells. 2002. Distribution and movement of shortnose sturgeon (*Acipenser brevirostrum*) in the Chesapeake Bay. *Estuaries* 25(1): 101–104.
- Wilberg, M. J., B. J. Irwin, M. L. Jones, and J. R. Bence. 2008. Effects of source-sink dynamics on harvest policy performance for yellow perch in southern Lake Michigan. *Fisheries Research* 94: 282 – 289.
- Wirgin, I., C. Grunwald, E. Carlson, J. Stabile, D. L. Peterson, and J. Waldman. 2005. Range-wide population structure of shortnose sturgeon *Acipenser brevirostrum* based on sequence analysis of the mitochondrial DNA control region. *Estuaries* 28(3): 406–421.
- Wirgin, I., C. Grunwald, J. Stabile, and J. R. Waldman. 2009. Delineation of discrete population segments of shortnose sturgeon *Acipenser brevirostrum* based on

mitochondrial DNA control region sequence analysis. *Conservation Genetics* online.

Woodland, R. J. and D. H. Secor. 2007. Year-class strength and recovery of endangered shortnose sturgeon in the Hudson River, New York. *Transactions of the American Fisheries Society* 136: 72–81.

Table 2.1. A summary of catch statistics and catch-per-unit-effort (CPUE; fish per net-hour) of shortnose sturgeon captured from the Ogeechee River from June – August, 2007 – 2009.

Year	Total Captures	In-Summer Recaptures	3-Year Recaptures	Unique Individuals	Net Hours	CPUE
2007	101	12	--	89	270	0.374
2008	86	12	25	61	170	0.506
2009	32	2	14	18	220	0.145

Table 2.2. AICc, delta AICc, AICc weights, model likelihood, and number of parameters (K) for the top four closed capture robust design models using covariates of temperature (Temp), dissolved oxygen (DO), and total effort in hours to estimate weekly capture (p) and recapture (c) probabilities of shortnose sturgeon from the Ogeechee River, GA within secondary periods (summers) of 2007 – 2009. The top four models used emigration parameters (γ' and γ'') that were modeled as zero or equal and constant (.) between primary periods and interactions between covariates of capture and recapture probabilities.

Model	AICc	Delta AICc	AICc Weights	Model Likelihood	K
$p = c$ (Temp * Effort); $\gamma' = \gamma''$ (0)	94.2951	0.0000	0.34592	1.0000	44
$p = c$ (DO * Effort); $\gamma' = \gamma''$ (0)	94.4377	0.1426	0.32211	0.9312	44
$p = c$ (Temp * Effort); $\gamma' = \gamma''$ (.)	95.7458	1.4507	0.16748	0.4842	45
$p = c$ (DO * Effort); $\gamma' = \gamma''$ (.)	95.9571	1.662	0.15069	0.4356	45

Table 2.3. Closed capture robust design model-averaged parameter estimates, standard errors (SE), and lower (LCI) and upper (UCI) 95% confidence intervals for survival, temporary emigration off of the study area (γ'') between years, probability of remaining off the study area (γ') between years, and abundance of shortnose sturgeon in the Ogeechee River, GA for 2007 – 2009.

Parameter	Estimate	SE	LCI	UCI
Survival from 2007 - 2008	0.737	0.328	0.092	0.987
Survival from 2008 - 2009	0.812	0.443	0.014	0.999
γ'' and γ'	0.160	0.275	0.003	0.913
Abundance 2007	404	117	175	633
Abundance 2008	264	70	126	402
Abundance 2009	203	124	32	446

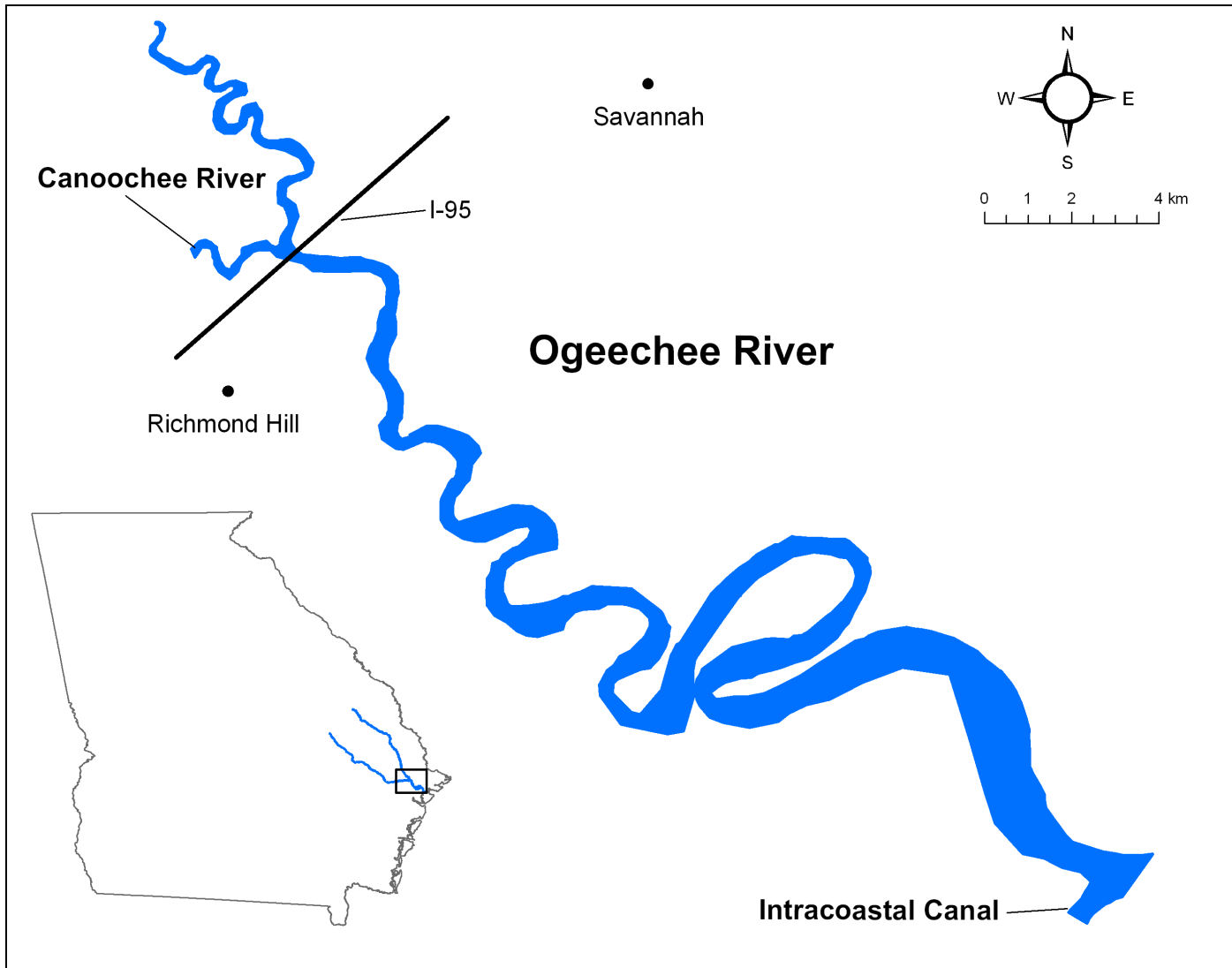


Figure 2.1. A map of the study area on the Ogeechee River, GA.

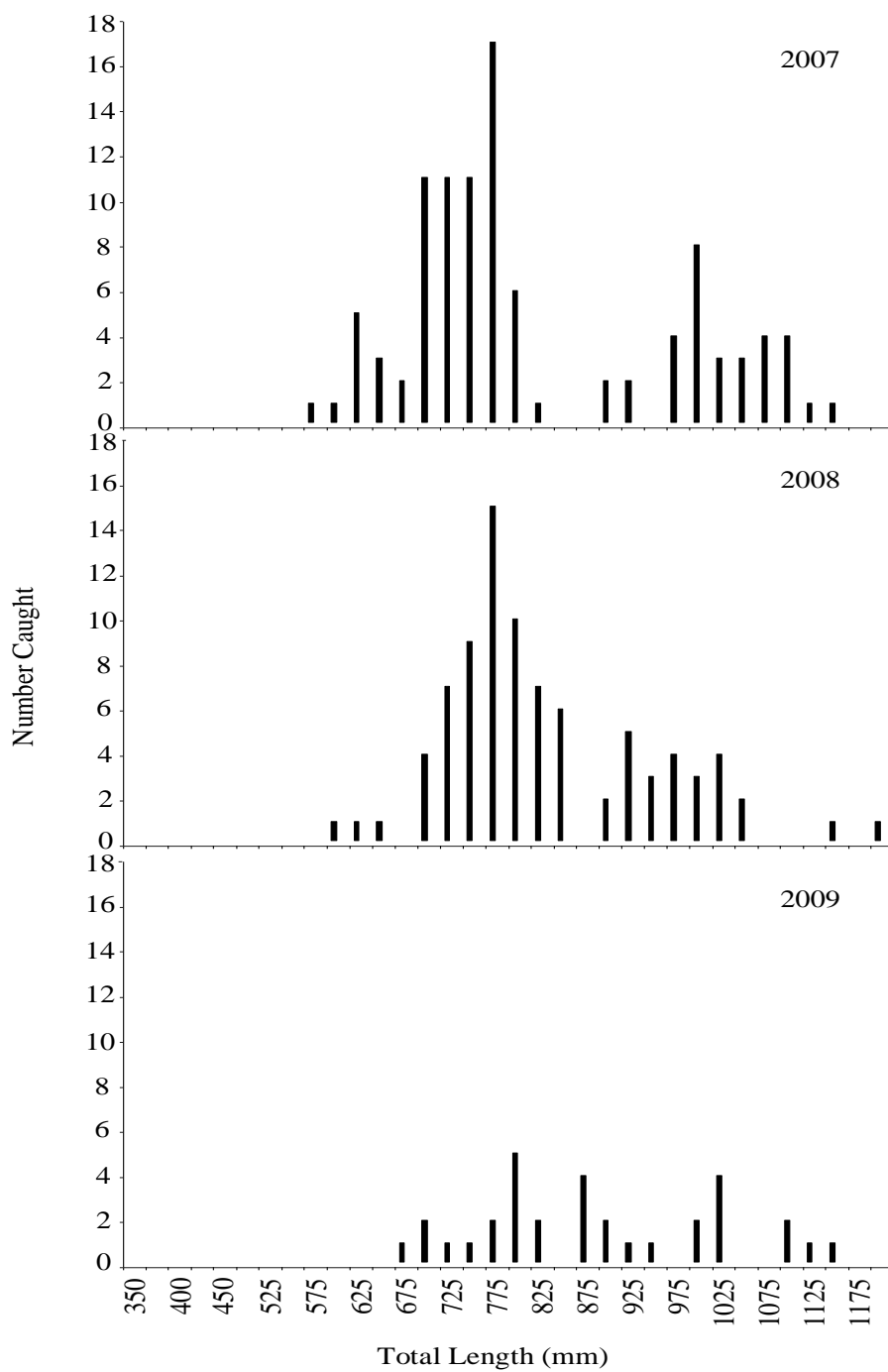


Figure 2.2. Length-frequency histograms of captured shortnose sturgeon from the Ogeechee River, GA during the summers of 2007 – 2009.

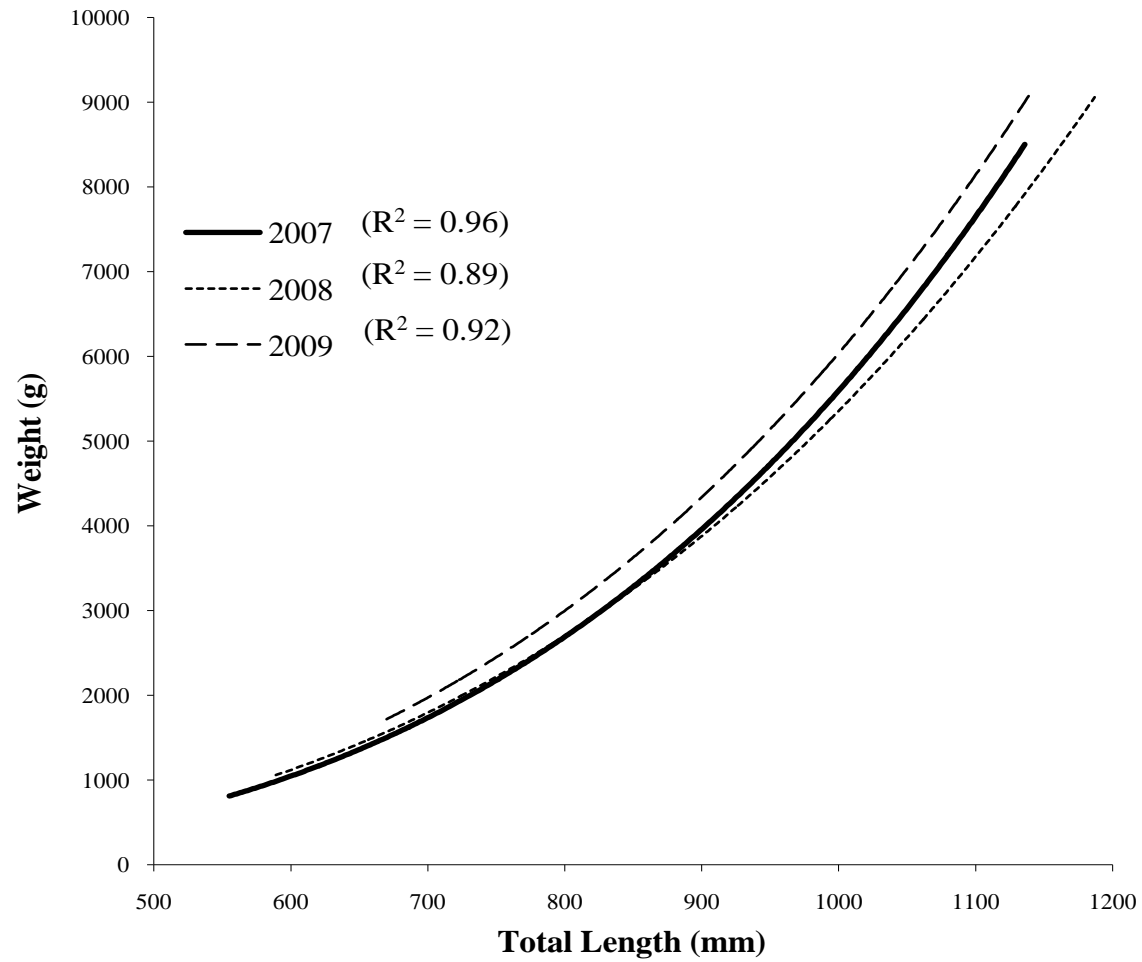


Figure 2.3. Annual length-weight relationships of captured shortnose sturgeon from the Ogeechee River, GA during the summers of 2007 – 2009.

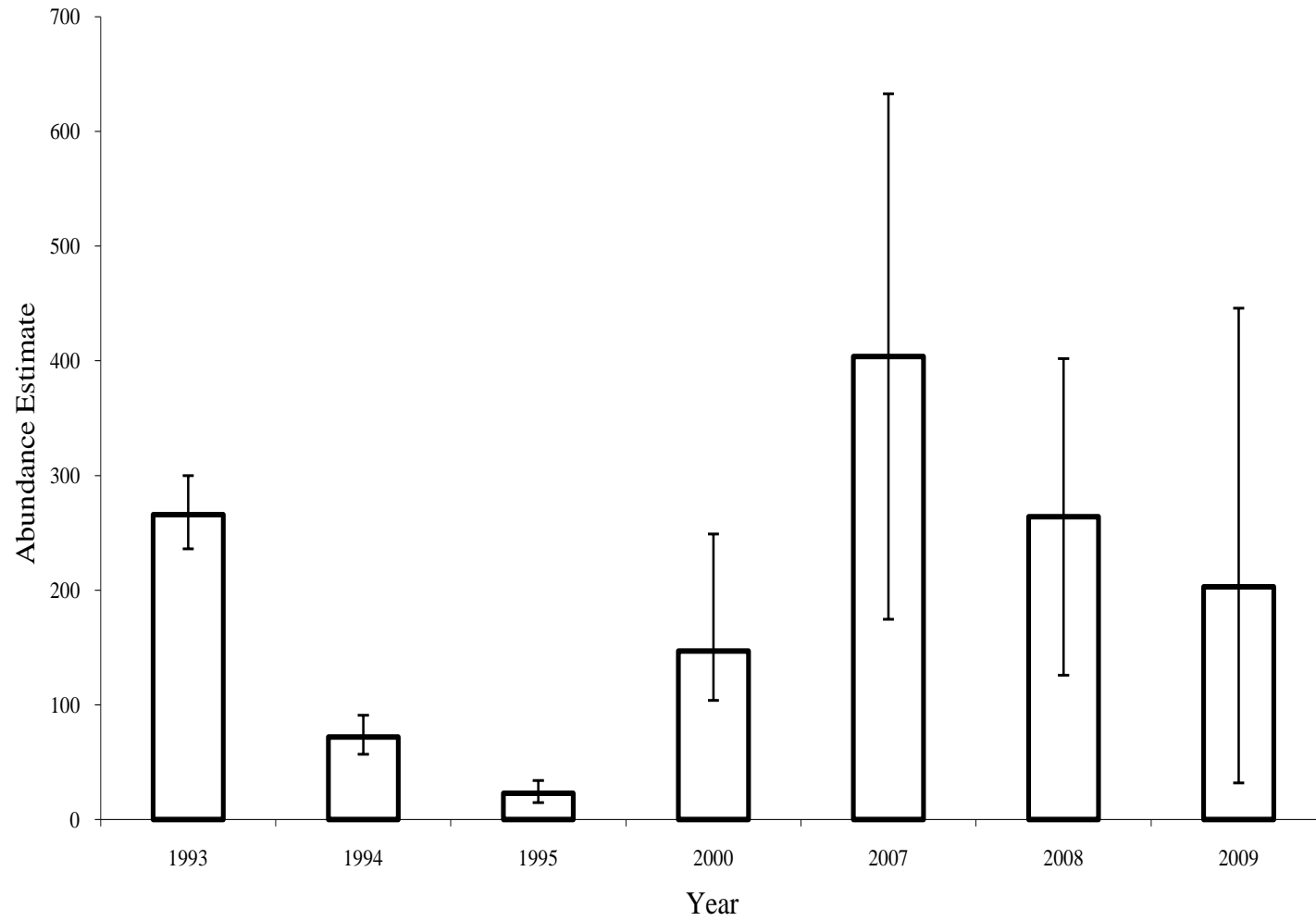


Figure 2.4. Trends in shortnose sturgeon abundance estimates (with 95% confidence intervals) in the Ogeechee River, GA. (Sources: 1993-1995, Weber et al. 1998; 2000, Fleming et al. 2003)

CHAPTER 3

MOVEMENTS OF THE SHORTNOSE STURGEON RELATIVE TO

HABITAT QUALITY OF THE OGEECHEE RIVER³

³ Farrae, D. J., S. E. Albeke, N. P. Nibbelink, and D. L. Peterson *to be submitted to*
Canadian Journal of Fisheries and Aquatic Sciences spring 2010

Abstract

Shortnose sturgeon, *Acipenser brevirostrum*, are endangered because of over-exploitation, habitat degradation, and a shrinking range. However, poor water quality may also be a threat to the species' recovery in many river systems, particularly in the southern half of the range. The primary goal of this study was to determine if habitat quality has impeded recovery of shortnose sturgeon in the Ogeechee River. We inserted ultrasonic transmitters in 18 adult shortnose sturgeon to monitor their monthly movements in relation to habitat suitability. Using ArcGIS, we constructed habitat quality models based on physiological tolerance to water temperature, dissolved oxygen, and salinity. Water quality data were collected at discrete points in the Ogeechee River and then used with kriging to interpolate values throughout the tidally influenced portion of the river. We used a modified kriging technique to replace Euclidean distance with stream-network distance to avoid the problems of using kriging in sinuous rivers. Telemetry results yielded a total of 492 relocation events, with a mean of 27 (range 1 - 56) relocations per fish. During the summer months (June - August), telemetered individuals remained congregated above the fresh-saltwater interface; however, they appeared to move in response to changing water quality conditions. The results of this study suggest that unsuitable habitat conditions from June – September may limit both the range and survival of shortnose in the Ogeechee River. Seasonal habitat availability in other southern rivers should be similarly analyzed for to assess potential correlations between the amount of suitable habitat and relative abundance.

Introduction

Shortnose sturgeon, *Acipenser brevirostrum*, are one of the most endangered members of the sturgeon family because of over-exploitation, depressed population levels, and a shrinking range (Bain et al. 2000, Jelks et al. 2008). They are a typical member of the family Acipenseridae in that they are long-lived, late maturing, and infrequent spawners. The species has been listed as endangered since 1967, becoming a charter member of the Endangered Species Act in 1973 (National Marine Fisheries Service (NMFS) 1998). Because of an international range including Atlantic coast rivers in both the US and Canada, it is also listed on the International Union for Conservation of Nature and Natural Resources Red List Threatened Species and has a global conservation status rank of G3(vulnerable) (Friedland and Kynard 2004, Jelks et al. 2008).

Historically, shortnose sturgeon were distributed among 25 river systems on the Atlantic coast of North America from the Saint John River in New Brunswick, Canada, to the St. John's River, Florida, although several southern populations are thought to be extirpated (Vladykov and Greeley 1963, Kynard 1997, NMFS 1998). Based on genetic evidence (Waldman et al. 2002) the mid-Atlantic bight comprises a distinct gap in the species' northern and southern distributions. An amphidromous species, shortnose typically inhabit both fresh and brackish waters of coastal rivers throughout various times of the year (Bemis and Kynard 1997). The bifurcated distribution and diversity of required habitats in northern and southern populations makes population management of shortnose sturgeon particularly difficult.

Presently, most shortnose sturgeon populations face multiple threats to recovery. In Georgia, shortnose sturgeon are caught incidentally in commercial fisheries targeting American shad, *Alosa sapidissima*, on the Altamaha (Heidt and Gilbert 1978, Collins et al. 2000, Peterson and Fleming 2008), Ogeechee, and Savannah rivers (Weber 1996). The commercial shad season in Georgia is open from January – March, coinciding with the upstream spawning migration of shortnose sturgeon. Although new studies of bycatch in these fisheries are now underway (D. Peterson, personal communication), results of previous studies in South Carolina suggest that mortality of shortnose sturgeon in commercial shad fisheries is likely suppressing the recovery of at least some populations (NMFS 1998, Collins et al. 2000).

Poor water quality may also be a threat to shortnose sturgeon recovery, particularly in southern rivers (NMFS 1998) where elevated summer temperatures and low dissolved oxygen (DO) levels may often exceed critical limits of the species. Previous studies have determined, in vitro, the physiological tolerances of young-of-year (YOY) shortnose sturgeon to changes in temperature, DO, and salinity (Table 3.1). These studies have shown, that juvenile shortnose sturgeon are largely intolerant of water temperatures >30 °C (Ziegeweid et al. 2008a), DO concentrations of <4.0 mg/L (Secor and Niklitschek 2001), and salinities >9 ppt (Jenkins et al. 1993). These studies have also shown that the interactive effects of these water quality variables may further reduce survival of YOY sturgeon, especially the combinations of high water temperature and low DO (Secor and Niklitschek 2001) and high water temperature and high salinity (Ziegeweid et al. 2008b). The limited

tolerance to low DO in sturgeons is because of a poor oxyregulatory system, low gill ventilation efficiency, and low hemoglobin oxygen affinity (Secor and Gunderson 1998, Secor and Niklitschek 2001). High salinities cause osmoregulatory stress manifested as dehydration and weight loss in YOY shortnose sturgeon (Jenkins et al. 1993). Thermal tolerances of juvenile and adult shortnose sturgeon are poorly understood. In many fishes, optimum temperatures are highest during the earliest life stages (Jobling 1994); however, confirmatory studies with shortnose sturgeon have not been attempted. Water temperatures $> 30^{\circ}\text{C}$ are typical during the summer months in many southern rivers including the Altamaha (Heidt and Gilbert 1978, DeVries 2006), Savannah (Collins et al. 2002), and Ogeechee rivers. Although the environmental tolerances of southern shortnose have not been well studied, Flournoy et al. (1992) found that Altamaha River shortnose sturgeon lose weight during summer months. More recently, DeVries (2006) suggested that shortnose sturgeon appear to congregate in freshwater habitats during the summer months to help minimize physiological stress when water temperatures exceed 30°C .

Although recent studies suggest that the absence of juvenile shortnose sturgeon in the Ogeechee River is indicative of persistent recruitment failure in this population (Fleming et al. 2003, Chapter 2), the cause remain unclear. Possible explanations include lack of suitable spawning habitat and poor survival of YOY sturgeon. Therefore, the primary goal of this study was to evaluate seasonal habitat conditions in the Ogeechee River. The specific objectives were (1) to quantify and qualify the amount of suitable habitat for YOY shortnose sturgeon during the summer, (2) to monitor seasonal movements of adult shortnose sturgeon to determine

how seasonal changes in water quality affect habitat use, and (3) to identify potential spawning migrations.

Site Description

The Ogeechee River is one of the longest free-flowing rivers on the East Coast, comprising 425 rkm of unimpounded riverine habitats (Weber 1996). One major tributary, the Canoochee River, drains into the Ogeechee River at rkm 55. The Ogeechee is classified as a “blackwater” system because of its tannic, nutrient-poor water, but unlike most blackwater rivers, its pH is roughly neutral (mean of 6.5 compared to 4.9 of the nearby Satilla River; Meyer et al. 1997). The Ogeechee River originates on the piedmont plateau in central GA and flows southeasterly through a largely undeveloped coastal plain watershed. Tidal amplitudes on the Ogeechee vary from 1.6 to 2.7 m (Weber 1996) and average annual discharge is $115 \text{ m}^3/\text{s}$ (Meyer et al. 1997). Maximum discharge occurs in spring and winter; however, tropical storms frequently cause brief periods of flooding during the summer and fall (Weber 1996, Meyer et al. 1997).

Methods

Seasonal movements of shortnose sturgeon were monitored using ultrasonic telemetry. Using surgical methods described by Collins et al. (2002), ultrasonic transmitters were implanted into each of 18 adult shortnose sturgeon to during the Fall and late Spring, 2007-2008. The transmitters (Sonotronics model CT-82-3-AA-HP; Tucson, AZ) were 85 mm long, 18 mm in diameter, and weighed 15 g in air. To ensure that transmitters did not exceed more than 2% of shortnose sturgeon body weight (Jepsen et al. 2002) only adult shortnose sturgeon $> 750 \text{ g}$ were selected for

transmitter implantation. To minimize the physiological stress of the surgical procedure, implantation of transmitters was conducted only during periods of ambient water temperatures $< 27^{\circ}\text{C}$ (Moser et al. 2000). Adult shortnose sturgeon were captured using anchored trammel and gill nets measuring 61 m by 2.5 m. Gill nets were constructed of 10.2, 12.7, and 15.2-cm monofilament mesh (stretch measure); trammel nets were constructed from a 7.6-cm mesh inner panel and two 30.5-cm mesh outer panels. The first 18 adults weighing >750 g were immediately placed into a holding tank filled with a buffered solution of 132 mg/L solution tricaine methanesulfonate (MS-222). Once the fish were completely anesthetized, they were placed on a portable surgical cart with a recirculating pump that maintained a steady flow of anesthetic over their gills during the entire surgical procedure (Kieffer and Kynard 1993, Hernandez-Divers et al. 2004, DeVries 2006). To determine sex and reproductive condition, a 1-cm incision was made dorsolaterally, approximately 1–2 cm above the ventral scutes and approximately midway between the pectoral and pelvic fins. A 5-mm laparoscope (Karl Storz model 26006 AA; Goleta, CA) was then inserted through this incision to view the gonads as described by Moser et al. 2000, Hernandez-Divers et al. 2004, and DeVries 2006. If the fish was confirmed to be a mature adult, a sterile scalpel was used to make a 5-cm incision in the ventrum, approximately 4–6 cm anterior to the pelvic girdle. The sterile transmitter was then placed into the body cavity through the incision and the wound was sutured using a 2/0 cutting needle attached to an absorbable monofilament polydioxanone suture (Ethicon; Cornelia, GA). The fish was then placed back into the river and held by

hand until it had fully recovered from the anesthetic. All individuals were released in good health at their original capture location.

Manual tracking of the sonic-tagged individuals was conducted 1-2 times weekly, using a portable receiver (Sonotronics model USR-96; Tucson, AZ) and hydrophone (Sonotronics model DH-4; Tucson, AZ). As individual sturgeon were re-located, the coordinates were recorded using a GPS receiver after which temperature, salinity, and DO were measured using a portable YSI meter. Manual tracking was augmented with an automated stationary receiver (Sonotronics model CUB-1; Tucson, AZ) positioned on the river bottom at rkm 65. The placement of the CUB-1 facilitated the detection of potential spawning migrations because this site was well upstream of non-spawning habitats of adult shortnose in the Ogeechee River (Weber et al. 1998, Fleming et al. 2003).

To monitor seasonal and spatial variations in water quality, weekly measures of temperature, salinity, and DO were collected at 1-km intervals throughout 2008 and 2009. Water quality data recorded during manual tracking and other field efforts were also used to maximize data available for monthly habitat modeling. Habitat variables were monitored both spatially and temporally to determine monthly habitat suitability for shortnose sturgeon throughout the tidally influenced reach of the river. Ordinary kriging was used to interpolate data values to the extent of our study area. To avoid potential inaccuracies of kriging in within a river, stream network distances were first calculated between each data collection site. The sites were then displayed as a straight line so that ordinary kriging could be used with Euclidean distance as a proxy of stream network distance. National Hydrography Dataset (NHD) vector

files (<http://nhd.usgs.gov/>) were used to extract the mainstem Ogeechee and Canoochee rivers as the base for analyses in ArcGIS (ESRI 2007). These lines were converted into a route feature class, using the length of the river/line to reference any given point instead of specific latitude and longitude coordinates. In this format, the measure field attribute was a measure of the distance along the line of each point. By using linear referencing, all sample points were located along the route feature. To perform ordinary kriging in Euclidean space, while avoiding the problems associated with river sinuosity, a new feature class line was digitized. The new line feature was comprised of two lines, each matching the exact river distance of the Ogeechee and Canoochee rivers, respectively. These new lines maintained the known stream network distances between sample locations that were calculated in the route feature. Thus, the “straightened” Canoochee River line was digitized to be perpendicular to the “straightened” Ogeechee River. This line feature class was then converted to a routed layer with sample points displayed onto the straight line features according to their stream network distances.

Because kriging cannot be computed along a line, we first created data above and below the straight lines. Lines were digitized on 50 m of either side of the straightened river lines. The new lines gave the straightened rivers a width of 100 m each - roughly the average width of both rivers within our study area. Sample points and corresponding data were replicated to these new lines to create two dimensions of sample points for subsequent kriging. The sample points were grouped by month for interpolation. Ordinary kriging was performed for each of the three water quality variables for each month of the study. Ordinary kriging is a standard tool available in

the Geostatistical Wizard of ArcGIS. We used a spherical variogram model with up to nine neighbors, but no less than three neighbors. After every kriging calculation, the extent was set to match a standard extent of the farthest upstream and downstream points from each river for ease of comparison and display.

To generate realistic graphical representations of the data, we converted the interpolated data values from the straightened river back to the sinuous river vector. To accomplish this, we first created points every 500 m within the total extent of the kriging and extracted predicted values from each of the kriged models to these points. To display the interpolated values, the predicted points were used as the midpoint for a line route-event that stretched 250 m upstream and downstream of the predicted point. This divided the study area into 500-m segments, each possessing individual assignments of habitat suitability.

Every prediction point was reclassified with a value of 0 when a water quality parameter was outside of the tolerance range or a 1 when those parameters fell within the tolerance range. Literature-based ranges in water quality parameters were determined as 30 °C for temperature (Ziegeweid et al. 2008a), 4.0 mg/L for DO (Secor and Niklitschek 2001), and 10 ppt for salinity (Jenkins et al. 1993). The reclassification values for each variable were added together to provide an integrated habitat value for every sample segment. A total value of 3 indicated that all three water quality parameters were within the physiological tolerance range for that segment, while a value of 0 indicated that all three parameters were outside the tolerance range. For display purposes, the color green was used for areas with a value of 3, yellow for 2, and red for 1 or less. To interpret the summed values of each

segments, we considered a summed value of 3 to represent suitable habitat, 2 as marginal, and 0-1 as unsuitable. Because previous studies have demonstrated an interactive effect of high water temperature, low DO, and high salinity on shortnose sturgeon tolerance, we considered habitat to be unsuitable when two or more variables fell outside the range of tolerance.

To compare actual habitat use with habitat quality, we displayed all telemetry relocation data on spatial maps of monthly habitat suitability. We then counted the number of occasions during each month when a transmittered sturgeon was found in each habitat type to approximate “percent use” in relation to habitat quality. The percent of habitat use was compared to the percent of each habitat’s availability to identify differences in habitat availability and habitat use. These differences were then interpreted as habitat preference (or avoidance) based on spatially and temporally explicit habitat conditions. These comparisons were also evaluated based on each individual water quality parameter to determine which variable (temperature, DO, or salinity) had the greatest influence on sturgeon movements.

Results

Ultrasonic transmitters were successfully implanted in 18 adult shortnose sturgeon from October 2007 – July 2008. Three of the sturgeon were female and 15 were male. The first two sturgeon received transmitters in early October 2007; one was relocated three days after surgery and then never relocated again, while the other was relocated once on December 17, 2007 and not again until June 4, 2008. The other 16 sturgeon were released between May 14, 2008 and July 28, 2008. Consequently, seasonal habitat use was evaluated from May 2008 until the end of the

study in September 2009. Manual tracking of transmittered fish yielded a total of 492 relocation events with a mean of 27 (range 1 - 56) relocations per fish. Sturgeon were relocated at a mean water temperature of 21.1 °C (range 7.4 – 31.1 °C), DO concentration of 6.24 mg/L (range 2.91 – 10.92 mg/L), and salinity of 1.0 ppt (range 0.0 – 18.8 ppt).

During the summer months (June - August), the transmittered individuals congregated near the confluence of the Ogeechee and Canoochee rivers at rkm 55. Throughout the rest of the year sturgeon moved freely throughout the lower 65 rkm of the River, including the lower estuary. During the spawning season, January – March, none of the telemetered fish moved upriver of the CUB-1 at rkm 65, suggesting there were no spawning migrations attempted by any of the tagged adults.

Over the entire analysis of habitat suitability (January 2008 – September 2009), river segments were characterized as suitable 75.86% of the time (Table 3.2). All three variables were never found to be beyond the tolerance threshold for one segment during the same month. From January – May 2008 water quality parameters were all within the suitable range throughout the entire study area (Figures 3.1 – 3.5). From June – September 2008, however, water quality degraded to mostly marginal and unsuitable habitat (Figures 3.6 – 3.9). From October 2008 – May 2009 the Ogeechee River was mostly suitable habitat quality (Figures 3.10 – 3.17). From June – September 2009 the study area was mostly a combination of suitable and marginal habitat quality (Figures 3.18 – 3.21).

Water quality at locations of transmittered fish was usually better than that in other available habitats. . Although the river was characterized as suitable for all

three water quality variables 75.86% of the study, sturgeon were located in this habitat 87.37% of the time (Table 3.2). For 15.15% of the study, salinity was the only variable over the threshold, but sturgeon were located in this habitat for 0.64% of relocation events (Table 3.2).

Discussion

Despite tracking adult shortnose sturgeon during two potential spawning seasons, not a single transmittered fish moved upstream of the CUB-1, suggesting that few, if any, individuals made spawning migrations during the study. This corroborates recent research efforts (Weber et al. 1998, Fleming et al. 2003, Farrae Ch. 2) in the Ogeechee River, which found few, if any, juveniles. Interestingly, juveniles were captured in 2004 (J. Fleming, personal communication), suggesting that successful spawning does occur intermittently. Although the reasons for this remain unclear, habitat conditions required for spawning may only occur infrequently in the Ogeechee River.

Shortnose sturgeon appeared to move in response to seasonal changes in water quality in the Ogeechee River. Poor water quality from June – September may limit the range and survival of juvenile and adult shortnose sturgeon. At times of high water temperature and salinity, sturgeon congregated in an area of about 15 rkm near the confluence of the Ogeechee and Canoochee rivers (Figures 3.6 – 3.9 and 3.18 – 3.21). The dispersion of shortnose sturgeon was most limited during the summer months (e.g., Figures 3.22 and 3.24), but their dispersion increased during winter (Figure 3.23). Intraspecific competition for resources could arise if all shortnose sturgeon are restricted to relatively small habitat patches. Our results support the

theory that poor summer water conditions may cause a habitat “squeeze” thereby potentially limiting recruitment of juveniles as well as survival of adult sturgeon (Secor and Niklitschek 2001). Our data for adult sturgeon correlate with the laboratory studies estimating the physiological tolerances of YOY shortnose sturgeon to water quality variables (Table 3.1).

Shortnose sturgeon movements appeared to be associated most with salinity of the Ogeechee River. This trend was most evident by comparing sturgeon use of river segments correlated to which environmental variables exceeded a threshold in the same segment. Over the entire study, salinity was the only variable over the threshold in 15.15% of river segments, but sturgeon were located in this habitat for only 0.64% of the time (Table 3.2). These data suggest that shortnose sturgeon may avoid salinities over 10 ppt during summer months. Conversely, DO was the only variable outside of the threshold range in 5.99% of segments and sturgeon were located in this habitat for 6.85% of the time (Table 3.2), signifying neither avoidance or preference for this habitat. Interestingly, 1.40% of segments had temperature as the only variable exceeding a threshold, but sturgeon were located in this habitat 5.14% of the time. This might indicate that temperatures exceeding 30 °C did not deter adult shortnose sturgeon. Over the entire study only 1.60% of segments were characterized as unsuitable with 2 or more variables exceeding a threshold, but sturgeon were never located in this habitat (Table 3.2). This likely suggested avoidance of these unsuitable habitats.

The temporal and spatial variability in water quality conditions may affect the fitness and survival of shortnose sturgeon at the southern extent of their range. For

example, the Altamaha River, the next major river south of the Ogeechee, has about 3.5 times more freshwater input and a watershed three times greater than the Ogeechee (Sheldon and Alber 2005). Under a range of flow conditions, the Altamaha River has 30-40 rkm of tidal freshwater habitat compared to only 0-25 rkm in the Ogeechee River (Sheldon and Alber 2005). The polyhaline zone of the Altamaha is limited to the lower 8 rkm, while in the Ogeechee this zone can be found as far upriver as rkm 25 (Sheldon and Alber 2005), which renders nearly 1/3 of all tidally influenced habitats unsuitable for shortnose during the summer months. In short, the lack of suitable habitat, particularly during the summer months, may explain why the Altamaha River population, estimated at 6300 (Devries 2006), is an order of magnitude larger than that of the Ogeechee River (Chapter 2). Another possible explanation for the discrepancies in abundance could be attributable to differences in the quality or amount of suitable spawning habitat; however, spawning habitat still needs to be identified and quantified in both the Altamaha and Ogeechee rivers. Future studies of shortnose in southern rivers, should address seasonal changes in water quality in evaluating “baseline” parameters of suitable habitat. These data will be critical in evaluating recovery potential of shortnose populations on a river-specific basis.

The results of this study, suggest that recurrent drought may be an especially important stochastic variable affecting long term population trends of shortnose sturgeon in southern rivers. During the first year of this study, a severe drought resulted in reduced water levels in most coastal rivers along the entire south Atlantic region. In the Ogeechee River, reduced freshwater inputs associated with persistent

drought conditions, undoubtedly exacerbated the poor water quality documented throughout the summer of 2008 (Figures 3.6 – 3.9). When the drought ended in 2009, habitat conditions improved (Figures 3.18 – 3.21), yet although more suitable habitat was available during the summer of 2009, telemetry data showed that the fish continued to congregate in the same limited areas of the river that they had used in the previous summer (Figures 3.22 and 3.24). Despite the many uncertainties regarding habitat changes that may result from global climate change, habitat conditions for Ogeechee shortnose sturgeon are not likely to improve within the foreseeable future. Limited data from fixed locations in Georgia estuaries indicate a significant increase in salinities between 1974 and 1992 in the Satilla and Savannah River estuaries (Alber and Sheldon 1999). Saltwater encroachment concurrent with increasing water temperatures could limit suitable habitats for shortnose sturgeon (Collins et al. 2002). Given their limited tolerance of salinity at water temperatures $>30^{\circ}$ C, shortnose sturgeon may be particularly sensitive to any environmental trend that increases summer water temperature. This may be especially problematic for southern populations, where high summer temperatures, saltwater intrusion, and hypoxic conditions are already viewed as a hindrance to recovery (NMFS 1998). Future studies are needed to monitor spatial and temporal changes in habitat suitability for shortnose sturgeon.

Researchers recently have been identifying the best methods to interpolate spatially explicit data in river systems. Ordinary kriging uses Euclidean distances to interpolate values, but this is inappropriate and inaccurate when data points are related by a network system (Little et al. 1997, Gardner et al. 2003, Lyon et al. 2008).

The use of stream distances within a river network has proven more reliable (Little et al. 1997, Gardner et al. 2003, Lyon et al. 2008); however, this method is more complex, requiring advanced GIS training (Ver Hoef et al. 2006). The kriging methods used in this study offer a simple but accurate alternative that can be easily applied with only a basic knowledge of GIS programming. Some researchers have proposed using direction-corrected kriging models for river systems to account for the relationship between points being controlled by flow in a single direction (Ver Hoef et al. 2006). However, our entire study area was tidally influenced; therefore, discrete points were related in both upstream and downstream directions and using a unidirectional kriging model would be inappropriate.

We suggest that future studies of shortnose sturgeon habitats, apply these methods to evaluate habitat quality in other river systems. As noted earlier, previous laboratory studies have defined the physiological tolerances of shortnose sturgeon and provided the basis for the habitat evaluation presented here. Similar lab studies also have been conducted on many other fishes, including striped bass (Secor et al. 2000), summer flounder (Malloy and Targett 1991), Atlantic salmon (Handeland et al. 1998), bull trout (Selong et al. 2001), and American shad (Zydlewski and McCormick 1997). Data from these experiments can be used to characterize habitat suitability in systems where water quality measurements are readily available. In this way routine water quality monitoring programs could be used to evaluate the quality and quantity of suitable habitat for a wide variety of aquatic species, based on the known range of their environmental tolerances.

The methods of water quality data collection used in this study could be improved upon by future researchers. Manual collection of water quality data is both time-consuming and expensive. Fortunately, a wide variety of automated devices are currently available. Although initial acquisition costs may be high, these devices are relatively inexpensive to maintain and operate, providing continuous, standardized water quality data over large spatial scales. When combined with the modified kriging methods presented in this study these data can provide sound data for evaluating spatial and temporal habitat trends.

Assessment of seasonal habitat use and quality continues to be a critical research objective of the NMFS Recovery Plan for Shortnose Sturgeon (1998). The methods and results presented in this study can be used to identify, and evaluate critical habitats for shortnose sturgeon throughout the species' range. The results of this study only provide a current assessment of habitat conditions for shortnose sturgeon within the Ogeechee River. Perhaps more importantly, however, our findings may provide a quantified baseline of seasonal habitat for comparisons with other shortnose sturgeon rivers. Effective management strategies for shortnose sturgeon recovery require a thorough understanding of how habitat quality affects population trends. Future studies are needed to help quantify this relationship and to determine how changes in seasonal habitat quality may influence the critical habitat needs of the species.

References

- Alber, M. and J. E. Sheldon. 1999. Trends in salinities and flushing times of Georgia estuaries. pp. 528–531 in K. J. Hatcher, editor. Proceedings of the 1999 Georgia Water Resources Conference. The University of Georgia. Athens, Georgia.
- Bain, M. B., N. Haley, D. L. Peterson, J. R. Waldman, and K. K. Arend. 2000. Harvest and habitats of Atlantic sturgeon *Acipenser oxyrinchus* Mitchill, 1815 in the Hudson River estuary: Lessons for sturgeon conservation. Boletín Instituto Espanol de Oceanografía 16: 43–53.
- Bemis, W. E. and B. Kynard. 1997. Sturgeon rivers: an introduction to acipensiform biogeography and life history. Environmental Biology of Fishes 48:167–183.
- Campbell, J. G. and L. R. Goodman. 2004. Acute sensitivity of juvenile shortnose sturgeon to low dissolved oxygen concentrations. Transactions of the American Fisheries Society 133: 772–776.
- Collins, M. R., S. G. Rogers, T. I. J. Smith, and M. L. Moser. 2000. Primary factors affecting sturgeon populations in the southeastern United States: fishing mortality and degradation of essential habitats. Bulletin of Marine Science 66(3): 917–928.
- Collins, M. R., W. C. Post, D. C. Russ, and T. I. J. Smith. 2002. Habitat use and movements of juvenile shortnose sturgeon in the Savannah River, Georgia-South Carolina. Transactions of the American Fisheries Society 131:975–979.

- DeVries, R. J. 2006. Population dynamics, movements, and spawning habitat of the shortnose sturgeon, *Acipenser brevirostrum*, in the Altamaha River System, Georgia. M.S. Thesis, University of Georgia, Athens, Georgia.
- Flournoy, P. H., S. G. Rogers, and P. S. Crawford. 1992. Restoration of shortnose sturgeon in the Altamaha River, Georgia. United States Fish and Wildlife Service Project Number AFS-2, Segments One and Two.
- Friedland, K. D. and B. Kynard. 2004. *Acipenser brevirostrum*. In: IUCN 2007. *2007 IUCN Red List of Threatened Species*. <www.icucnredlist.org> Downloaded on 07 March 2008.
- Gardner, B., P. J. Sullivan, and A. J. Lembo, Jr. 2003. Predicting stream temperatures: geostatistical model comparison using alternative distance metrics. *Canadian Journal of Fisheries and Aquatic Sciences* 60: 344–351.
- Handeland, S. O., A. Berge, B. T. Bjornsson, and S. O. Stefansson. 1998. Effects of temperature and salinity on osmoregulation and growth of Atlantic salmon (*Salmo salar* L.) smolts in seawater. *Aquaculture* 168: 289–302.
- Heidt, A. R. and R. J. Gilbert. 1978. The shortnose sturgeon in the Altamaha River drainage, Georgia. Pages 54-60 in R.R. Odum and L. Landers, editors. *Proceedings of the rare and endangered wildlife symposium*. Georgia Department of Natural Resources, Game and Fish division, Technical Bulletin WL 4, Athens, Georgia.
- Hernandez-Divers, S. J., R. S. Bakal, B. H. Hickson, C. A. Rawlings, H. G. Wilson, M. Radinsky, S. M. Hernandez-Divers, and S. R. Dover. 2004. Endoscopic sex

- determination and gonadal manipulation in Gulf of Mexico sturgeon (*Acipenser oxyrhincus desotoi*). *Journal of Zoo and Wildlife Medicines* 35(4): 459–470.
- Jelks, H. L., S. J. Walsh, N. M. Burkhead, S. Contreras-Balderas, E. Diaz-Pardo, D. A. Hendrickson, J. Lyons, N. E. Mandrak, F. McCormick, J. S. Nelson, S. P. Platania, B. A. Porter, C. B. Renaud, J. J. Schmitter-Soto, E. B. Taylor, and M. L. Warren Jr. 2008. Conservation status of imperiled North American freshwater and diadromous fishes. *Fisheries* 33: 372–386.
- Jenkins, W. E., T. I. J. Smith, L. D. Heyward, and D. M. Knott. 1993. Tolerance of shortnose sturgeon, *Acipenser brevirostrum*, juveniles to different salinity and dissolved oxygen concentrations. *Proceedings of the Annual Conference of the Southeast Association of Fish and Wildlife Agencies* 47: 476–484.
- Jepsen, N., A. Koed, E. B. Thorstad, and E. Baras. 2002. Surgical implantation of telemetry transmitters in fish: how much have we learned? *Hydrobiologia* 483: 239–248.
- Jobling, M. 1994. *Fish Bioenergetics*. Chapman & Hall, London.
- Kieffer, M. C. and B. Kynard. 1993. Annual movements of shortnose and Atlantic sturgeons in the Merrimack River, Massachusetts. *Transactions of the American Fisheries Society* 122: 1088–1103.
- Kynard, B. 1997. Life History, latitudinal patterns, and status of the shortnose sturgeon, *Acipenser brevirostrum*. *Environmental Biology of Fishes* 48: 319–334.

- Little, L. S., D. Edwards, and D. E. Porter. 1997. Kriging in estuaries: as the crow flies, or as the fish swims? *Journal of Experimental Marine Biology and Ecology* 213: 1–11.
- Lyon, S. W., J. Seibert, A. J. Lembo, T. S. Steenhuis, and M. T. Walter. 2008. Incorporating landscape characteristics in a distance metric for interpolating between observations of stream water chemistry. *Hydrology and Earth System Sciences* 12: 1229–1239.
- Malloy, K. D. and T. E. Targett. 1991. Feeding, growth, and survival of juvenile summer flounder *Paralichthys dentatus*: experimental analysis of the effects of temperature and salinity. *Marine Ecology Progress Series* 72: 213–223.
- Meyer, J. L., A. C. Benke, R. T. Edwards, J. B. Wallace. 1997. Organic matter dynamics in the Ogeechee River, a blackwater river in Georgia, USA. *Journal of North American Benthological Society* 16(1): 82–87.
- Moser, M. L., M. Bain, M. R. Collins, N. Haley, B. Kynard, J. C. O’Herron II, G. Rogers, and T. S. Squiers. 2000. A protocol for use of shortnose and Atlantic sturgeons. NOAA Technical Memorandum NMFS-OPR-18.
- National Marine Fisheries Service (NMFS). 1998. Final recovery plan for the shortnose sturgeon, *Acipenser brevirostrum*. Prepared by the Shortnose Sturgeon Recovery Team for the National Marine Fisheries Service, Silver Spring, Maryland. 104pp.
- Peterson, D. L. and J. Fleming. 2008. Bycatch in the Altamaha River American shad set-net fishery. Report to NMFS, 6 pp.

- Secor, D. H. and T. E. Gunderson. 1998. Effects of hypoxia and temperature on survival, growth, and respiration of juvenile Atlantic sturgeon, *Acipenser oxyrinchus*. Fisheries Bulletin 96: 603–613.
- Secor, D. H., T. E. Gunderson, and K. Karlsson. 2000. Effect of temperature and salinity on growth performance in anadromous (Chesapeake Bay) and nonanadromous (Santee-Cooper) strains of striped bass *Morone saxatilis*. Copeia 1: 291–296.
- Secor, D. H. and E. J. Niklitschek. 2001. Hypoxia and sturgeons: report to the Chesapeake Bay Program dissolved oxygen team. Technical Report Series No. TS-314-01-CBL; Chesapeake Biological Laboratory, Solomons, Maryland.
- Selong, J. H., T. E. McMahon, A. V. Zale, and F. T. Barrows. 2001. Effect of temperature on growth and survival of bull trout, with application of an improved method for determining thermal tolerance in fishes. Transactions of the American Fisheries Society 130: 1026–1037.
- Sheldon, J. E. and M. Alber. 2005. Comparing transport times through salinity zones in the Ogeechee and Altamaha river estuaries using squeezebox. In K. J. Hatcher, editor, Proceedings of the 2005 Georgia Water Resources Conference. The University of Georgia. Athens, Georgia.
- Ver Hoef, J. M., E. Peterson, and D. Theobald. 2006. Spatial statistical models that use flow and stream distance. Environmental and Ecological Statistics 13: 449–464.

- Vladykov, V. D. and J. R. Greeley. 1963. Order Acipenseroidei. Pages 24-60 in V. H. Olsen, editor. Fishes of the western North Atlantic, part III. Memoirs of the Sears Foundation for Marine Research, New Haven, Connecticut. 630 pp.
- Waldman, J. R., C. Grunwald, J. Stabile, and I. Wirgin. 2002. Impacts of life history and biogeography on the genetic stock structure of Atlantic sturgeon *Acipenser oxyrinchus oxyrinchus*, Gulf sturgeon *Acipenser oxyrinchus desotoi*, and shortnose sturgeon *A. brevirostrum*. *Journal of Applied Ichthyology* 18: 509–518.
- Weber, W. 1996. Population size and habitat use of shortnose sturgeon, *Acipenser brevirostrum*, in the Ogeechee River System, Georgia. M.S. Thesis, University of Georgia, Athens, Georgia.
- Weber, W., C. A. Jennings, and S. G. Rogers. 1998. Population size and movement patterns of shortnose sturgeon in the Ogeechee River System, Georgia. *Proceedings of the Annual Conference of the Southeast Association of Fish and Wildlife Agencies* 52: 18–28.
- Wehrly, K. E., T. O. Brenden, and L. Wang. 2009. A comparison of statistical approaches for predicting stream temperatures across heterogeneous landscapes. *Journal of the American Water Resources Association* 45(4): 986–997.
- Ziegeweid, J. R., C. A. Jennings, and D. L. Peterson. 2008a. Thermal maxima for juvenile shortnose sturgeon acclimated to different temperatures. *Environmental Biology of Fishes* 82: 299–307.

- Ziegeweid, J. R., C. A. Jennings, D. L. Peterson, and M. C. Black. 2008b. Effects of salinity, temperature, and weight on the survival of young-of-year shortnose sturgeon. *Transactions of the American Fisheries Society* 137:1490–1499.
- Zydlewski, J. and S. D. McCormick. 1997. The ontogeny of salinity tolerance in the American shad, *Alosa sapidissima*. *Canadian Journal of Fisheries and Aquatic Sciences* 54: 182–189.

Table 3.1. A meta-analysis of studies on the physiological tolerances of young-of-year shortnose sturgeon to water temperature (T), dissolved oxygen (DO), and salinity at various ages of days-post-hatch (dph).

Source	Mortality/ Effect	T (°C)	DO (mg/L)	Salinity (ppt)	Age (dph)
Campbell and Goodman 2004	50%	25	2.7	2	77
Campbell and Goodman 2004	50%	22	2.2	4	104
Campbell and Goodman 2004	50%	30	3.1	2	100
Jenkins et al. 1993	47, 100%	21 - 23	7 - 8	15, 20	63
Jenkins et al. 1993	33, 47, 100%	21 - 23	7 - 8	11, 13, ≥ 15	76
Jenkins et al. 1993	0%	21 - 23	≥ 4	≥ 0	11 - 330
Jenkins et al. 1993	86%	22.5	2.5	0	64
Jenkins et al. 1993	12, 12%	22.5	2.5	0	104, 310
Jenkins et al. 1993	0, 100%	21 - 23	7 - 8	7, 15	11 - 330
Jenkins et al. 1993	100%	21 - 23	7 - 8	> 25	330
Secor and Niklitschek 2001	stressful	22-27	4.3 - 4.7		30 - 200
Secor and Niklitschek 2001	lethal	22-27	≤ 3.3		30 - 200
Ziegeweid et al. 2008a	CTmax	~ 34.5	> 7	0	64-140
Ziegeweid et al. 2008a	LTmax	~ 35.5	> 7	0	64-140
Ziegeweid et al. 2008b	50%	28.2 - 30.7	6.0 - 8.9	0	≤ 112
Ziegeweid et al. 2008b	100%	30	6.0 - 8.9	0	70
Ziegeweid et al. 2008b	26%	30	6.0 - 8.9	0	94
Ziegeweid et al. 2008b	0%	30	6.0 - 8.9	0	112
Ziegeweid et al. 2008b	50%	23	6.0 - 8.9	14.8	66
Ziegeweid et al. 2008b	50%	27.2	6.0 - 8.9	12	69
Ziegeweid et al. 2008b	50%	23.3	6.0 - 8.9	16.4	69
Ziegeweid et al. 2008b	50%	23.2	6.0 - 8.9	19.1	86

Ziegeweid et al. 2008b	50%	27.2	6.0 - 8.9	16.2	96
Ziegeweid et al. 2008b	50%	28.6	6.0 - 8.9	14.2	101
Ziegeweid et al. 2008b	50%	23.2	6.0 - 8.9	20.9	107
Ziegeweid et al. 2008b	50%	27.2	6.0 - 8.9	18.7	119
Ziegeweid et al. 2008b	50%	27.2	6.0 - 8.9	19.6	144
Ziegeweid et al. 2008b	75 - 95%	31.1	6.0 - 8.9	≤ 8.5	144
Ziegeweid et al. 2008b	100%	31.1	6.0 - 8.9	≥ 16.5	144

Table 3.2. A frequency table comparing locations of telemetered sturgeon to habitat quality of Ogeechee and Canoochee river segments (500 m) from January 2008 – September 2009. The three variables analyzed were dissolved oxygen (DO), water temperature (T), and salinity. A value of 1 indicates that the variable was not beyond the literature-derived threshold; 0 indicates that it was beyond the threshold.

DO	T	Salinity	# Locations	% Locations	# Segments	% Segments
1	1	1	408	87.37	1848	75.86
0	1	1	32	6.85	146	5.99
1	0	1	24	5.14	34	1.40
1	1	0	3	0.64	369	15.15
1	0	0	0	0.00	22	0.90
0	1	0	0	0.00	16	0.66
0	0	1	0	0.00	1	0.04

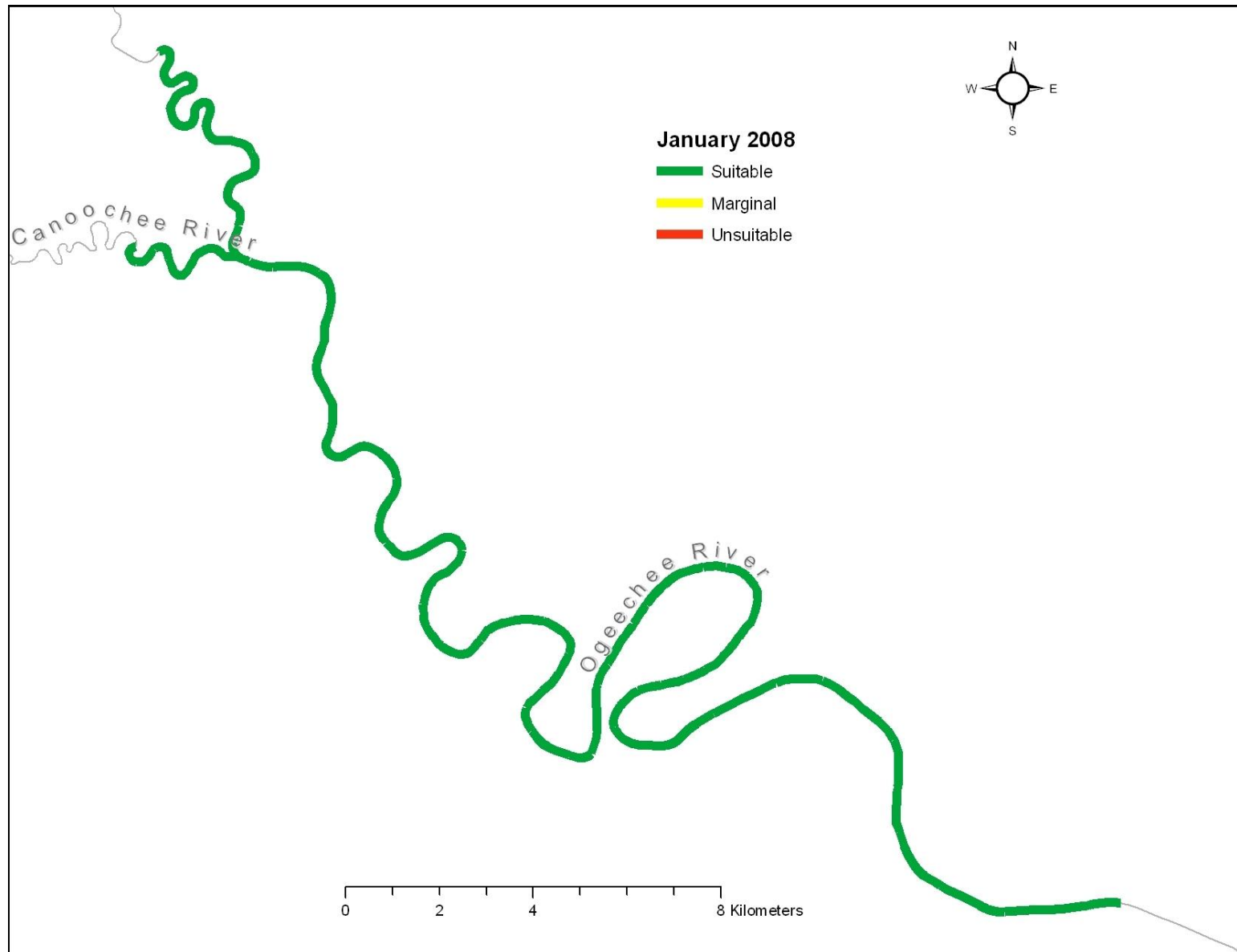


Figure 3.1. Habitat suitability for shortnose sturgeon in the Ogeechee River in January 2008.

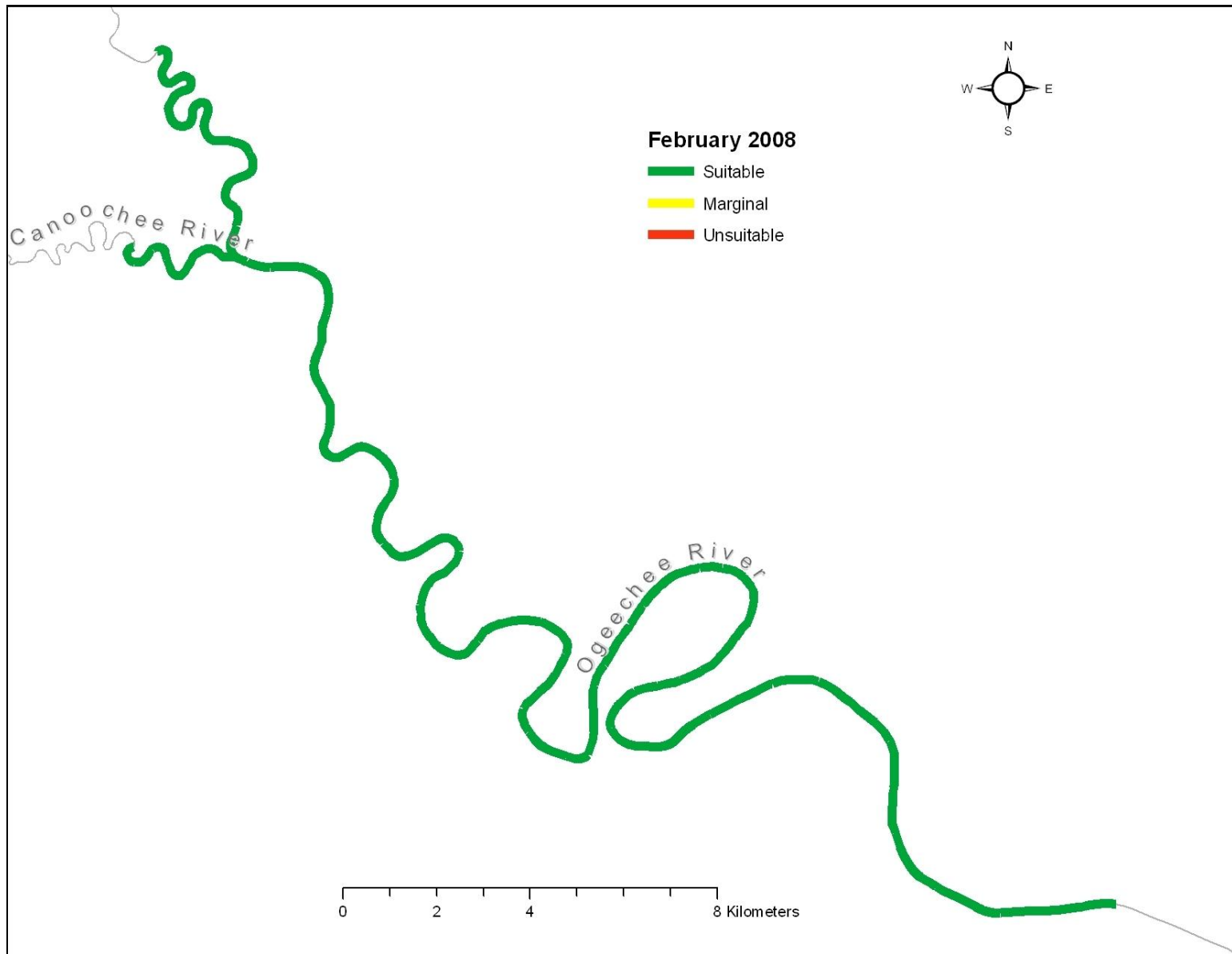


Figure 3.2. Habitat suitability for shortnose sturgeon in the Ogeechee River in February 2008.

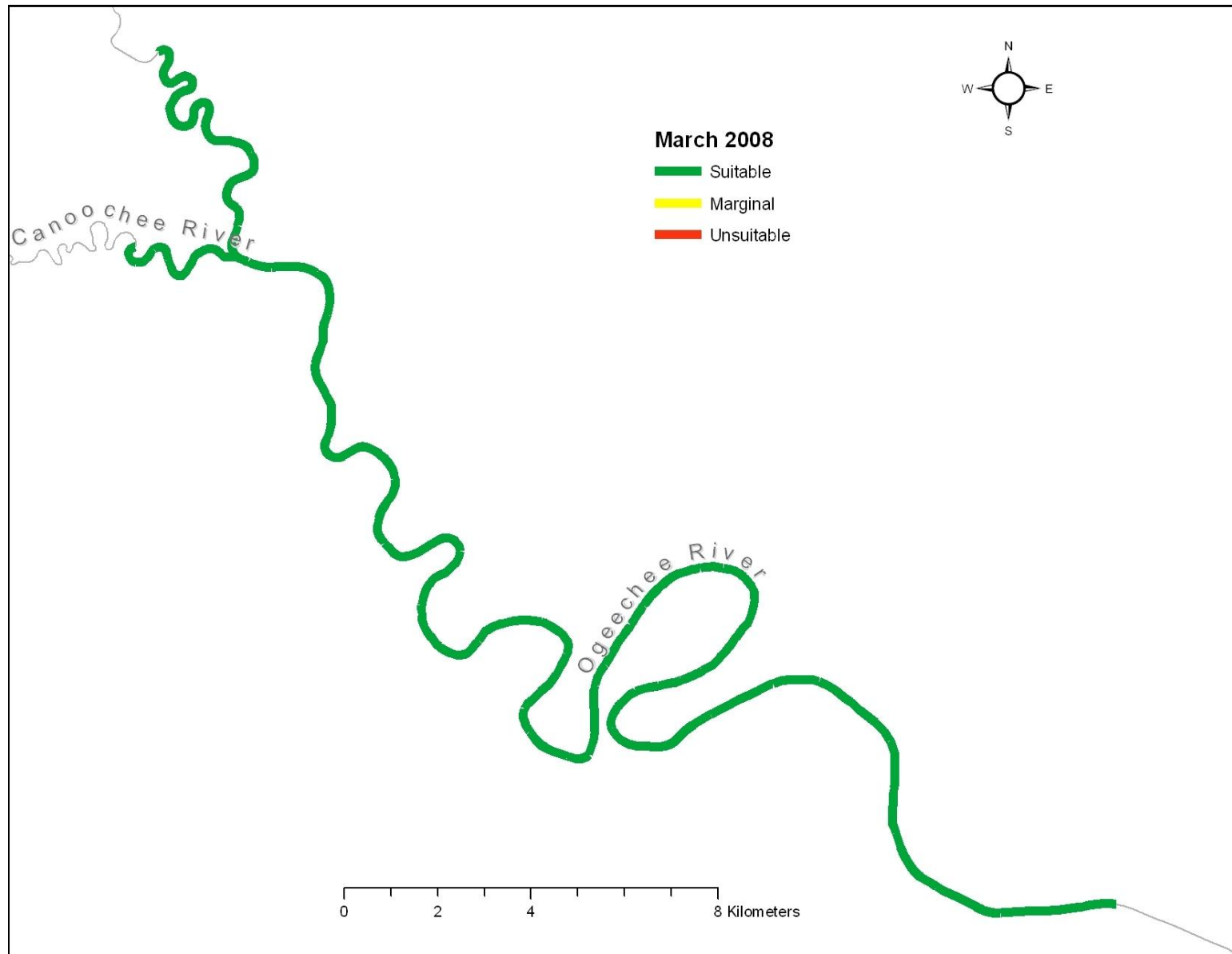


Figure 3.3. Habitat suitability for shortnose sturgeon in the Ogeechee River in March 2008.

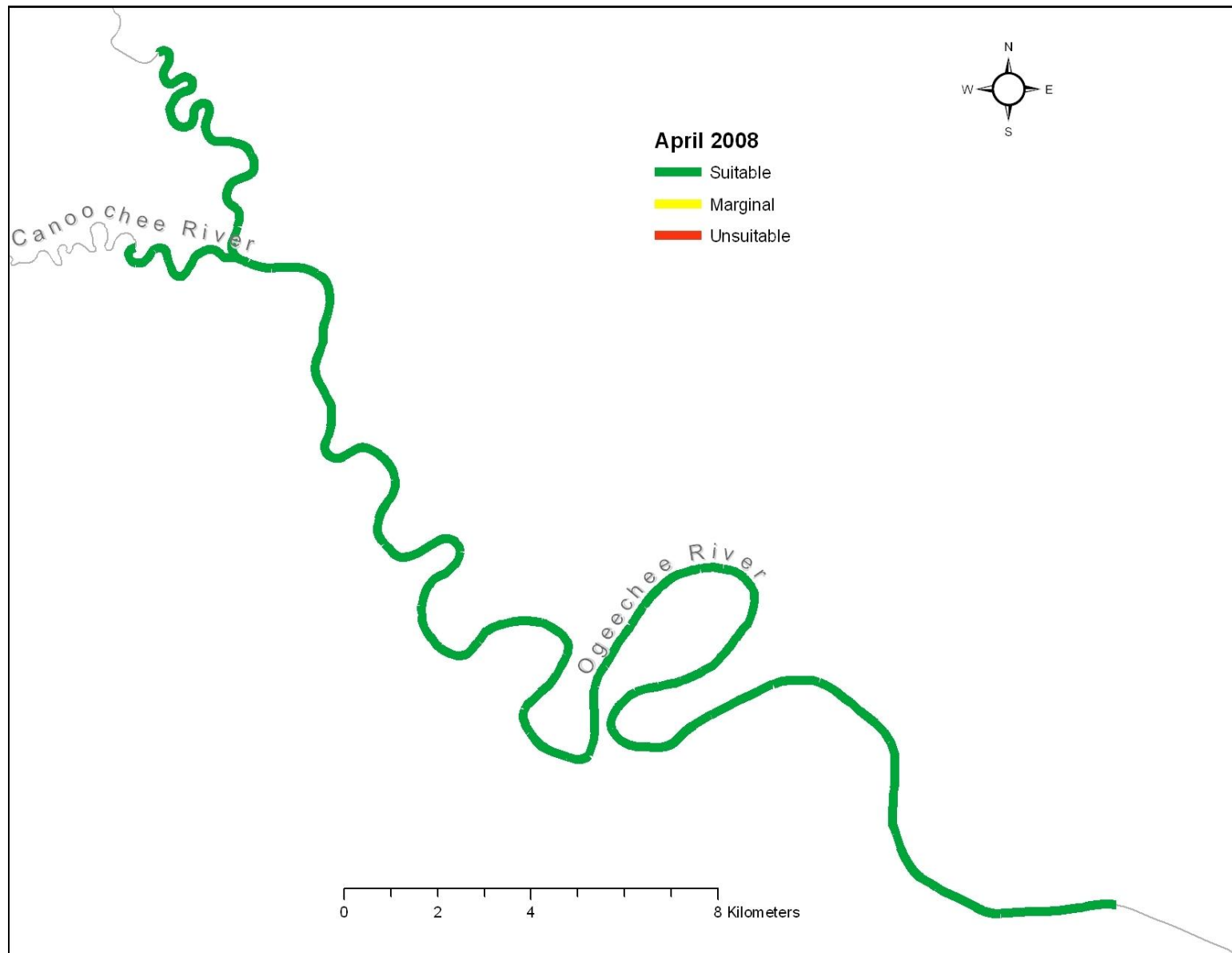


Figure 3.4. Habitat suitability for shortnose sturgeon in the Ogeechee River in April 2008.

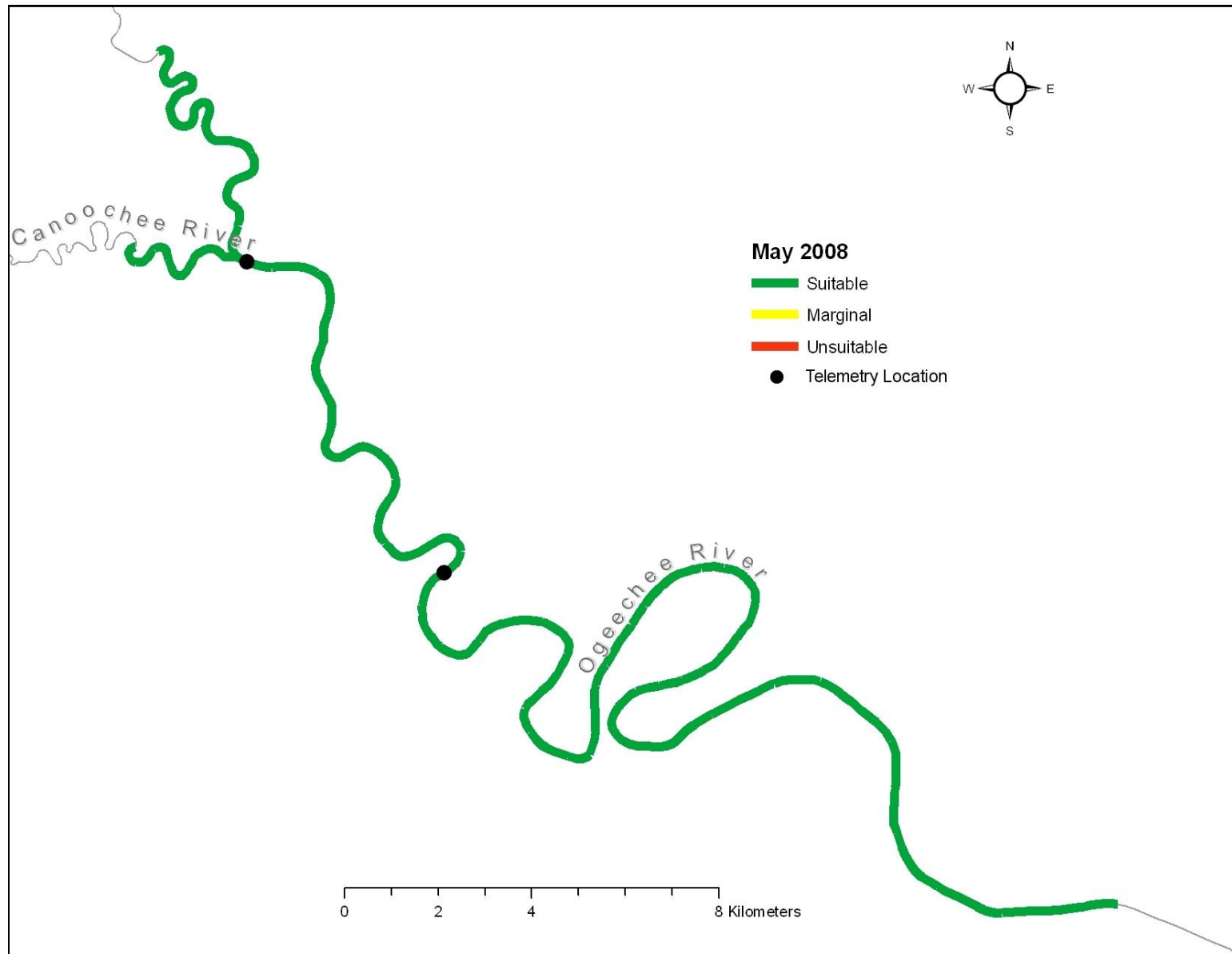


Figure 3.5. Habitat suitability compared to movements of shortnose sturgeon in the Ogeechee River in May 2008.

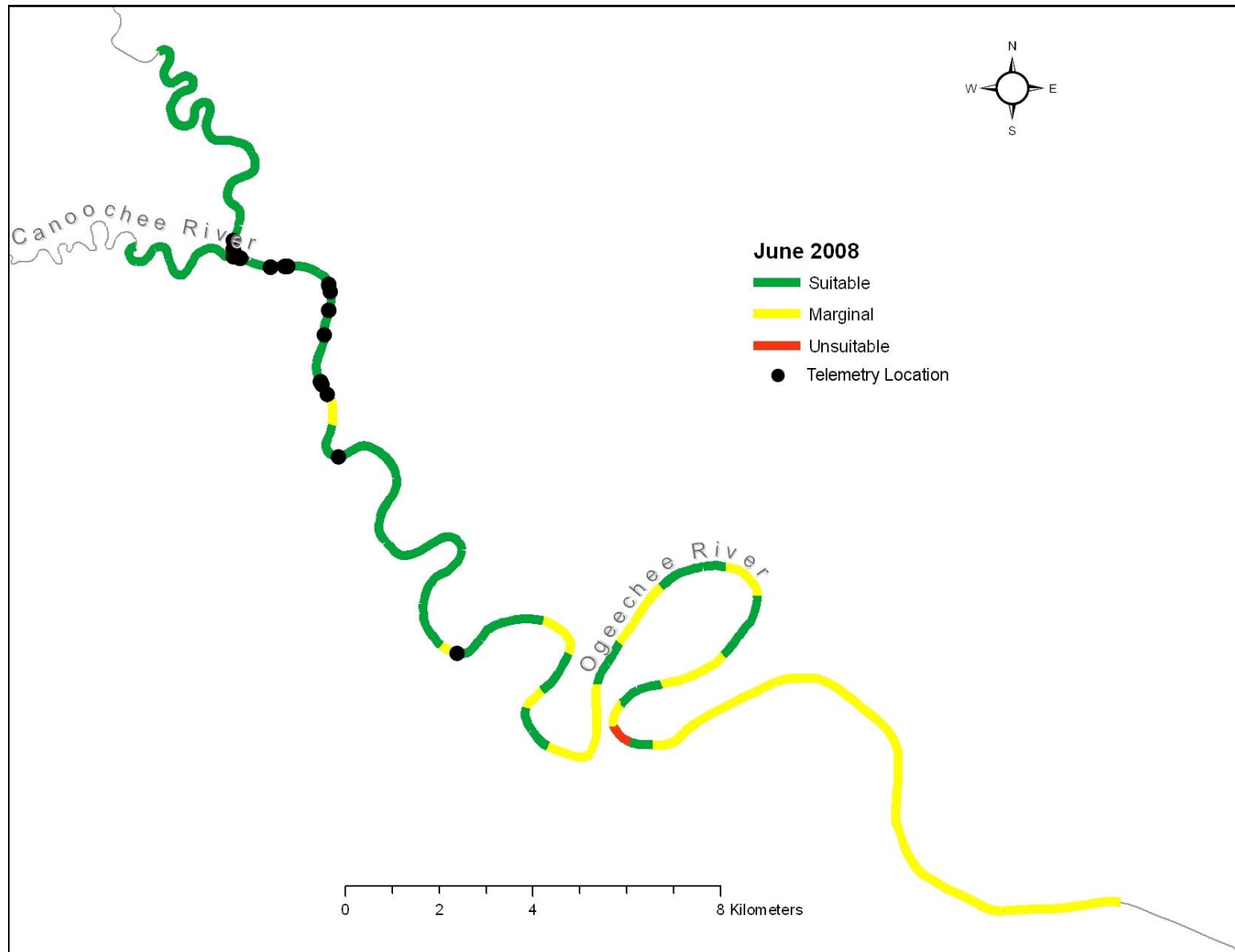


Figure 3.6. Habitat suitability compared to movements of shortnose sturgeon in the Ogeechee River in June 2008.

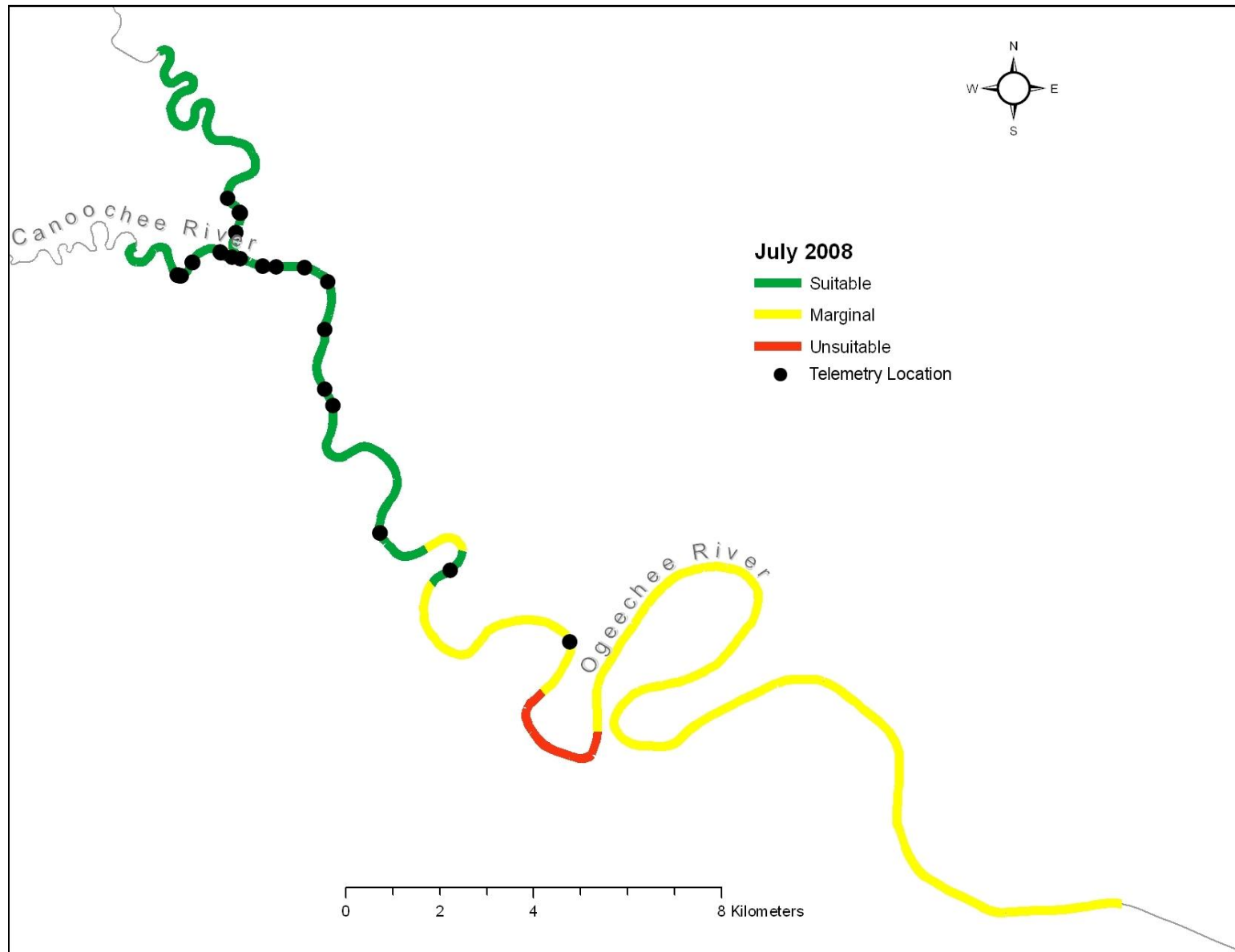


Figure 3.7. Habitat suitability compared to movements of shortnose sturgeon in the Ogeechee River in July 2008.

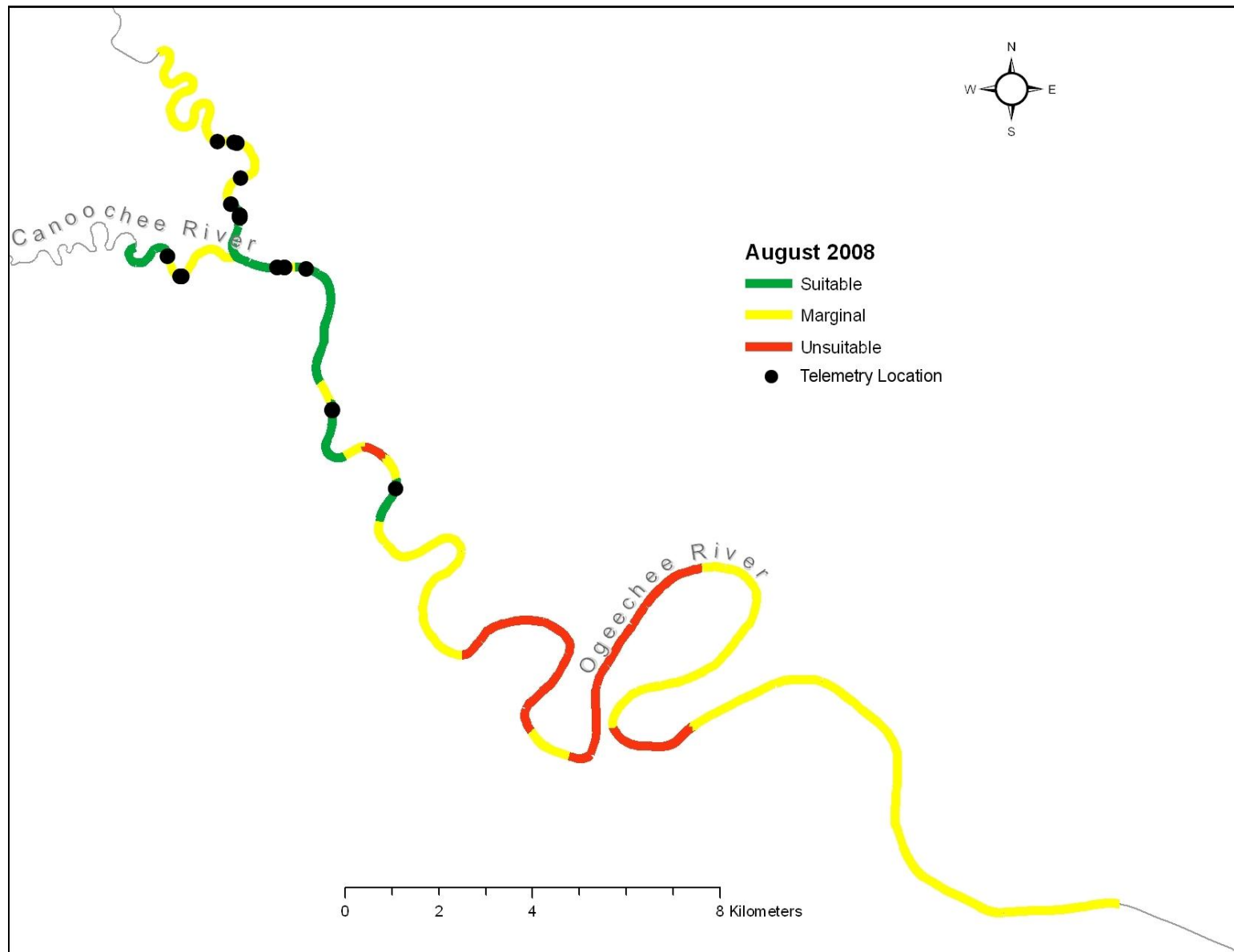


Figure 3.8. Habitat suitability compared to movements of shortnose sturgeon in the Ogeechee River in August 2008.

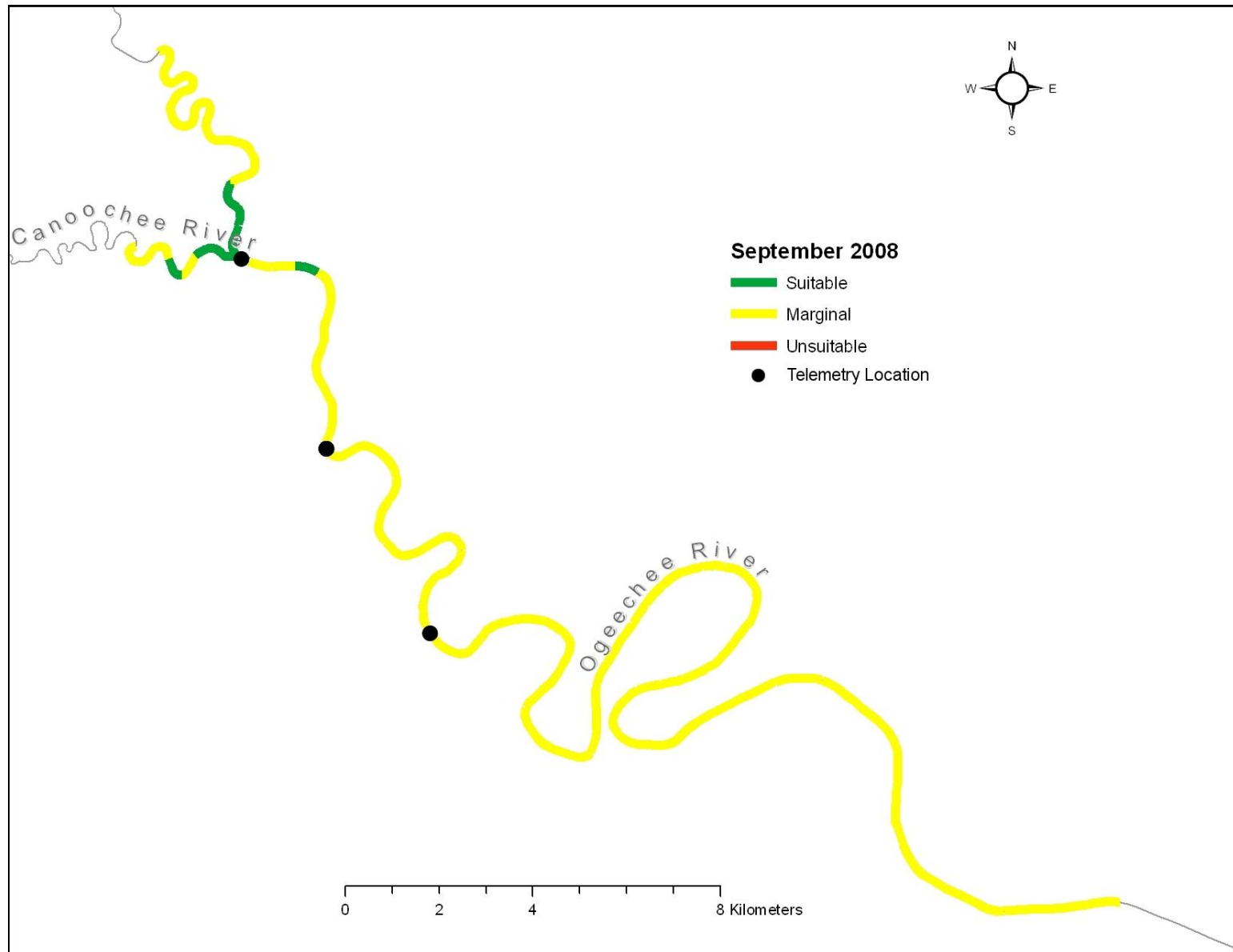


Figure 3.9. Habitat suitability compared to movements of shortnose sturgeon in the Ogeechee River in September 2008.

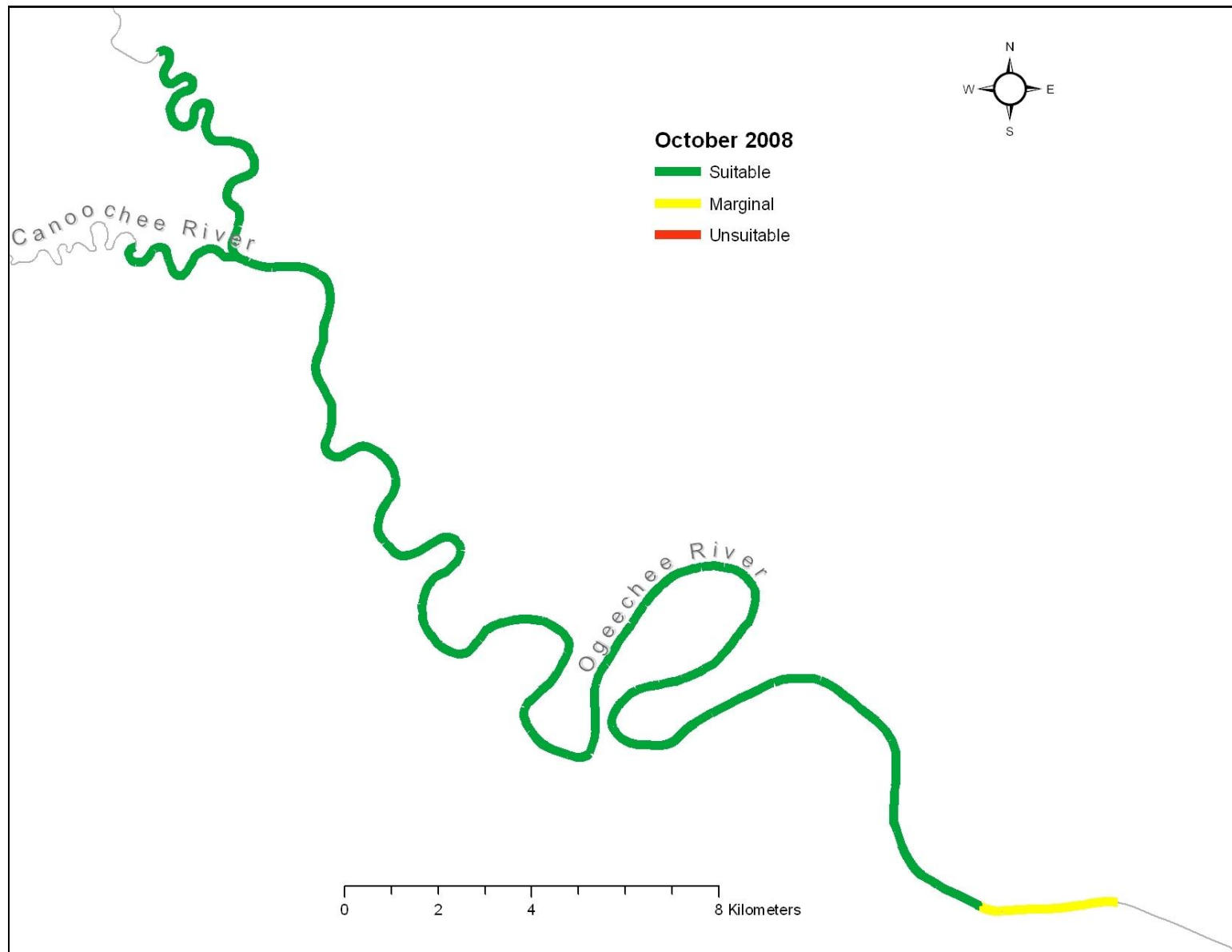


Figure 3.10. Habitat suitability for shortnose sturgeon in the Ogeechee River in October 2008 (*telemetry data missing).

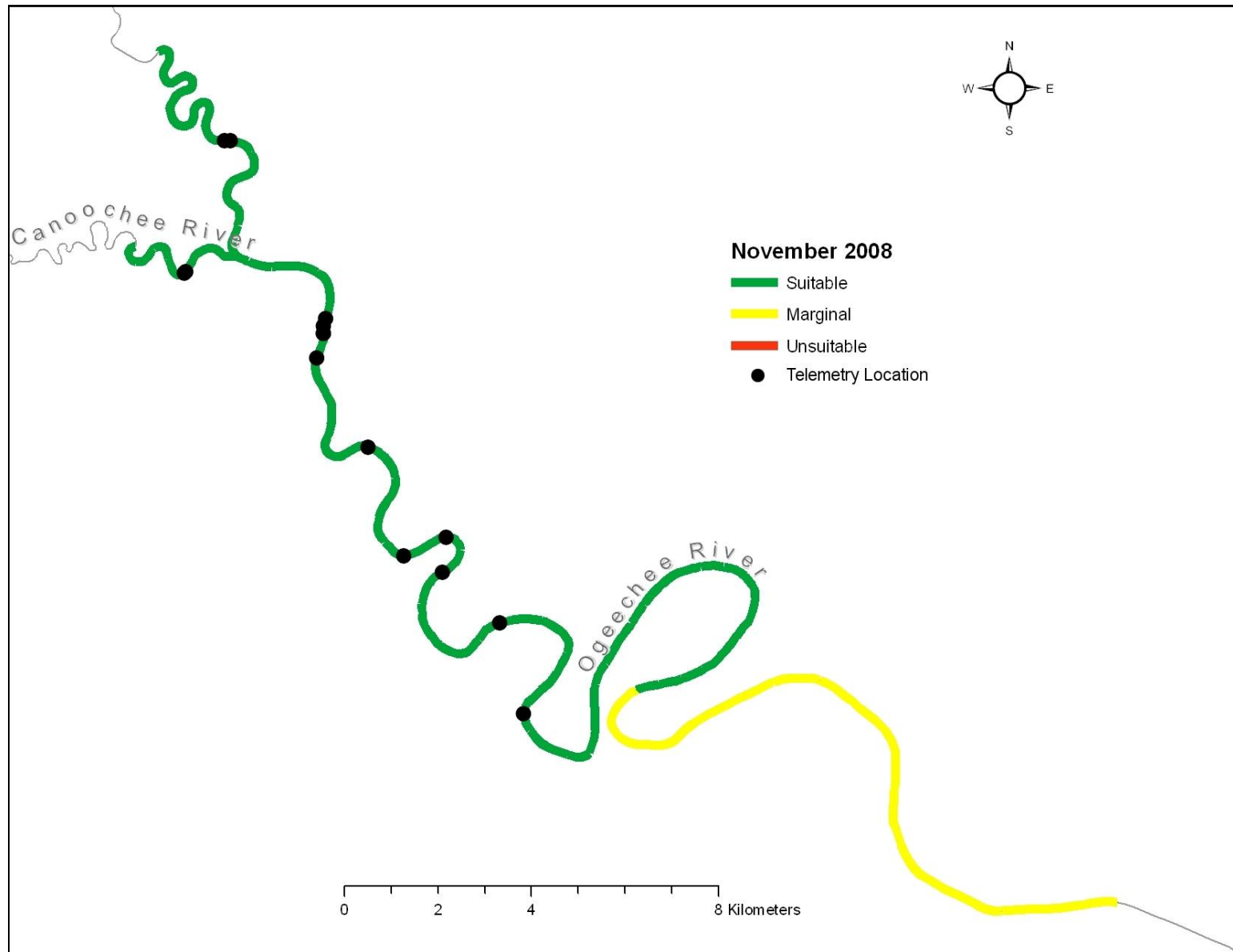


Figure 3.11. Habitat suitability compared to movements of shortnose sturgeon in the Ogeechee River in November 2008.

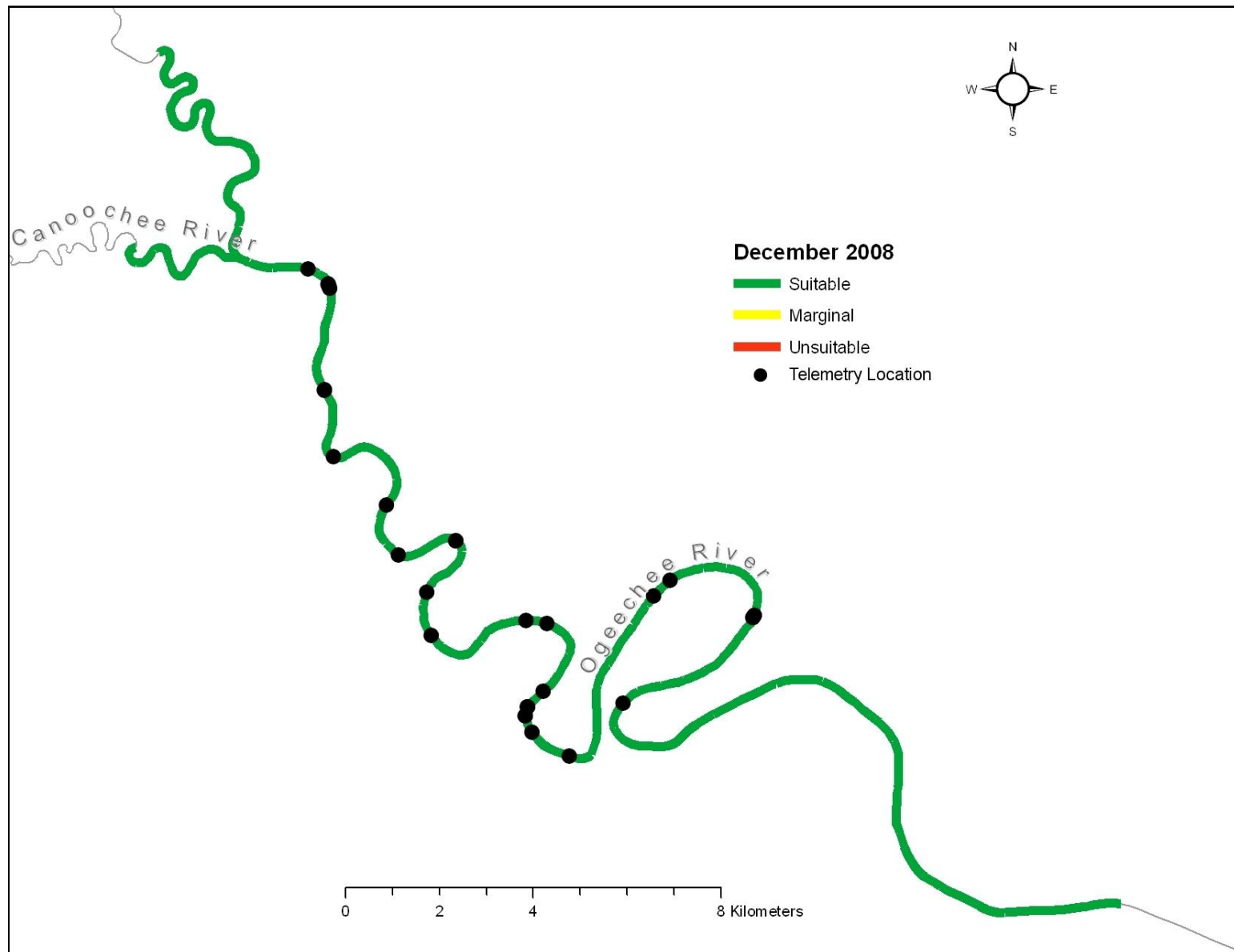


Figure 3.12. Habitat suitability compared to movements of shortnose sturgeon in the Ogeechee River in December 2008.

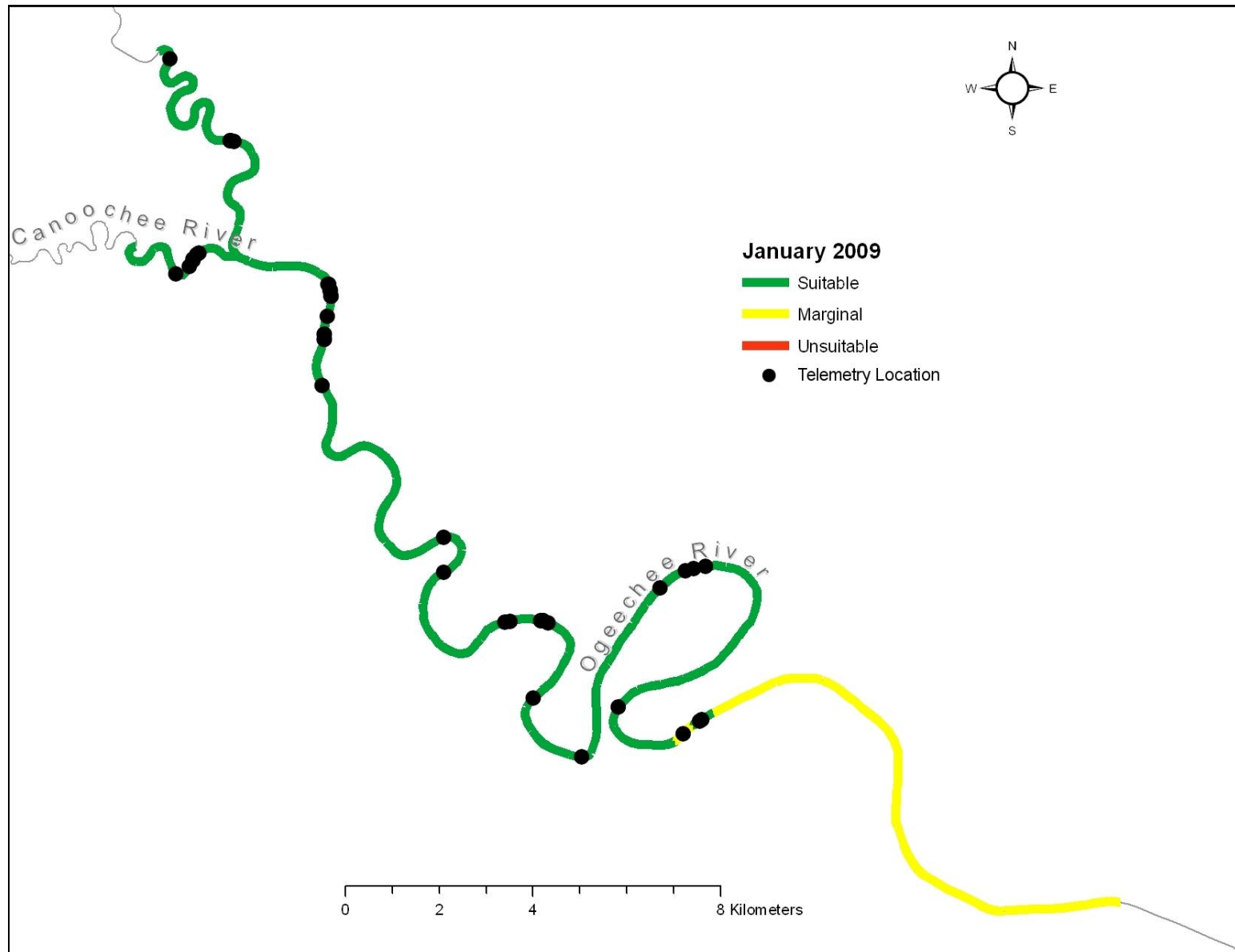


Figure 3.13. Habitat suitability compared to movements of shortnose sturgeon in the Ogeechee River in January 2009.

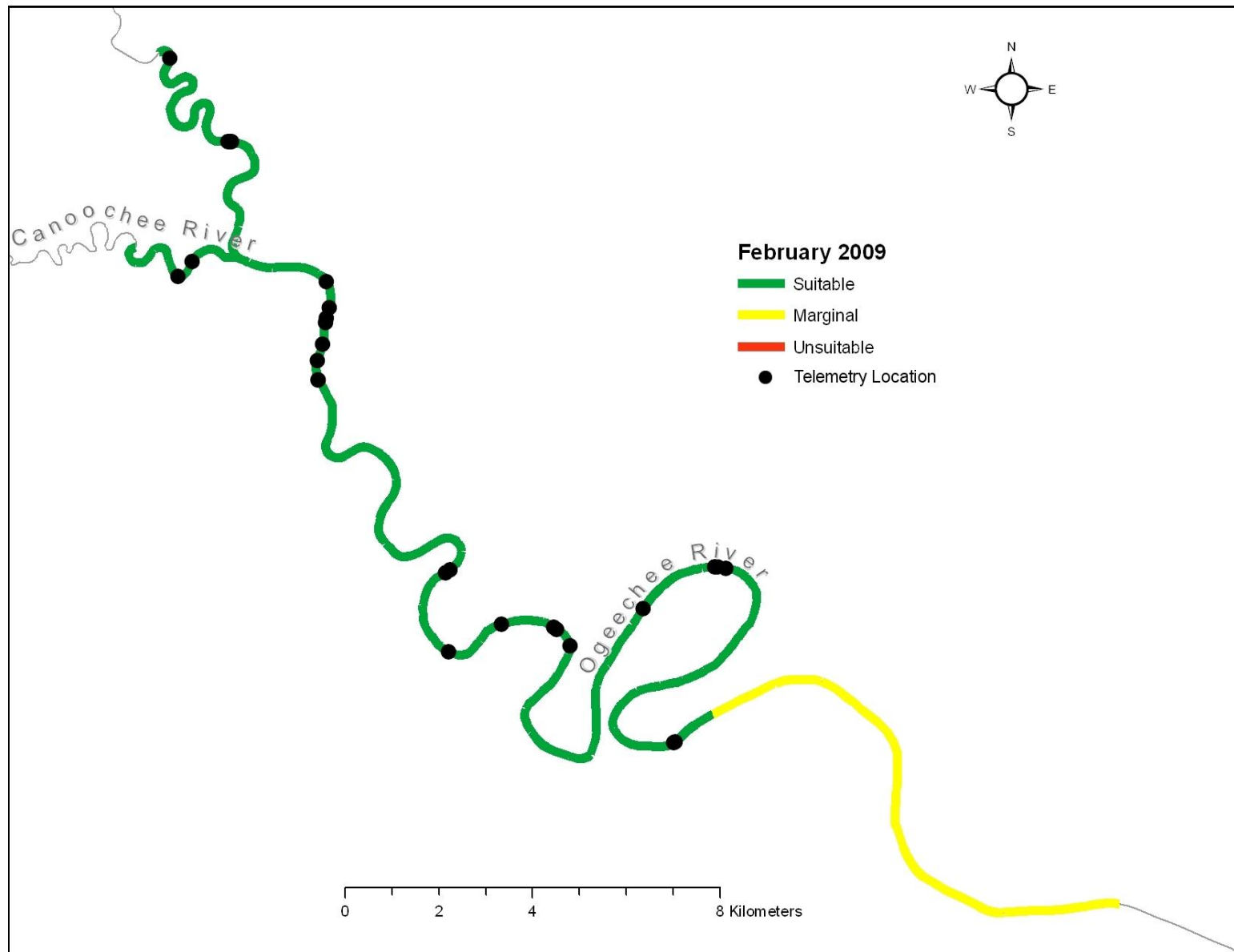


Figure 3.14. Habitat suitability compared to movements of shortnose sturgeon in the Ogeechee River in February 2009.

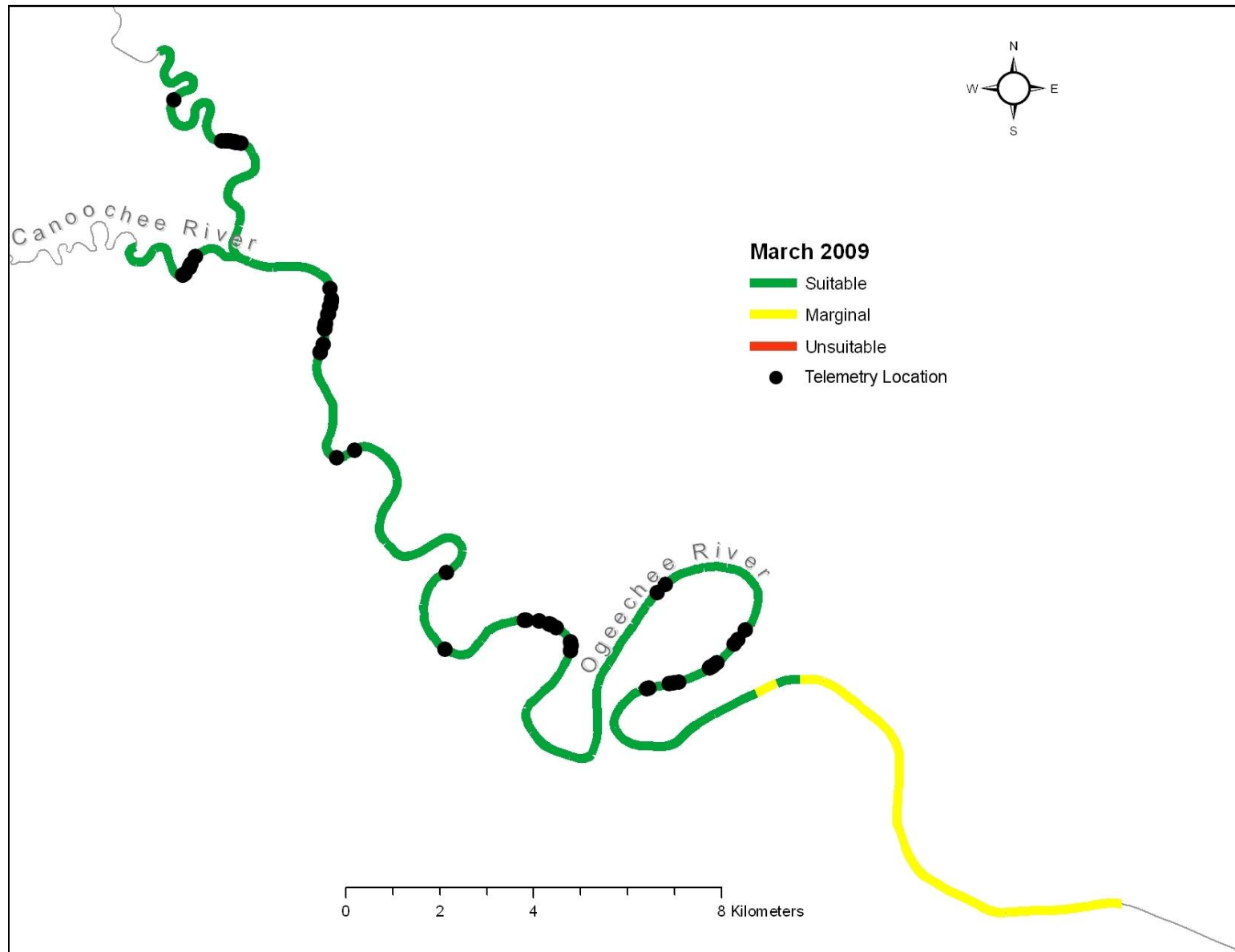


Figure 3.15. Habitat suitability compared to movements of shortnose sturgeon in the Ogeechee River in March 2009.

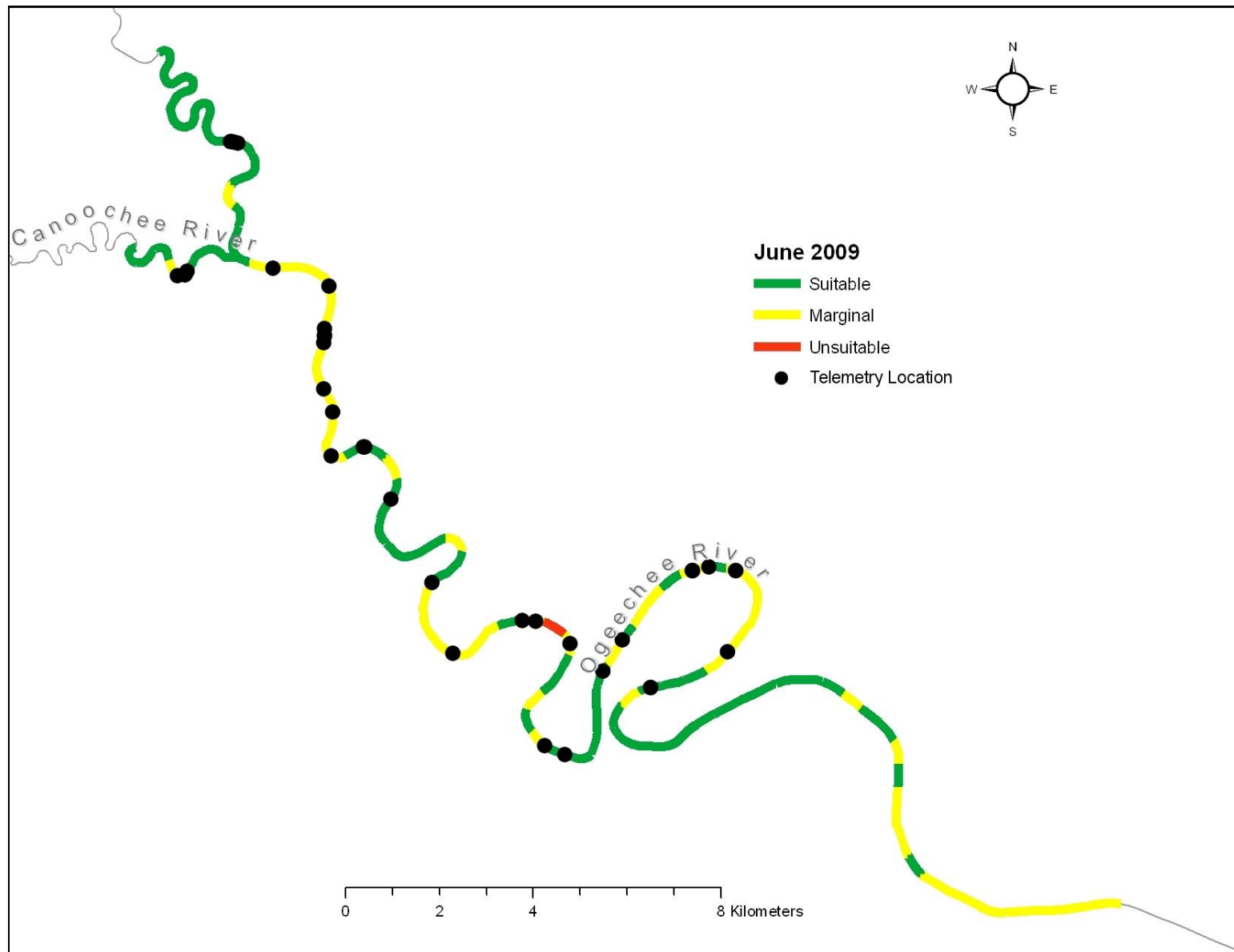


Figure 3.18. Habitat suitability compared to movements of shortnose sturgeon in the Ogeechee River in June 2009.

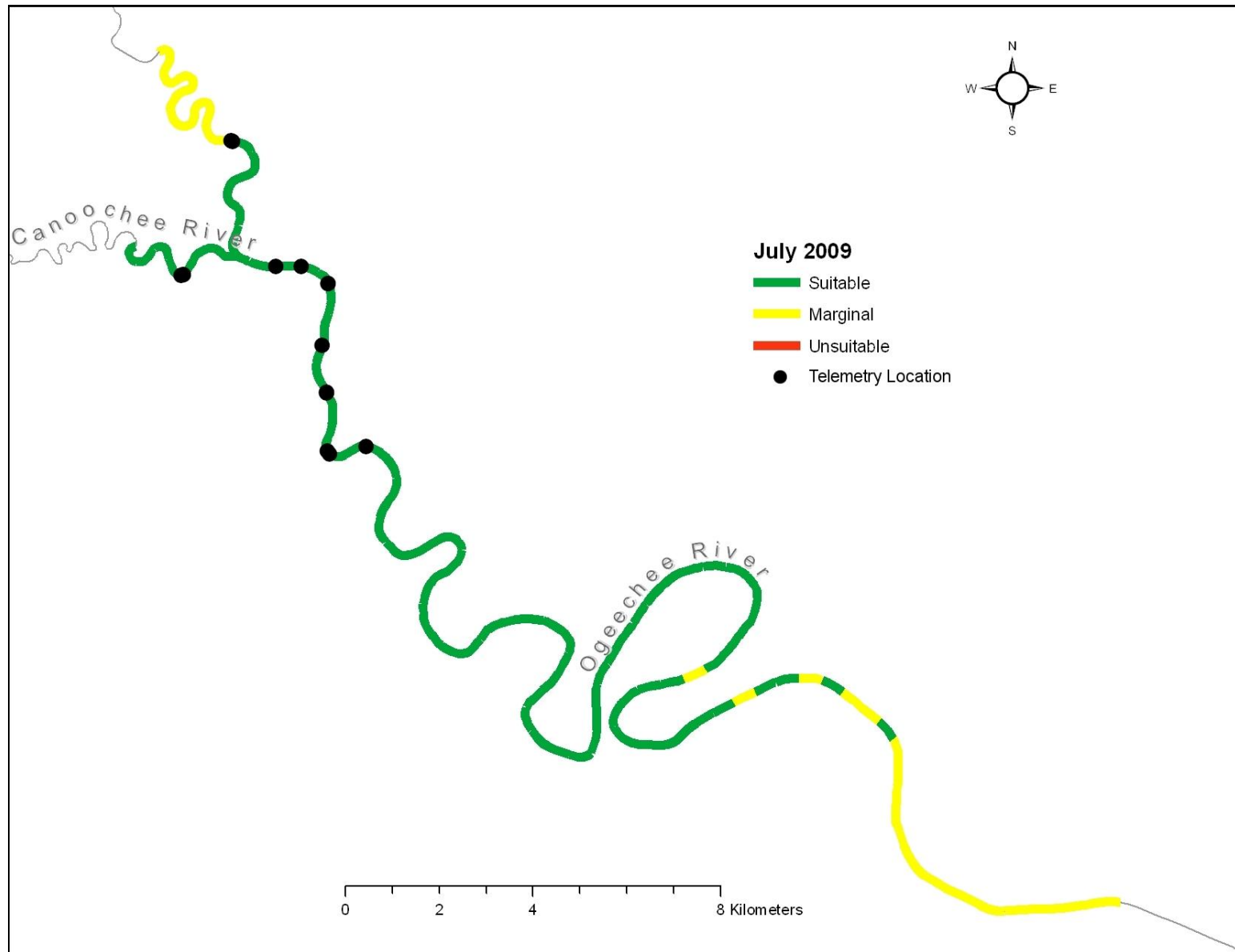


Figure 3.19. Habitat suitability compared to movements of shortnose sturgeon in the Ogeechee River in July 2009.

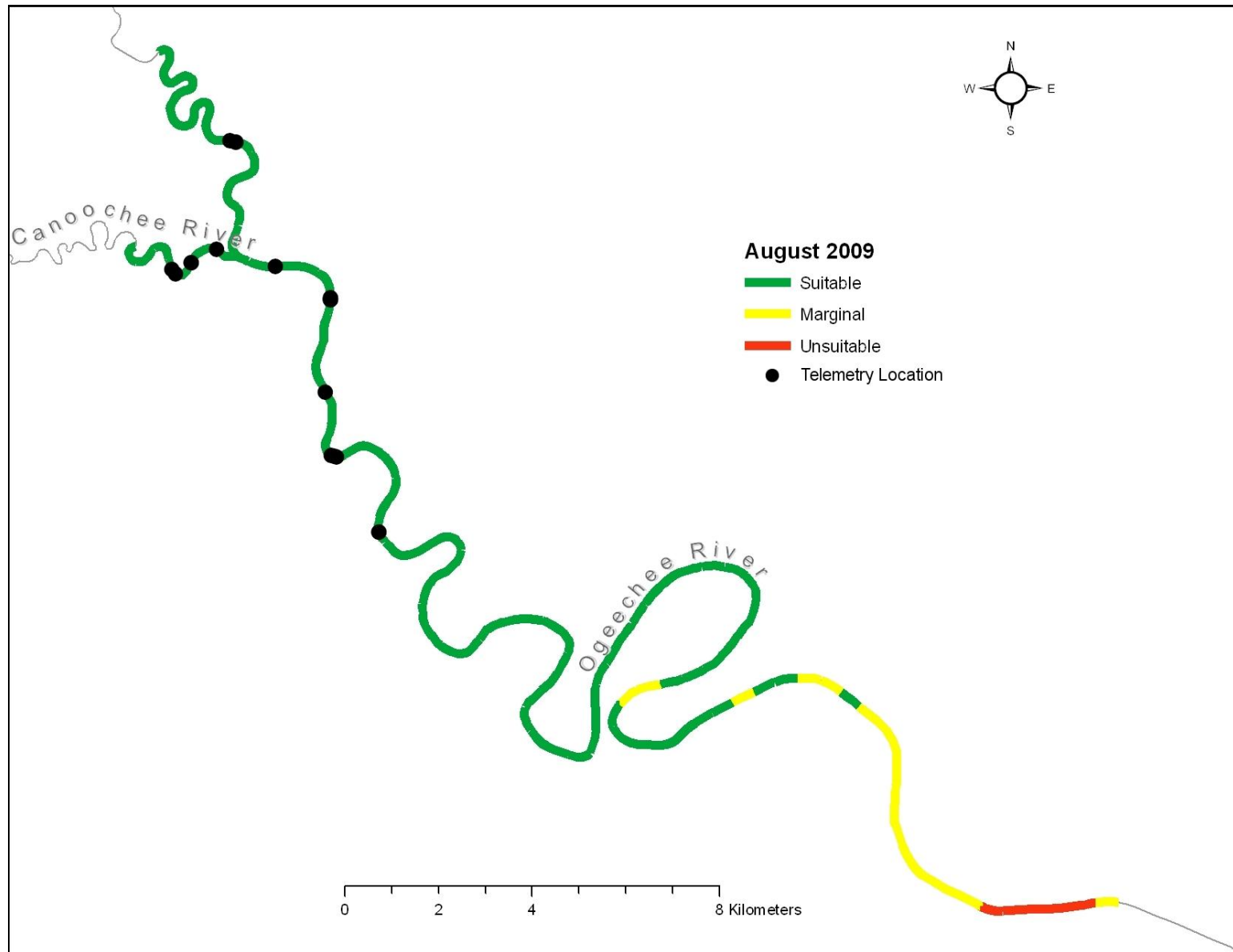


Figure 3.20. Habitat suitability compared to movements of shortnose sturgeon in the Ogeechee River in August 2009.

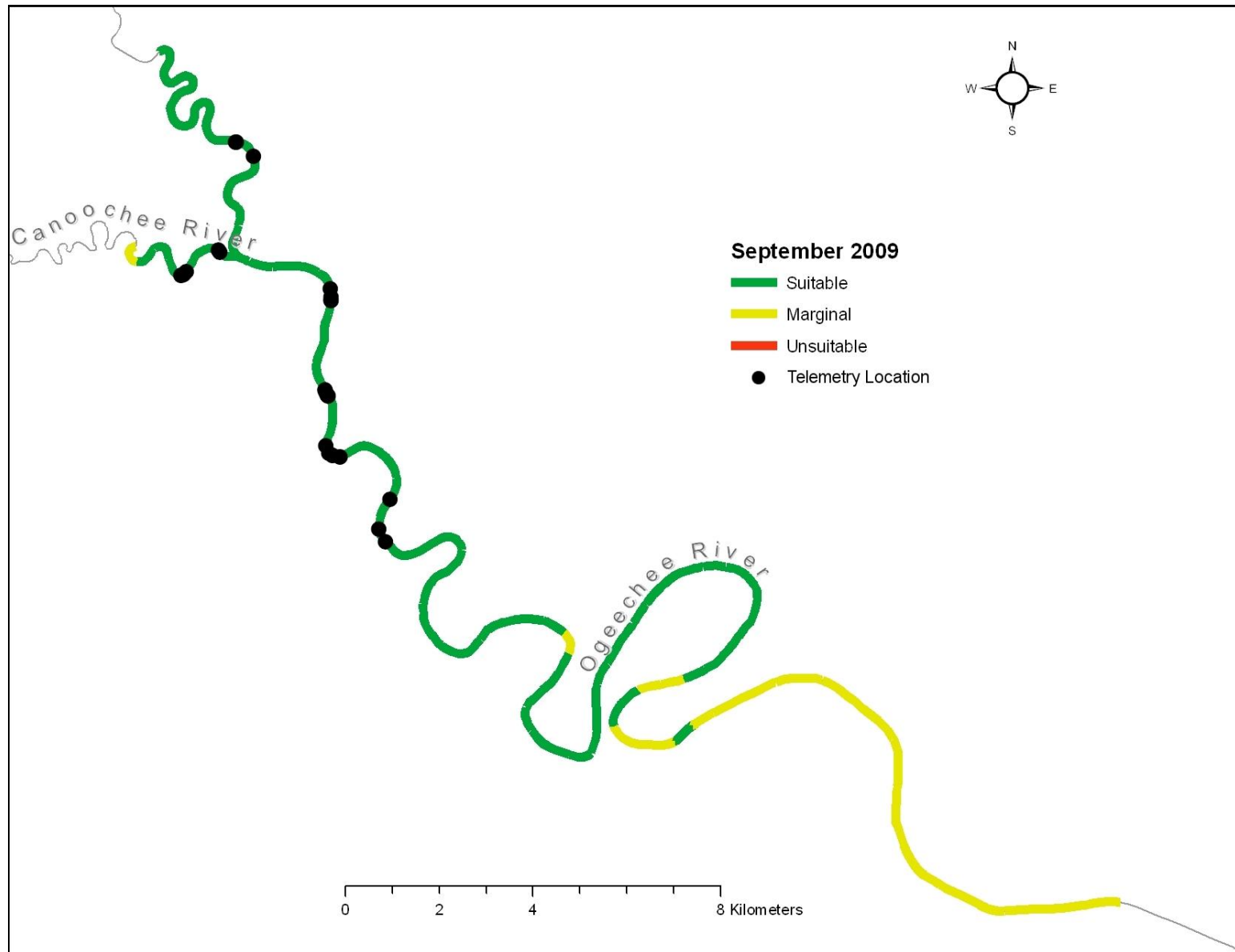


Figure 3.21. Habitat suitability compared to movements of shortnose sturgeon in the Ogeechee River in September 2009.

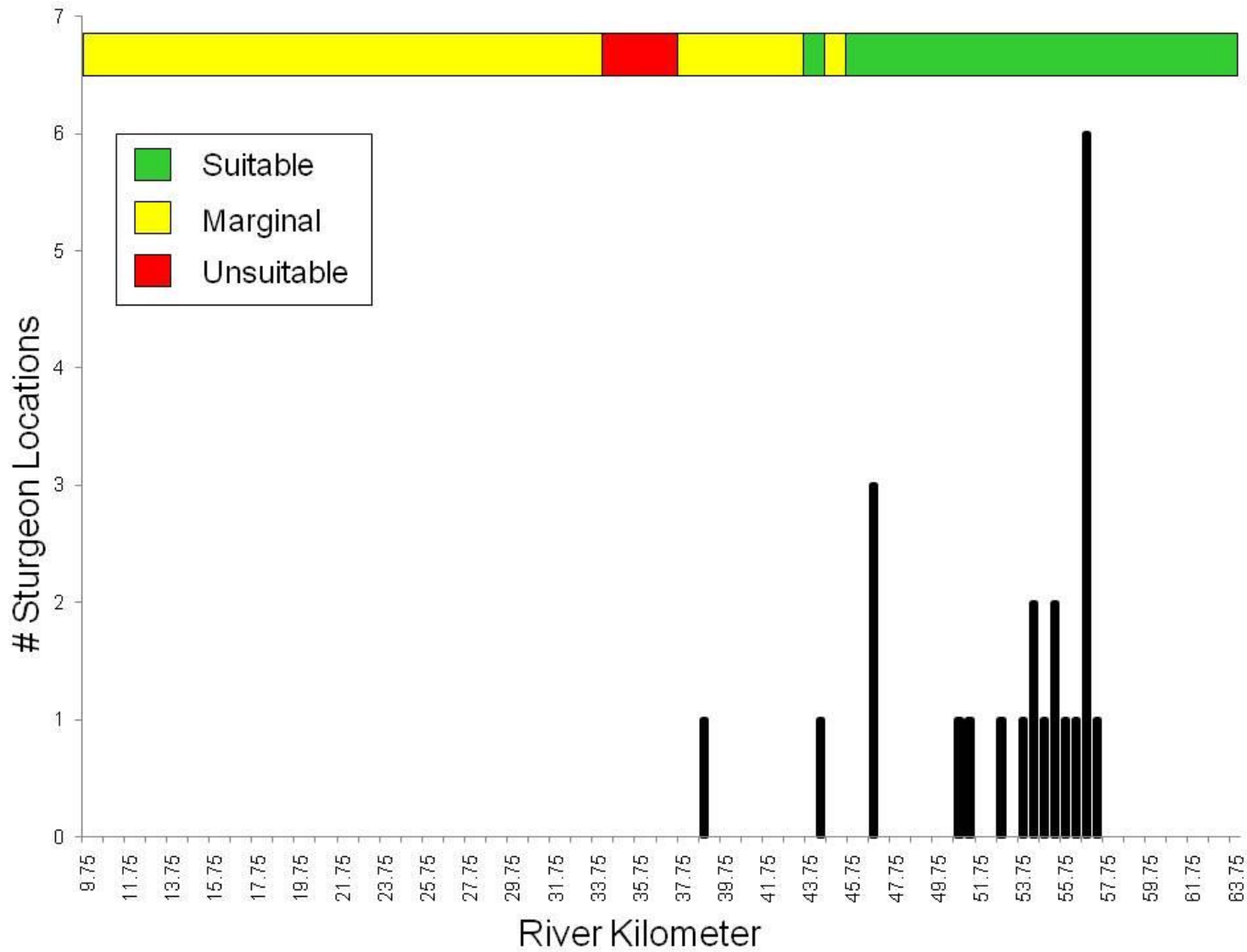


Figure 3.22. A comparison of habitat suitability and number of sturgeon locations via telemetry per 500 m segment of the mainstem Ogeechee River during July 2008.

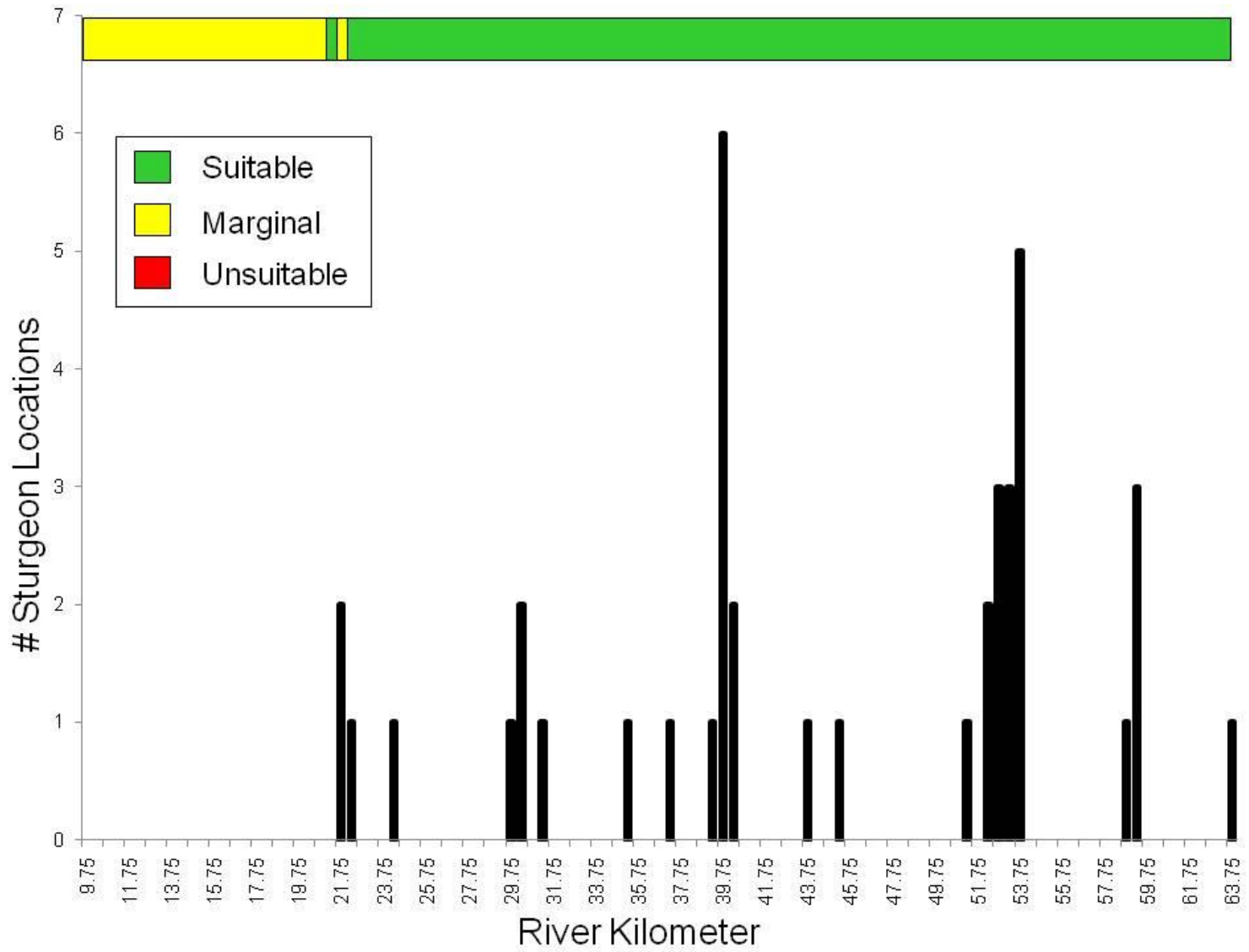


Figure 3.23. A comparison of habitat suitability and number of sturgeon locations via telemetry per 500 m segment of the mainstem Ogeechee River during January 2009.

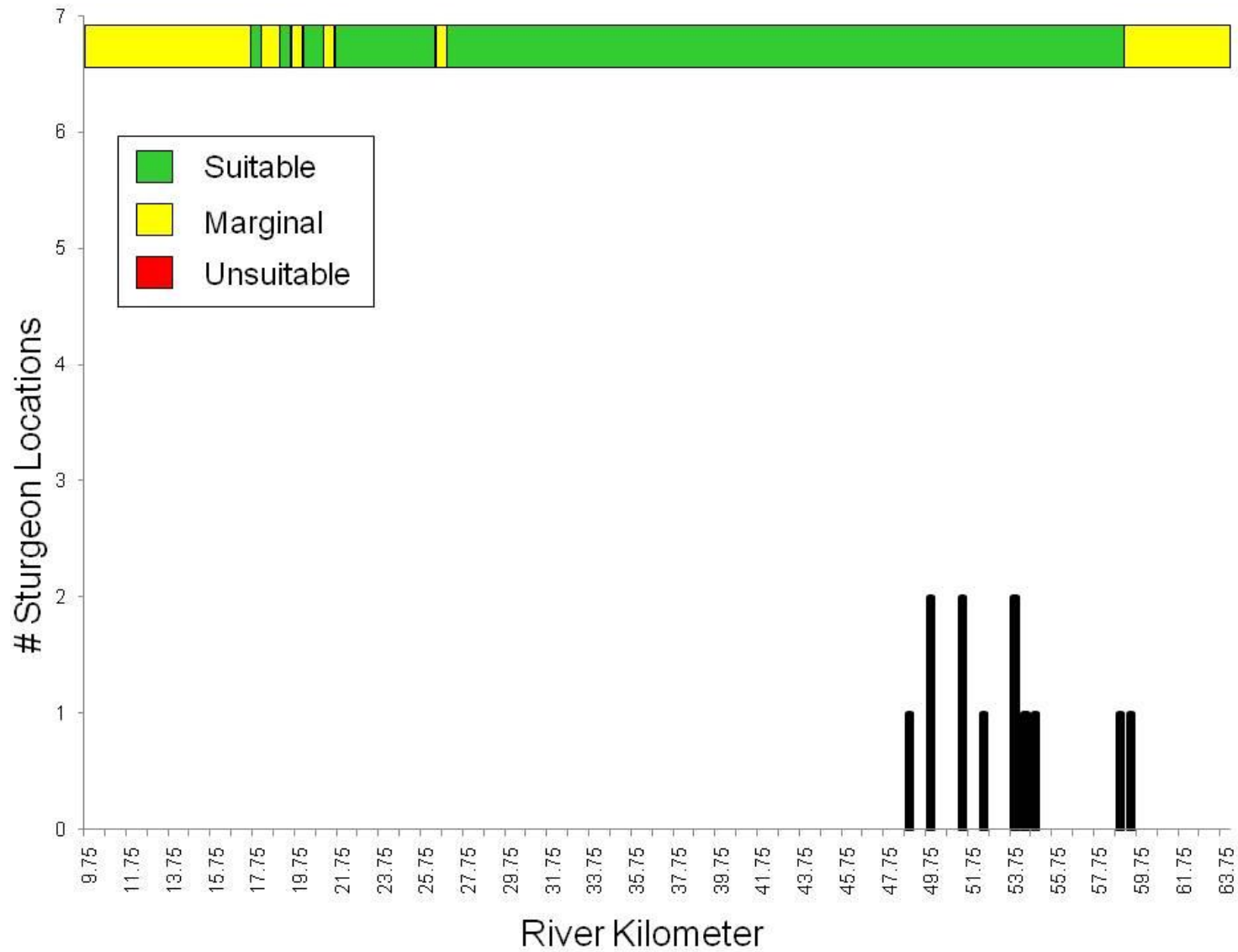


Figure 3.24. A comparison of habitat suitability and number of sturgeon locations via telemetry per 500 m segment of the mainstem Ogeechee River during July 2009.

CHAPTER 4

CONCLUSIONS

Shortnose sturgeon of the Ogeechee River do not appear to form a unique population. The current, and historical, lack of juveniles in the Ogeechee River appears to indicate persistent recruitment failure. Poor summer habitat quality severely limits habitat suitability and availability and may constitute a population bottleneck. However, abundance estimates have remained static over the last 15 years, despite being protected by the Endangered Species Act. If the Ogeechee supported a unique population of shortnose sturgeon, then persistent recruitment failure and poor habitat should lead to local extirpation. In support of my theory that the Ogeechee River is not a unique population, I identified several movements of shortnose sturgeon to and from the neighboring Altamaha River. Genetically, the stocks of shortnose in the Altamaha and Ogeechee rivers are indistinguishable (Wirgin et al. 2005, Wirgin et al. 2009). I believe that the stocks of shortnose sturgeon in these two rivers form a source-sink metapopulation.

Previous studies have proposed that large density-dependent populations may serve as sources for source-sink metapopulations with smaller neighboring river systems (Kynard 1997, Walsh et al. 2001). If most immigrants in the Ogeechee originate from the Altamaha River, as our field evidence and separate genetic analyses all suggest, then the two stocks meet the description of a source-sink metapopulation (Pulliam 1988, Figueira and Crowder 2006, Wilberg et al. 2008).

The Ogeechee River stock may be limited by a lack of suitable habitat during the physiologically stressful summer months. Shortnose sturgeon appeared to move in response to water quality conditions, avoiding what I characterized as most unsuitable. I found that during these conditions, shortnose sturgeon used only a small, ~ 15 rkm segment of the Ogeechee River near the confluence with the Canoochee River. With all sturgeon located in such a small portion of the river, intraspecific competition for resources would likely increase significantly. My results support the theory that poor summer water conditions may cause a habitat “squeeze,” thereby limiting juvenile recruitment as well as adult survival (Secor and Niklitschek 2001). These limiting factors may be less severe on the larger Altamaha River population. For example, the Altamaha River has ~3.7 times more freshwater input and a watershed three times greater than the Ogeechee (Sheldon and Alber 2005). No published studies exist, but the amount of suitable habitat during the summer is likely much larger in the Altamaha River than the Ogeechee River.

Future studies of the Ogeechee River shortnose sturgeon stock are needed to continue monitoring population trends and better assess the exact relationship between this stock and the neighboring Altamaha River stock. Because recruitment and abundance are subject to stochastic and environmental influences, long-term studies are required to draw broad conclusions about population and reproductive status. Identification of migratory routes between the Ogeechee and Altamaha rivers is necessary to properly protect all habitat used by shortnose sturgeon. Other river systems should be analyzed to determine the possibility of source-sink metapopulations and to support genetic delineation of DPS's. Additionally, other

river systems should be analyzed for summer water quality conditions using methods similar to ours to determine correlation between relative abundance and habitat availability. Future research should try to identify and quantify suitable spawning habitat in the Ogeechee River.

Our research fulfilled one of the goals of the NMFS Recovery Plan (1998) for the shortnose sturgeon: determine abundance, age structure, and recruitment for population segments. Additionally, assessing shortnose sturgeon habitat use and quality is one of the primary objectives of the NMFS Recovery Plan (1998). The knowledge gained from this study can be used to protect and restore critical habitats for sturgeon. Effective management strategies for the recovery of shortnose sturgeon require a better understanding of the influence of habitat quality on populations. Our study provides the methods necessary to analyze this relationship and provide a quantified estimate of how habitat quality affects the movement of shortnose sturgeon.

References

- Figueira, W. F. and L. B. Crowder. 2006. Defining patch contribution in source-sink metapopulations: the importance of including dispersal and its relevance to marine systems. *Population Ecology* 48: 215 – 224.
- Kynard, B. 1997. Life History, latitudinal patterns, and status of the shortnose sturgeon, *Acipenser brevirostrum*. *Environmental Biology of Fishes* 48: 319–334.
- National Marine Fisheries Service (NMFS). 1998. Final Recovery Plan for the shortnose sturgeon, *Acipenser brevirostrum*. Prepared by the Shortnose Sturgeon Recovery Team for the National Marine Fisheries Service, Silver Spring, Maryland. 104pp.
- Pulliam, H. R. 1988. Sources, sinks, and population regulation. *The American Naturalist* 132(5): 652 – 661.
- Secor, D. H. and E. J. Niklitschek. 2001. Hypoxia and sturgeons: report to the Chesapeake Bay Program dissolved oxygen team. Technical Report Series No. TS-314-01-CBL; Chesapeake Biological Laboratory, Solomons, Maryland.
- Sheldon, J. E. and M. Alber. 2005. Comparing transport times through salinity zones in the Ogeechee and Altamaha river estuaries using squeezebox. *In* K. J. Hatcher, editor, Proceedings of the 2005 Georgia Water Resources Conference. The University of Georgia. Athens, Georgia.
- Walsh, M. G., M. B. Bain, T. Squiers Jr., J. R. Waldman, and I. Wirgin. 2001. Morphological and genetic variation among shortnose sturgeon *Acipenser brevirostrum* from adjacent and distant rivers. *Estuaries* 24(1): 41–48.

- Wilberg, M. J., B. J. Irwin, M. L. Jones, and J. R. Bence. 2008. Effects of source-sink dynamics on harvest policy performance for yellow perch in southern Lake Michigan. *Fisheries Research* 94: 282 – 289.
- Wirgin, I., C. Grunwald, E. Carlson, J. Stabile, D. L. Peterson, and J. Waldman. 2005. Range-wide population structure of shortnose sturgeon *Acipenser brevirostrum* based on sequence analysis of the mitochondrial DNA control region. *Estuaries* 28(3): 406–421.
- Wirgin, I., C. Grunwald, J. Stabile, and J. R. Waldman. 2009. Delineation of discrete population segments of shortnose sturgeon *Acipenser brevirostrum* based on mitochondrial DNA control region sequence analysis. *Conservation Genetics* online.