DECLINE AND RECOVERY OF STRIPED BASS IN THE SAVANNAH RIVER ESTUARY: SYNTHESIS AND RE-ANALYSIS OF HISTORICAL INFORMATION AND EVALUATION OF RESTORATION POTENTIAL

by

THOMAS ROBERT REINERT

(Under the direction of Cecil A. Jennings)

ABSTRACT

Since the lower Savannah River Estuary was first settled in 1733, shaping and deepening the river channel to provide easy, safe access to the sea has been a near continuous effort. Once averaging about 3 m in depth, the channel is now over 12 m deep, and currently there is an investigation evaluating a further deepening of up to 2 m. These modifications to the estuary have not been without unintended environmental consequences. The saltwater-freshwater interface has moved nearly 25 km upriver since it was first measured in the 1700s. In 1977, saltwater intrusion was exacerbated by the operation of a tide gate in the Back River channel of the estuary. Salinity increased in the Savannah National Wildlife Refuge and converted much of the tidal-freshwater marsh to less desirable brackish and saline marsh. Further, the salinity shift affected the freshwater spawning and nursery grounds of the striped bass *Morone saxatilis*. As a result, striped bass reproduction declined by 96% and adult striped bass abundance declined by 97%. Restoration efforts (which included stock enhancement and habitat mitigation) have resulted in increased striped bass adult abundances and

increased egg production. Previous studies concluded that restoration of the Back River, considered the primary striped bass spawning ground, was paramount and would allow latitude for additional harbor development. However, use of egg surrogates to evaluate sampling efficiency has led to the discovery that sampling biases may have fostered faulty conclusions: historic egg abundance has been at least an order of magnitude greater in the Front River than in the Back River. We now know we must regard the estuary as a whole system, rather than as individual reaches. Considering this, and the currently proposed deepening, models were employed to evaluate the effect of increased salinity on striped bass eggs and larvae immediately upstream of the harbor. Deepening scenarios that result in upstream isohaline shifts greater than 2 km will have significant impacts on striped bass recruitment potential. Overall, the striped bass population appears to be recovering, although the prospect of additional deepening may threaten that recovery.

INDEX WORDS: Striped bass, Savannah River Estuary, Stock enhancement, Harbor deepening, Egg surrogates, Bayesian belief network

DECLINE AND RECOVERY OF STRIPED BASS IN THE SAVANNAH RIVER ESTUARY: SYNTHESIS AND RE-ANALYSIS OF HISTORICAL INFORMATION AND EVALUATION OF RESTORATION POTENTIAL

by

THOMAS ROBERT REINERT

B.S., Wake Forest University, 1991

M.S., Louisiana State University, 1993

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

Fulfillment of the Requirements for the Degree

DOCTOR OF PHILOSOPHY

ATHENS, GEORGIA 2004

© 2004 Thomas Robert Reinert All Rights Reserved

DECLINE AND RECOVERY OF STRIPED BASS IN THE SAVANNAH RIVER ESTUARY: SYNTHESIS AND RE-ANALYSIS OF HISTORICAL INFORMATION AND EVALUATION OF RESTORATION POTENTIAL

by

THOMAS ROBERT REINERT

Major Professor: Cecil A. Jennings

Committee: Merryl Alber Gene S. Helfman James T. Peterson

Electronic Version Approved:

Maureen Grasso Dean of the Graduate School The University of Georgia May 2004 "I my selfe at the turning of the tyde, have seene such multitudes passe out of a pound, that it seemed to mee, that one might goe over their backs drishod."

> - Thomas Morton, 1637, describing spawning runs of striped bass in New England; from his "New English Canaan, Containing an Abstract of New England".

"The gage of a river's importance has been largely determined by its navigability...As communication and trade increased, rivers in their natural state were not always adequate to the demands of the carriers in which cargo was transported."

> – M. L. Granger, 1968, from "Savannah Harbor: Its Origins and Development, 1733 - 1890." U. S. Army Corps of Engineers, Savannah District.

ACKNOWLEDGMENTS

"A journey of a thousand miles must begin with a single step."

Lao-tzu, 5th century, B.C.

"It ain't over till it's over."

Lawrence P. "Yogi" Berra, 20th century, A.D.

Two quotes, uttered millennia apart, yet each equally appropriate to describe the path toward completion of a dissertation. It has been a long and enjoyable path, and many friends have helped me on that journey. All along the way, they have provided support, friendship, sympathy, advice, and all the things good people do for each other. I need to thank those that worked long hours, in inclement weather, and under the constant threat of sand gnat attack in the lower Savannah River Estuary. Much of your hard work is being translated here into this dissertation and the publications I hope to follow. I want to thank many of the faculty, staff, and fellow students at the University of Georgia and the Warnell School of Forest Resources for your assistance and support. I especially want to thank Bruce Bongarten for his unwavering support and kindness.

I thank the members of my committee: Merryl Alber, Gene Helfman, Cecil Jennings and Jim Peterson. They have been helpful, considerate, constructive, and patient. Although unable to officially serve on my committee, Mike Van Den Avyle provided the spark that got me started (a 6-month job that stretched into over 4 years as Research Coordinator for the Savannah River Estuary striped bass project). I thank him for the opportunity that eventually led to this undertaking and for his continued support

and assistance. I especially need to thank my major advisor, Cecil Jennings. Despite a full-plate of students and other projects, Cecil took me on and helped me shape our research into what has become this dissertation. He has been a boss, advisor, mentor, colleague, critic, editor, and above all, a good friend. I have learned much from him, only a small portion of it is reflected in these pages. I am a better researcher, writer, and more importantly, a better person because of him.

Lastly, I need to thank my family. My sister, Jennifer, and her husband Kem, have been loving and supportive and have brought great joy into my life in the form of Hayden Christopher Morris. I want to thank my dear Libby, who is supremely understanding and thoughtful. I could not ask for a better person to be in my life. Lastly, I want to acknowledge my parents, Dr. Bob and Shirley. They have always supported me and given me all the benefits and more than any child deserves. They have provided me with unconditional love and given me purpose. My dad has been the greatest role model a son could have. It is to them I dedicate this work.

> "Afoot and light-hearted I take to the open road, Healthy, free, the world before me, The long brown path before me leading wherever I choose"

> > - Walt Whitman, Song of the Open Road

TABLE OF CONTENTS

	Page
ACKNOWLE	DGMENTSv
LIST OF TAE	BLES ix
LIST OF FIG	URES x
CHAPTER	
1	INTRODUCTION1
	LITERATURE CITED7
2	LITERATURE REVIEW AND CHAPTER ORGANIZATION
	STRIPED BASS LIFE HISTORY
	A HISTORY OF POPULATION DECLINES
	STRIPED BASS IN GEORGIA17
	CHAPTER ORGANIZATION
	LITERATURE CITED
3	DECLINE AND RECOVERY OF STRIPED BASS, MORONE SAXATILIS,
	IN THE SAVANNAH RIVER ESTUARY, GEORGIA - SOUTH
	CAROLINA
	INTRODUCTION
	POPULATION DECLINE
	TIDE GATE INFLUENCES
	MITIGATION AND MONITORING

	NEW INVESTIGATIONS42
	CONCLUSIONS44
	FUTURE CONCERNS46
	LITERATURE CITED47
4	ESTIMATING HISTORIC STRIPED BASS MORONE SAXATILIS
	REPRODUCTIVE EFFORT IN THE SAVANNAH RIVER ESTUARY,
	GEORGIA-SOUTH CAROLINA
	INTRODUCTION
	METHODS
	RESULTS
	DISCUSSION65
	LITERATURE CITED69
5	MODELING THE EFFECTS OF HARBOR DEEPENING ALTERNATIVES
	ON THE RECOVERY OF STRIPED BASS IN THE SAVANNAH RIVER
	ESTUARY, GEORGIA-SOUTH CAROLINA, U.S.A
	INTRODUCTION
	METHODS82
	RESULTS
	DISCUSSION90
	LITERATURE CITED95
6	CONCLUSIONS
	LITERATURE CITED

LIST OF TABLES

Page
Table 3-1. Numbers of striped bass stocked into the Savannah River Estuary, 1990-
2003
Table 4-1. Releases and captures of striped bass egg surrogates (gellan beads) in the
Savannah River Estuary, 1999-2000
Table 4-2. Estimated sampling efficiency at the historic egg sampling station in the
Back River, Savannah River Estuary, 1999-2000
Table 4-3. Estimated egg abundance at the Front River and Back River reference
stations of the Savannah River Estuary, 1978-2000
Table 5-1. Selected distribution and associated scale and shape parameters
Table 5-2. Multinomial logit model of striped bass egg abundance by river kilometer
versus river discharge in the Savannah River Estuary during sampling seasons
1990-91, 1994-2000
Table 5-3. Example of conditional survival probabilities for striped bass larvae in the
Savannah River Estuary based on estimated salinity levels
Table 5-4. Categorical model parameters, prior probability used in model process, and
source/rationale of how each was selected for root nodes in the Bayesian belief
network

LIST OF FIGURES

	P	age
Figure 1-1.	1816 map of the lower Savannah River, Georgia	9
Figure 1-2	1855 map of the Savannah River, Georgia	10

Figure 1-2. 1855 map of the Savannah River, Georgia	10
Figure 1-3. 1901 map of the city of Savannah, Chatham County and the Savannah	
River, Georgia	11
Figure 1-4. Map of Savannah River Estuary, Georgia-South Carolina, showing major	
highways, tide gate, diversion canal, and Savannah National Wildlife Refuge	12
Figure 3-1. Map of Savannah River Estuary, Georgia-South Carolina, showing major	
highways, tide gate, diversion canal, and Savannah National Wildlife Refuge	53
Figure 3-2. Catch-per-unit effort of adult striped bass in the Savannah River Estuary,	
Georgia-South Carolina, 1977-2003.	54
Figure 3-3. Striped bass egg density in the Savannah River Estuary, Georgia-South	
Carolina	55
Figure 3-4. Salinity levels in the Back River, Savannah River Estuary, Georgia-South	
Carolina, 1990-1991	56
Figure 3-5. Catch per unit effort of sub-adult striped bass in the Savannah River	
Estuary, Georgia-South Carolina, 1990-2003	57
Figure 4-1. Map of the Savannah River Estuary including Front, Middle, and Back river	
channels, major highways, tide gate, and diversion canal	75

Figure 4-2	. Estimated striped bass egg abundance in the Savannah River Estuary,
1978	-2000
Figure 4-3	. Historic egg densities in the Savannah River Estuary, 1978-200077
Figure 5-1	. Map of Savannah River Estuary, Georgia-South Carolina, showing
main	tained river channel, major highways, tide gate, and diversion canal $\ldots \ldots 105$
Figure 5-2	. Influence diagram representing how deepening options for the Savannah
Harb	or may affect striped bass recruitment potential
Figure 5-3	. Examples of statistical distributions fit to salinity data collected in the
Sava	nnah River Estuary, Georgia-South Carolina, 1997 and 1999
Figure 5-4	. Percent of striped bass eggs captured by river kilometer in the Front River,
Sava	nnah River Estuary, 1994-2000
Figure 5-5	. Bayesian Belief Network depicting joint probability distribution of salinity-
base	d survival of striped bass eggs and larvae and predicted egg distribution in
the S	Savannah River Estuary
Figure 5-6	5. Estimated relative change in striped bass recruitment potential
Figure 5-7	. Tornado diagram for one-way sensitivity analysis with model components
liste	d from greatest to least influential for the Savannah Harbor deepening
scen	arios
Figure 5-8	. Response profile of striped bass recruitment potential with proportion of
strip	ed bass egg occurrence

CHAPTER 1

INTRODUCTION

Since its founding in 1733 by General James Edward Oglethorpe, the city of Savannah has been intimately tied to the river and the commerce associated with it. Oglethorpe describes the site (from Harden 1913):

I fixed upon a healthy situation about ten miles from the sea. The river here forms a half moon, along the South side of which the Banks are about forty foot high; and upon the top a Flat, which they call a Bluff...Ships that draw 12 foot water can ride within ten yards of the Bank...The River is pretty wide, the water fresh, and from the key of the town you see its whole course to the sea...and the other way you see the River for about six miles up into the country...the stream being wide, and bordered with high woods on both sides. The river has played an integral part in the history of Savannah, from its colonial founding to the present day (Granger 1968). The inland river bluff provided protection from hurricanes as well as enemies, the river mouth formed a natural harbor protected by 2 islands (Tybee and Cockspur; Figure 1-1), and the river, being navigable to the eventual trading center that would become Augusta (river kilometer [rkm] 312), was an avenue for commerce. As Oglethorpe noted, the water was fresh, which was desirable for reducing ship fouling by marine organisms. Freshwater apparently extended well downstream to Long Island (approximately rkm 6; Granger 1968; see Figure 1-1). Additional indications of the freshwater character of the river in the vicinity of the city are given by Francis Moore in, A Voyage to Georgia, begun in the year 1735" (as reprinted in Harden 1913). He describes Hutchinson s Island (directly across from Savannah) as partly open pasture with the remainder, woods in which there are many bay trees eighty foot high. Moore likely is referring to magnolia trees (probably southern magnolia *Magnolia grandiflora* but possibly sweetbay *M. virginiana* or bay loblolly *Gordonia lasianthus*), a fairly common component of southeastern bottom land habitats that are moisture but not very salt tolerant (B. Bongarten, University of Georgia, personal communication). Today, the area around Hutchinson s Island is primarily brackish and saltwater marsh (Pearlstine et al. 1993) and the bottomland forest has receded upstream several miles (personal observation).

Maintaining a channel of adequate depth for contemporary shipping needs has been a primary goal for the city. The river history is mainly a chronological detailing of hydraulic works in the harbor and lower river, from the early primitive operations of removing sunken vessels...to building jetties and retaining walls and designing cuts and fills to improve navigation (Granger 1968, p. 6-7). In the early 1800s, soundings in the river channel rarely exceeded 20 feet (6 m; Figure 1-1), but problems of shoaling were recognized, particularly at the tip of Fig Island, an area known as The Wrecks (where ships were often scuttled during times of war to create obstructions and protect the city from invaders). At that time, the Savannah River flowed primarily into the Back River at an area known as the Cross Tides (Figure 1-2). Because of the greater flow, the Back River was as much as 3.4 m deeper than the channel in front of the city. The problems of preventing the *waste* of needed water for Front River by allowing its flow in the

unused Back River...became an important problem, (Granger 1968, p. 1; emphasis added). Plans to close Cross Tides and shunt most if not all water to the city harbor began in the early 19th century, but closure was not completed until the 1870s. Increased flow to the harbor area would help with shoaling problems along the channel, particularly at The Wrecks. However, during the Civil War, both intentional and unintentional ship sinking occurred, creating additional obstructions in the river channel (Granger 1968).

Historically, the river was fresh, but continual modifications allowed gradual saltwater intrusion into the estuary. In 1875, records indicate that the river was entirely fresh (surface to bottom) at a point off Elba Island (about rkm 15), but that at rkm 13, the saltwater wedge (where fresh river water mixes with saline ocean water) could be detected. At that time, channel depth was about 3.8 m mean low water (MLW: Granger 1968). Channel maintenance and restructuring continued, and by the turn of the twentieth century, the channel had been dredged to 7.9 m MLW (Figure 1-3). By the late 1960s, harbor depth was 11.6 m MLW and the salt wedge had reached the city of Savannah (rkm 24; Rees 1972). In addition, shoaling of sediments in the harbor area continued to be a problem. In 1977, a tide gate went into operation on the Back River in conjunction with a diversion canal connecting the Back, Middle, and Front rivers (Figure 1-4). Flood tides were captured by the tide gate and forced through the diversion canal during ebb flow. The increased flow of water that would otherwise be wasted in the unused Back River, with a lower sediment load, would flush the inner harbor, thus reducing the need for continual maintenance dredging and helping to keep shipping berths free from excess sand and silt. The most recent alteration was a 1.2 m

deepening in 1993-1994, which created a channel depth of 12.8 m MLW up to rkm 32 (Figure 1-4). Currently, the saltwater wedge typically is located above rkm 30. Efforts to further improve Savannah Harbor for perceived shipping needs continue. In 1996, the Georgia Ports Authority (GPA) began sponsoring studies to evaluate deepening the 12.8 m channel by up to 2 m.

Prior to the advent of federal environmental protection legislation (National Environmental Policy Act of 1969, Clean Water Act of 1972, Endangered Species Act of 1973, among others), impacts to the natural environment and the plants and animals that occurred there often were not thoroughly considered when implementing major changes such as harbor deepening. Increases in estuarine salinity, primarily because of harbor modifications such as the tide gate and diversion canal, are thought to be the primary causes of the decline of the Savannah striped bass (Morone saxatilis) population (Van Den Avyle and Maynard 1994). The possible environmental consequences of a deeper harbor are to further increase salinity in the upper estuary, decrease dissolved oxygen at depth, and increase flushing rates in the lower estuary. All of these potential effects may severely affect natural resources, including tidalfreshwater marsh plant communities, the endangered shortnose sturgeon (Acipenser *brevirostrum*), and the now presumably recovering striped bass population. Because of these concerns, GPA also is sponsoring environmental impact assessments focusing on natural resources and, in particular, the potential impact of deepening on the salinity distribution within the Savannah River Estuary (SRE).

The striped bass population in the SRE is of special concern for a variety of reasons. They are an important component of estuarine communities along the Atlantic

Coast (Setzler et al. 1980) and once provided an important recreational fishery in Georgia. Additionally, striped bass from the Savannah and neighboring Ogeechee River are genetically distinct from striped bass in other South Atlantic rivers (I. Wirgin, New York University Medical Center, personal communication), and their eggs have unique characteristics making them especially suited to the SRE (Bergery et al. 2003). Coincident with the loss of spawning and nursery habitat for striped bass was a reduction in the tidal freshwater marsh community in the Savannah National Wildlife Refuge, a 10725 ha tract of coastal riverine and wetland habitats (Brown et al. 1987; see Figure 1-4). Concern for these resources prompted habitat and striped bass restoration efforts. The striped bass fishery was closed in 1988, the striped bass stockenhancement program began in 1990, the tide gate was decommissioned in 1991, and the diversion can al was filled in 1992 (see Figure 1-4).

With this dissertation project, I will present an in-depth examination of the recent history of striped bass in the SRE, evaluate population and habitat restoration efforts to date, and model the recruitment potential of this endemic, economially-important species. This analysis will include a case-history synthesis of striped bass restoration efforts in the SRE to date, chronicling the stocking program, habitat restoration efforts, and monitoring program. I will also provide estimates of historical spawning activity in the SRE using recently developed models derived from egg surrogates. This analysis will re-evaluate past conclusions about the importance of Front and Back river spawning locations. I will then present the development of a probability-based decisionanalysis network for evaluating the future success of striped bass restoration efforts in light of potentially competing harbor development goals. Hopefully, these efforts will

result in a picture of what was, what is, and what may yet be for the striped bass of the Savannah River Estuary.

LITERATURE CITED

- Bergey, L. L., R. A. Rulifson, M. L. Gallagher, and A. S. Overton. 2003. Variability of Atlantic Coast striped bass egg characteristics. North American Journal of Fisheries Management 23:558-572.
- Brown, J. D., E. M. EuDaly, and J. P. Davis. 1987. An innovative analysis of port development impacts on a coastal National Wildlife Refuge. In: Coastal Zone 87:
 Proceedings of the Fifth Symposium on Coastal and Ocean Management, O. T. Magoon, H. Converse, D. Miner, and L. T. Tobin, eds. American Society of Civil Engineers, New York.
- Granger, M. L. 1968. Savannah Harbor: its origin and development, 1733 1890. U.S. Army Corps of Engineers, Savannah District, Savannah, Georgia.
- Harden, W. 1913. A History of Savannah and South Georgia, Volume 1. Lewis Publishing Company, Chicago.
- Pearlstine, L. G., W. M. Kitchens, P. J. Latham, and R. D. Bartleson. 1993. Tide gate influences on a tidal marsh. Water Resources Bulletin 29: 1009-1019.
- Rees, R. A. 1972. A survey of the aquatic organism populations of the Savannah andOgeechee river estuaries and their relationship in the diet of the striped bass,*Morone saxatilis*, (Walbaum). Masters thesis, University of Georgia, Athens.
- Setzler, E. M., W. R., Boynton, K. V. Wood, H. H. Zion, L. Lubbers, N. K. Mountford, P.
 Frere, L. Tucker, and J. A. Mihursky. 1980. Synopsis of biological data on striped bass, *Morone saxatilis* (Walbaum). National Oceanic and Atmospheric
 Administration, Technical Report, National Marine Fisheries Service Circular 433:
 Food and Agriculture Organization Synopsis No. 121.

Van Den Avyle, M. J. and M. A. Maynard. 1994. Effects of saltwater intrusion and flow diversion on reproductive success of striped bass in the Savannah River estuary.
 Transactions of the American Fisheries Society 123:886-903.



Figure 1-1. 1816 map of the lower Savannah River, Georgia. Note, map is south-top oriented. Soundings are in feet. Hogh s Island is the current Elba Island. Source: Hargrett Rare Book and Manuscript Library, University of Georgia (http://www.libs.uga.edu/darchive/hargrett/maps/maps.html).



Figure 1-2. 1855 map of the Savannah River, Georgia. The area known as Cross Tides is the river channel between Hutchinson s Island (directly across from the city of Savannah) and Argyle Island, upstream. Source: Hargrett Rare Book and Manuscript Library, University of Georgia

(http://www.libs.uga.edu/darchive/hargrett/maps/maps.html).



Figure 1-3. 1901 map of the city of Savannah, Chatham County and the Savannah River, Georgia. Note, map is south-top oriented. Text from map reads, Navigable channel of the Savannah River with depth of 26 feet of water to the city (26 feet = 7.9 m). The Cross-Tides channel (between Hutchinson's and Argyle islands) is now blocked. Source: Hargrett Rare Book and Manuscript Library, University of Georgia (http://www.libs.uga.edu/darchive/hargrett/maps/maps.html).



Figure 1-4. Current map of Savannah River Estuary, Georgia-South Carolina, showing major highways, tide gate, diversion canal, and Savannah National Wildlife Refuge (shaded area). Front River maintained channel depth of 12.8 m mean low water extends up to river kilometer 32.

CHAPTER 2

LITERATURE REVIEW AND CHAPTER ORGANIZATION

STRIPED BASS LIFE HISTORY

Striped bass *Morone saxatilis* are large bony fish of the order Perciformes, family Moronidae, native to the Atlantic and Gulf coasts of North America. Populations are known from the St. Lawrence River, Quebec, to the St. John's River, Florida, and along the northern Gulf Coast from Florida as far west as Louisiana (Setzler et al. 1980). The Gulf and Atlantic stocks are genetically distinct, and stocks within the Atlantic population also are genetically and meristically distinguishable (Setzler et al. 1980; Hill et al. 1989; Wirgin et al. 1989; Wirgin et al. 1991). Striped bass have been stocked extensively in freshwater impoundments across the country and along the Pacific Coast. In the late 1800s, about 400 individuals from New Jersey were introduced into the San Francisco Bay. Since then, those individuals have established a population along the Pacific Coast from Ensenada, Mexico, to British Columbia (Setzler et al. 1980, Waldman et al. 1997).

Striped bass typically are anadromous and spawn in fresh or nearly fresh waters during the spring, usually when water temperatures are between 18-21 C (range: 12-24 C; Hill et al. 1989). Larvae feed on zooplankton, and juveniles consume small shrimps and other crustaceans, worms, and insects (Boynton et al. 1981; Cooper et al. 1998; Limburg et al. 1999). Adults tend to be piscivorous but are known to consume invertebrates as well, particularly blue crab *Callinectes sapidus* (Setzler et al. 1980; Tupper and Able 2000). Adults may live over 20 years, but most over age 11 are females. Striped bass reach large sizes (20-30 kg fish are not uncommon) and typically are the top predator in systems where they occur (Koo 1970; Setzler et al. 1980). The largest recorded striped bass weighed about 57 kg and was captured in North Carolina waters in 1891 (Setzler et al. 1980).

Striped bass stock dynamics vary across their native and introduced ranges. Populations from the Roanoke River, Chesapeake Bay, Delaware River, and Hudson River form a panmictic metapopulation along the north Atlantic Coast of the United States (Koo 1970). Coastal migrations occur in the spring and summer with adults moving in a northerly direction before returning to natal rivers in the fall and winter (Setzler et al. 1980). Although this metapopulation consists primarily of the aforementioned stocks (Bielawski and Pumo 1997), there is some evidence of limited contribution from Canadian stocks (Wirgin et al. 1993). In contrast, stocks from the Gulf of Mexico and those south of the Roanoke River are primarily riverine, rarely venturing into the open ocean (Hill et al. 1989). The introduced population along the Pacific Coast may have isolated into riverine stocks and there is some evidence of genetic differentiation (Waldman et al. 1997). Additionally, inland reservoir stockings have resulted in self-sustaining populations in several cases, the first and most well documented of which is the Santee-Cooper population in South Carolina (Surber 1957; Bulak et al. 1997).

A HISTORY OF POPULATION DECLINES

Striped bass have been of great importance to North Americans since colonists first settled North America and likely were of equal importance to indigenous peoples prior to first contact. Indeed, early contact between wary Native Americans and colonists often was facilitated by trading striped bass for brisket (Prince 1736). Histories of New England are replete with descriptions of the multitudes in which striped bass were captured, and yet, early colonists understood that the resource was in need of protection. In 1639, a Boston court decreed that utilizing cod or striped bass for composting was illegal (Fearing 1903).

Historically, striped bass have approached the importance of codfish to American fisheries (Alperin 1987). Commercial and recreational fisheries developed along the Atlantic and Pacific coasts and flourished through much of the twentieth century. In the early 1970s, commercial catch in Maryland peaked at 2268 t, but annual catch had declined to just over 200 t by 1983 (Setzler-Hamilton et al. 1988). The decline occurred across the Chesapeake Bay population and eventually prompted a complete moratorium on capture in an effort to save the most important fishery of the Chesapeake Bay. A striped bass Fishery Management Plan was implemented to protect remaining fish and prompt recovery. Compliance across all states from North Carolina to New England was assured through passage of the 1984 Atlantic Striped Bass Conservation Act (16 U.S.C. 1851). Although primarily blamed on overfishing, water quality effects were likely contributors to the decline as well (Goodyear et al. 1985; Price et al. 1985). Increasing eutrophication in upper bay areas reduced

submerged aquatic vegetation cover and decreased oxygen levels, particularly during the warm summer months (Coutant 1985; Coutant and Benson 1990).

Over the last 30 years and for varied reasons, many other striped bass stocks rangewide have suffered population declines as well. Stock reduction in the Delaware River were attributed to excessive pollution (Chittenden Jr. 1971). The Sacramento-San Joaquin population began to decline in the late 1970s, primarily because of water withdrawals and diversions and possibly contaminants (Stevens et al. 1985; Saiki and Palawski 1990). Few data exist for Canadian populations, but those stocks probably have been affected by overfishing and hydrologic alterations (e.g., St. Lawrence Seaway construction) since the 1950s (Rulifson and Dadswell 1995). In the 1970s, Roanoke River striped bass were affected by inadequate instream flows, which affected spawning habitat (Rulifson and Manooch 1990; Zincone Jr. and Rulifson 1991). All of the stocks described above supported large commercial fisheries at one time, and the Chesapeake Bay is once again supporting commercial harvest (Richards and Rago 1999). Smaller, riverine stocks south of the Roanoke River and along the Gulf Coast typically have only supported recreational fisheries. As such, few published reports exist on population levels for these stocks.

With increasing understanding of the importance of biodiversity and genetic diversity within populations, striped bass in the Gulf of Mexico and south Atlantic are of particular interest. Genetics of the Gulf Coast strain have been examined repeatedly, and researchers have found that the genotype may be in danger of introgression from introduced Atlantic Coast fish (Dunham et al. 1988; Wirgin et al. 1989; Wirgin et al. 1997). Because striped bass south of the Roanoke River tend to be

riverine and endemic to their natal rivers, these stocks may have been isolated long enough to develop distinct genotypes. Some of these stocks, most notably that of the Santee-Cooper system, have been genetically distinguished (Dunham et al. 1988; Wirgin et al. 1989). The population in the Savannah/Ogeechee rivers of Georgia is genetically distinguishable from that of the neighboring Santee/Congaree coastal drainage in South Carolina (I. Wirgin, New York University Medical Center, personal communication).

STRIPED BASS IN GEORGIA

In Georgia, large runs of Atlantic Coast striped bass were common in the Savannah, Ogeechee, and Altamaha rivers until the 1960s (Whaley et al. 1969). These runs, however, have only occasionally supported commercial exploitation; peak production (5900 kg) occurred in 1889 (Rulifson et al. 1982). As is common throughout their range, striped bass and striped bass hybrids (crossed with white bass, *M. chrysops*) provide highly popular recreational fisheries along these rivers and in Georgia s inland reservoirs. This popularity may be responsible for the population reductions seen in Georgia s coastal rivers, as Georgia anglers landed a reported 2700 kg of striped bass in 1973 (Hill et al. 1989). Despite smaller runs in the 1970s, striped bass fishing in Georgia remained popular. Recently, *Morone* fisheries accounted for a significant portion of the \$1.2 billion in annual angler expenditures in Georgia (U.S. DOI 1998; Carl Hall, Georgia Department of Natural Resources [GA-DNR], personal communication). Historically, the Savannah River hosted Georgia s most important striped bass fishery and became the source of brood fish for the GA-DNR *Morone* stocking program.

Research efforts investigating the status of striped bass in the Savannah River Estuary (SRE) intensified in the late 1970s. In 1977, research was initiated that examined striped bass reproductive output in the SRE in anticipation of the operation of a tide gate (Dudley and Black 1978). The tide gate s primary purpose was to alter flow patterns in the lower estuary to flush depositional sediments from harbor berths and reduce maintenance dredging costs. However, the primary spawning ground for Savannah River striped bass was found to be 33-40 km from the Atlantic Ocean in the Back River, in the midst of the Savannah National Wildlife Refuge, and just upstream of the tide gate. Results from the 1978 spawning season (the first year of tide gate operation) indicated that increased salinity in spawning areas potentially affected striped bass spawning and egg and larval survival. Despite these results, the tide gate was effective at its intended purpose and continued to operate.

In 1984, striped bass spawning patterns remained unchanged, although the amount of eggs captured in the SRE was considerably reduced (Larson 1985). In 1986, a more detailed investigation began to examine spawning success and pathways of egg and larval transport. In 1989, survival of eggs and larvae in various salinities was examined. These efforts resulted in two of the most recent publications (Van Den Avyle and Maynard 1994; Winger and Lasier 1994) detailing the status of the striped bass population in the SRE but only presented data collected through 1989. These studies indicated that striped bass spawning had declined to extraordinarily low levels and eggs that were spawned were transported quickly to areas of harmful or lethal salinity. Tide

gate operation was implicated as the cause of increased salinity in the previously freshwater spawning grounds and subsequent decline of the striped bass population (Van Den Avyle et al. 1990). Historic spawning grounds became unsuitable through increases in salinity, and spawning either ceased or moved upriver. Different flow patterns transported spawned eggs to the industrial harbor and regions of toxic and lethal salinity. These conclusions were responsible, in part, for the decommissioning of the tide gate in 1991 and the filling of the diversion canal in 1992.

In response to the declining striped bass population, the states of Georgia and South Carolina adopted a fishing moratorium (in 1988 and 1991, respectively) to protect remaining adult fish. In 1990, GA-DNR adopted a management objective of re-establishing a self-sustaining striped bass population in the SRE through stock enhancement. The river that once supplied broodstock for state-wide *Morone* stocking efforts was to become the recipient of hatchery-reared fish in an effort to restore the population. To date, the program has stocked over 1.5 million fish in the SRE (Wallin and Van Den Avyle 1995b; GA-DNR, unpublished data).

Since 1990, monitoring efforts have focused on the adult population and egg production. Within the last several years, annual electrofishing surveys have shown an apparent increase in the number of fish greater than 9.0 kg (those fish capable of spawning large clutches of eggs), and catch-per-unit-effort for ages 2+ is near levels seen prior to the decline. Currently, stocked fish constitute a majority (>80%) of the population, which demonstrates the success of the stocking program but also a continued lack of natural recruitment (GA-DNR, unpublished data). Additionally, egg production remains well below that of historic levels (Will et al. 2000).

To evaluate the success of striped bass restoration efforts in the SRE and to predict the potential for further recovery, I have organized this dissertation into 3 research chapters to be submitted as separate publications. The first chapter examines the history of restoration efforts in the SRE and chronicles the results of stock enhancement. The second chapter uses models recently developed to predict historic annual egg production and re-examines previously held assumptions about where striped bass primarily spawned in the SRE. The third chapter employs a decisionanalysis approach to evaluate the potential effect harbor deepening may have on future striped bass recruitment. These chapters are more thoroughly explained in the following section.

CHAPTER ORGANIZATION

<u>Chapter 3: Decline and recovery of striped bass, Morone saxatilis, in the Savannah</u> <u>River Estuary, Georgia-South Carolina</u>

Much time, effort, and money have been dedicated to striped bass issues in the SRE since the early 1980s. Studies on why the population declined and how to restore it to a self-sustaining level have resulted in three master's theses (Larson 1985; Hendrickx Jr. 1996, Sinclair Jr.1996), several final reports (e.g., Van Den Avyle 1990; Wallin and Van Den Avyle 1995a, 1995b; Reinert et al. 1996, 1998a; Will et al. 2000, 2001), and several manuscripts (e.g.; Van Den Avyle and Maynard 1994; Winger and Lasier 1994; Wallin and Van Den Avyle 1995c; Reinert et al. 1998b; Van Den Avyle and Wallin 2001; Will et al. 2002). These reports and publications generally are limited in temporal scale or address specific issues within the overall goal of striped bass

restoration. The most recent comprehensive study of the Savannah River striped bass population is presented in Van Den Avyle and Maynard (1994) and only includes research results through 1989. An overall examination of the stock enhancement program, restoration efforts to date, and evaluation of the current status of the striped bass population in the SRE is necessary.

The time-line of striped bass research in the SRE may be divided into two phases: pre-1990 and post-1990. I chose 1990 as the watershed year because it marked the inception of the state-sponsored stock enhancement program and the conclusion of a U.S. Fish and Wildlife-sponsored study implicating tide gate operation in the decline of the striped bass population (Van Den Avyle et al. 1990). Research prior to 1990 focused on the environmental effects of the tide gate and on determining the cause(s) of striped bass decline. Research post-1990 primarily has been concerned with evaluating and improving the stock-enhancement program and monitoring egg and adult abundances in the SRE. These investigations have addressed a variety of topics central to the issue of striped bass restoration and have resulted in a few publications in the peer-reviewed literature, primarily dealing with selection of stocking sites (W allin and Van Den Avyle 1995c) and tag retention (W allin and Van Den Avyle 1994; Reinert et al. 1998b; Van Den Avyle and Wallin 2001).

The information available for a synthesis of striped bass restoration efforts in the SRE is comprised of the aforementioned publications and reports as well as unpublished data collected by the GA-DNR. This chapter will chronicle the history of the decline, restoration stocking efforts, monitoring programs (both for eggs and adults), and environmental restoration assessments. The objective of this chapter is to

synthesize the many disparate elements that have comprised striped bass research in the SRE over the last two decades and synthesize them into a thorough case-history with current stock status and an identification of future research needs and priorities. This chapter will address the need for a summary of SRE striped bass recovery by synthesizing published and unpublished material to provide an overview of what has happened to the SRE striped bass and what is being done to restore it to a self-sustaining level.

<u>Chapter 4: Estimating historic striped bass (Morone saxatilis) reproductive effort in the</u> <u>Savannah River Estuary, Georgia-South Carolina</u>

The primary goal of the GA-DNR stock enhancement program has been to re-establish the striped bass population in the Savannah River. Stocking has been successful at increasing the number of individuals in the population, but the restoration of a self-sustaining population is still in question. One method used to assess the recovery of striped bass in the SRE has been sampling for eggs during the striped bass spawning season. Standardized egg sampling in the SRE began in 1986 and has occurred intermittently since that time (Van Den Avyle et al. 1990; Wallin and Van Den Avyle 1995a; Reinert et al. 1996, 1998a; Will et al. 2000). Results from past egg sampling efforts have allowed only relative comparisons: egg densities (#/100 m³) at each station and during the entire sampling season could be compared and evaluated based on previous years results, however this index was predicated on the assumption that sampling efficiency was equal in all reaches of the SRE. Using CPUE as an index of reproductive effort, the Back River was assumed to be the primary spawning ground for striped bass. Thus, the Back River was considered the most critical area for habitat

recovery, potentially at the expense of other areas in the SRE (namely the industrial harbor). Use of gellan beads as egg surrogates has uncovered biases in these conclusions related to differences in river channel morphology and hydrology. These biases developed because estimates of sampling efficiency for the egg sampling gear had not been established. Assumptions of egg sampling included equal probability of capture in all areas of the river during all flows. Use of egg surrogates has shown these assumptions to be false.

Sampling efficiency is highest in the Back River. The Back River is narrower and shallower than the Front River; the egg sampling gear samples a greater proportion of the water column in the Back River than in the Front River and apparently captures more eggs (or beads) per unit volume. Additionally, these studies have demonstrated previously unsuspected pathways of egg distribution in the SRE. Eggs spawned in the Front River do not necessarily remain there, and the same is true for eggs spawned in the upper reaches of the Back River. Because of the biases associated with differing sampling efficiencies in the estuary and the alternative egg distribution pathways, researchers may have underestimated the importance of spawning levels in the Front River. In this chapter, I will use the relationships developed by use of gellan beads as egg surrogates to estimate sampling efficiency at two historically productive sampling stations (one station each in the Front and Back rivers). These adjusted sampling efficiencies will be used as a more accurate index of striped bass reproductive effort that has taken place in the SRE as far back as 1978.
<u>Chapter 5: Modeling the impacts of harbor deepening alternatives on the recovery of</u> Savannah River striped bass

Currently, the Georgia Ports Authority (GPA) is pursuing a harbor deepening of up to 2 m (from the current mean low-water depth of 12.8 m). Natural resource agencies have expressed concern over the potential consequences of such an endeavor, and GPA has initiated studies to address those concerns. GPA is modeling the potential changes in hydrology and water quality that may be associated with the various deepening alternatives. Restoration of a self-sustaining population of striped bass may be confounded by a deeper harbor that allows increased saltwater intrusion into spawning and rearing habitats in the Front and possibly Back rivers.

One method of modeling the potential conflict between spawning success of striped bass and increased salinity in the SRE is to use a Bayesian probability network (Reckhow 1999; Varis and Kuikka 1999). 'Bayes nets' are based on graphical models that display functional dependencies within the system of interest. Next, data and expert opinion are used to assign probabilities for the dependence linkages (e.g., salinity at a particular site in the estuary primarily is dependent upon tidal stage and river discharge). Predictions from Bayes nets are probabilistic (rather than point estimates with confidence intervals, common in traditional statistical modeling) and explicitly incorporate uncertainty, which facilitates computation and explanation (Reckhow 1999). The graphical representation allows more intuitive model construction and is easier to explain to managers and decision makers. The process is stochastic and allows multiple interpretations of probabilities to be incorporated and compared (Haas et al. 2000). Because uncertainty is expressed probabilistically and outcomes

are expressed as discrete levels (e.g., p[salinity >9 ppt = 0.35] or a 35% chance that salinity will be > 9 ppt), results are more meaningful and applicable for decision makers and managers.

Survival of striped bass eggs and larvae in the SRE will be modeled with a Bayes net framework. Using historical information on river discharge, tidal phase, spawning times and locations, and transport processes of eggs, the survival probability of eggs will be calculated for possible outcomes of harbor deepening. Because the model will be based on a salinity shift, and not a specific deepening option, evaluation of various deepening and mitigation scenarios will be possible. Once the environmental modeling has been completed, predicted shifts in the salinity regime may be evaluated using the decision-model developed here. Potentially, a deepening alternative that either does not affect or affects only a small percentage of striped bass eggs can be identified.

LITERATURE CITED

- Alperin, I. M. 1987. Management of migratory Atlantic Coast striped bass: an historical perspective, 1938-1986. Fisheries 12:2-3.
- Bielawski, J. P. and D. E. Pumo. 1997. Randomly amplified polymorphic DNA (RAPD) analysis of Atlantic coast striped bass. Heredity 78:32-40.
- Boynton, W. R., T. T. Polgar, and H. H. Zion. 1981. Importance of juvenile striped bass food habits in the Potomac Estuary. Transactions of the American Fisheries Society 110:56-63.
- Bulak, J. S., J. S. Crane, D. H. Secor, and J. M. Dean. 1997. Recruitment dynamics of striped bass in the Santee-Cooper system, South Carolina. Transactions of the American Fisheries Society 126: 133-143.
- Chittenden, M. E. Jr. 1971. Status of striped bass, *Morone saxatilis*, in the Delaware River. Chesapeake Science 12:131-136.
- Cooper, J. E., R. A. Rulifson, J. J. Isely, and S. E. Winslow. 1998. Food habits and growth of juvenile striped bass, *Morone saxatilis*, in Albemarle Sound, North Carolina. Estuaries 21:307-317.
- Coutant, C. C. 1985. Striped bass, temperature, and dissolved oxygen: a speculative hypothesis for environmental risk. Transactions of the American Fisheries Society 114:31-61.
- Coutant, C. C. and D. L. Benson. 1990. Summer habitat suitability for striped bass in Chesapeake Bay: reflections on a population decline. Transactions of the American Fisheries Society 119:757-778.

- Dudley, R. G. and K. N. Black. 1978. Distribution of striped bass eggs and larvae in the Savannah River estuary. Proceedings of the Annual Conference Southeastern Association of Fish and Wildlife Agencies 32:561-570.
- Dunham, R. A., R. O. Smitherman, R. W. Chapman, T. Hess, and C. Mesing. 1988.
 Mitochondrial DNA polymorphism of striped bass in the southeastern United
 States. Proceedings of the Annual Conference Southeastern Association of Fish
 and Wildlife Agencies 42:21-26.
- Fearing, D. B. 1903. Some early notes on striped bass. Transactions of the American Fisheries Society 32:90-108.
- Goodyear, C. P., J. E. Cohen, and S. W. Christensen. 1985. Maryland striped bass: recruitment declining below replacement. Transactions of the American Fisheries Society 114:146-151.
- Haas, T. C., D. C. Lee, and J. T. Peterson. 2000. An introduction to decision analysis for natural resources management. American Fisheries Society Continuing Education
 Workshop. August 20, 2000, St. Louis, MO.
- Hendrickx, E. J. Jr. 1996. Physiological stress in cultured striped bass: quantifying the effects of routine handling and stocking procedures. Master's thesis. University of Georgia, Athens.
- Hill, J., J. W. Evans, and M. J. Van Den Avyle. 1989. Species profiles: Life histories and environmental requirements of coastal fishes and invertebrates (South Atlantic)-Striped Bass. U.S. Fish and Wildlife Service Biological Report 82(11.118):35.
- Koo, T. S. Y. 1970. The striped bass fisheries in the Atlantic states. Chesapeake Science 11:73-93.

- Larson, S. C. 1985. The distribution and abundance of striped bass eggs in the lower Savannah River. Master's thesis. University of Georgia, Athens.
- Limburg, K. E., M. L. Pace, and K. K. Arend. 1999. Growth, mortality, and recruitment of larval *Morone* spp. in relation to food availability and temperature in the Hudson River. Fishery Bulletin 97:80-91.
- Price, K. S., D. A. Flemer, J. L. Taft, G. B. Mackiernan, W. Nehlsen, R. B. Biggs, N. H. Burger, and D. A. Blaylock. 1985. Nutrient enhancement of Chesapeake Bay and its impact on the habitat of striped bass: a speculative hypothesis. Transactions of the American Fisheries Society114:97-106.
- Prince, T. 1736. A chronological history of New-England in the form of annals. S. Gerrish, Boston. Microfilm. Ann Arbor, Michigan, University Microfilms 1 reel. 35 mm. American Culture Series, Reel 11.122.
- Reckhow, K. H. 1999. Water quality prediction and probability network models. Canadian Journal of Fisheries and Aquatic Sciences 56:1150-1158.
- Reinert, T. R., K. L. Jefferson, and C. A. Jennings. 1998a. Abundance and distribution of striped bass eggs and larvae in the Savannah River Estuary - Implications for channel dredging window. Final Report, U.S. Army Corps of Engineers Savannah District, Savannah, Georgia.
- Reinert, T. R., J. Wallin, M. C. Griffin, M. J. Conroy, and M. J. Van Den Avyle. 1998b.
 Long-term retention and detection of oxytetracycline marks applied to
 hatchery-reared larval striped bass, *Morone saxatilis*. Canadian Journal of
 Fisheries and Aquatic Sciences 55:539-543.

- Reinert, T. R., J. Wallin, and M. J. Van Den Avyle. 1996. Abundance and distribution of striped bass eggs and larvae in the Savannah River Estuary - Implications for channel dredging window, 1994 - 1996. Final Report, U.S. Army Corps of Engineers Savannah District, Savannah, Georgia.
- Richards, R. A. and P. J. Rago. 1999. A case history of effective fishery management: Chesapeake Bay striped bass. North American Journal of Fisheries Management 19:356-375.
- Rulifson, R. A. and M. J. Dadswell. 1995. Life history and population characteristics of striped bass in Atlantic Canada. Transactions of the American Fisheries Society 124:477-507.
- Rulifson, R. A., M. T. Huish and R. W. Thoesen. 1982. Anadromous fish in the southeastern United States and recommendations for development of a management plan. U.S. Fish and Wildlife Service, Fishery Resources, Region IV, Atlanta, Georgia.
- Rulifson, R. A. and C. S. Manooch. 1990. Recruitment of juvenile striped bass in the Roanoke River, North Carolina, as related to reservoir discharge. North American Journal of Fisheries Management 10:397-407.
- Saiki, M. K. and D. U. Palawski. 1990. Selenium and other elements in juvenile striped bass from the San Joaquin valley and San Francisco Estuary, California Archives of Environmental Contamination and Toxicology 19:717-730.
- Setzler, E. M., W. R., Boynton, K. V. Wood, H. H. Zion, L. Lubbers, N. K. Mountford, P. Frere, L. Tucker, and J. A. Mihursky. 1980. Synopsis of biological data on striped

bass, *Morone saxatilis* (Walbaum). National Oceanic and Atmospheric
Administration Technical Report, National Marine Fisheries Service Circular 433:
Food and Agriculture Organization Synopsis No. 121.

- Setzler-Hamilton, E. M., J. A. Whipple and R. B. MacFarlane. 1988. Striped bass populations in Chesapeake and San Francisco bays: two environmentally impacted estuaries. Marine Pollution Bulletin 19:466-477.
- Sinclair, T. B. Jr. 1996. Estuarine distribution of juvenile striped bass in relation to salinity and river discharge. Master's thesis. University of Georgia, Athens.
- Stevens, D. E., D. W. Kohlhorst, L. W. Miller, and D. W. Kelley. 1985. The decline of striped bass in the Sacramento-San Joaquin Estuary, California. Transactions of the American Fisheries Society 114:12-30.
- Surber, E. W.1957. Results of striped bass (*Roccus saxatilis*) introductions into freshwater impoundments. Proceedings of the Annual Conference Southeastern Association of Fish and Wildlife Agencies 11:273-276.
- Tupper, M. and K. W. Able. 2000. Movements and food habits of striped bass (*Morone saxatilis*) in Delaware Bay (USA) salt marshes: comparison of a restored and a reference marsh. Marine Biology 137:1049-1058.
- U.S. Department of the Interior (U.S. DOI), Fish and Wildlife Service and the U.S. Department of Commerce, Bureau of the Census. 1998. 1996 Survey of Fishing, Hunting, and Wildlife-Associated Recreation -- Georgia. U.S. Fish and Wildlife Service Report FHW/96-GA.

- Van Den Avyle, M. J. and M. A. Maynard. 1994. Effects of saltwater intrusion and flow diversion on reproductive success of striped bass in the Savannah River estuary.
 Transactions of the American Fisheries Society 123:886-903.
- Van Den Avyle, M. J., M. A. Maynard, R. C. Klinger, and V. S. Blazer. 1990. Effects of Savannah Harbor development on fishery resources associated with the Savannah National Wildlife Refuge. Final Report. U.S. Fish and Wildlife Service. Atlanta, Georgia.
- Van Den Avyle, M. J. and J. E. Wallin. 2001. Retention of internal anchor tags by juvenile striped bass. North American Journal of Fisheries Management 21: 656-659.
- Varis, O. and S. Kuikka. 1999. Learning Bayesian decision analysis by doing: lessons from environmental and natural resources management. Ecological Modelling 119:177-195.
- Waldman, J. R., R. E. Bender, and I. I. Wirgin. 1997. Multiple population bottlenecks and DNA diversity in populations of wild striped bass, *Morone saxatilis*. Fishery Bulletin 96:614-620.
- Wallin, J. E. and M. J. Van Den Avyle. 1994. Retention of coded wire tags by juvenile striped bass. Proceedings of the Annual Conference Southeastern Association of Fish and Wildlife Agencies 48:550-554.
- -----. 1995a. Annual trends and spatial patterns of striped bass egg abundance in the Savannah River. Final report. Georgia Department of Natural Resources, Atlanta, Georgia.

- -----. 1995b. Evaluation of the Savannah River striped bass stocking program, 1990-1994. Final report. Georgia Department of Natural Resources, Atlanta, Georgia.
- -----. 1995c. Interactive effects of stocking site salinity and handling stress on survival of striped bass fingerlings. Transactions of the American Fisheries Society 124:736-745.
- Will, T. A., T. R. Reinert, and C. A. Jennings. 2000. Spatial assessment of current and historic spawning sites of striped bass, *Morone saxatilis*, in the Savannah River Estuary. Final report. Georgia Department of Natural Resources, Atlanta, Georgia.
- -----. 2001. Assessment of spawning sites and reproductive status of striped bass, *Morone saxatilis*, in the Savannah River Estuary. Final Report. Georgia Ports Authority, Savannah, Georgia.
- -----. 2002. Maturation and fecundity of a stock-enhanced population of striped bass, *Morone saxatilis* (Walbaum), in the Savannah River Estuary, USA. Journal of Fish Biology 60:532-544.
- Winger, P. V. and P. J. Lasier. 1994. Effects of salinity on striped bass eggs and larvae from the Savannah River, Georgia. Transactions of the American Fisheries Society 123:904-912.
- Wirgin, I. I., C. Grunwald, S. J. Garte, and C. Mesing. 1991. Use of DNA fingerprinting in the identification and management of a striped bass population in the southeastern United States. Transactions of the American Fisheries Society 120:273-282.

- Wirgin, I. I., L. Maceda, J. Stabile, and C. Mesing. 1997. An evaluation of introgression of Atlantic Coast striped bass mitochondrial DNA in a Gulf of Mexico population using formalin-preserved museum collections. Molecular Ecology 6: 907-916.
- Wirgin, I., T-L. Ong, L. Maceda, J. R. Waldman, D. Moore, and S. C. Courtenay. 1993.
 Mitochondrial DNA variation in striped bass (*Morone saxatilis*) from Canadian rivers. Canadian Journal of Fisheries and Aquatic Sciences 50:80-87.
- Wirgin, I. I., R. Proenca, and J. Grossfield. 1989. Mitochondrial DNA diversity among populations of striped bass in the southeastern United States. Canadian Journal of Zoology 67:891-907.
- Whaley, G., H. Rainey, C. Parker, G. D. Adams, and H. Leggett. 1969. A report to the Legislature on the striped bass (rockfish) in Georgia; its status, potential and current research and management efforts by the State Game and Fish Commission. The Striped Bass Subcommittee of the House of Representatives. Atlanta, GA. 9 p.
- Zincone, L. H. Jr., and R. A. Rulifson. 1991. Instream flow and striped bass recruitment in the lower Roanoke River, North Carolina. Rivers 2:25-137.

CHAPTER 3

DECLINE AND RECOVERY OF STRIPED BASS, *MORONE SAXATILIS*, IN THE SAVANNAH RIVER ESTUARY, GEORGIA-SOUTH CAROLINA¹

submitted to Fisheries.

¹Reinert, T.R., C.A. Jennings, M.J. Van Den Avyle, J. Wallin, and T.A. Will. To be

INTRODUCTION

In Georgia, Atlantic Coast striped bass Morone saxatilis are native to the Savannah, Ogeechee, and Altamaha rivers (Hill et al. 1989) and have been introduced into other river systems and reservoirs throughout the state. Although commonly found in estuarine waters, striped bass in Georgia tend to be riverine, rarely entering the open ocean. However, movement between adjacent rivers via coastal waters occasionally has occurred (Smith 1970; Dudley et al. 1977). As is common throughout their range, striped bass and striped bass hybrids (crossed with white bass, M. chrysops) provide popular fisheries in Georgia s rivers and reservoirs. In 1996, Morone fisheries accounted for a significant portion of the \$1.2 billion in annual angler expenditures in Georgia (U.S. DOI 1998; Carl Hall, Georgia Department of Natural Resources [GA-DNR], personal communication). Striped bass populations in Georgia s coastal rivers rarely have supported commercial exploitation, although a nominal fishery in the Savannah River existed during the late-19th and early-20th centuries. Production peaked at 5900 kg in 1889 but subsequent catches were not large enough to support the fishery which subsequently closed in the early 1900's (Rulifson et al. 1982).

Because of the increasing popularity of sport fishing in general, and *Morone* fisheries in particular, GA-DNR began hatchery production of striped bass and hybrid striped bass for state-wide distribution. Successful introduction of striped bass into South Carolina reservoirs (Surber 1957) further increased the desire for large-scale hatchery production of striped bass in Georgia. During the 1970s, GA-DNR annually collected broodfish, typically females 9.0 kg from the Savannah River Estuary for the

Morone stocking program. To enhance the local fishery, the estuary itself began receiving hatchery-produced fish in 1980. Striped bass stockings by GA-DNR from 1980-1989 totaled over 1 million fish (Wallin and Van Den Avyle 1995b).

In 1977, striped bass reproduction was investigated in anticipation of operation of a tide gate in the lower estuary (Dudley and Black 1978; see Figure 3-1). Flood tides were captured by the tide gate and forced through a diversion canal into the harborarea during ebb flow. The purpose of the tide gate was to alter flow patterns in the lower estuary, to flush depositional sediments from harbor berths, and thereby reduce maintenance dredging costs. However, the primary spawning ground for Savannah River striped bass was thought to be between river kilometers (rkm) 33-40 of the Back River, in the midst of the Savannah National Wildlife Refuge and just upstream of the tide gate (Figure 3-1). Dudley and Black (1978) concluded that increased salinity in the upper Back River resulted from tide gate operation and potentially affected striped bass spawning habitat as well as egg and larval survival. Additionally, changing hydrodynamics as a result of tide gate action could force eggs and larvae into the industrial port through the diversion canal (see Figure 3-1) and potentially encounter pollutants and higher salinities. These altered flows also had the potential of transporting eggs and larvae more rapidly downstream to areas of harmful salinity. Despite these warnings and biological consequences, the tide gate, which was effective at its intended engineering purpose, continued in full operation.

POPULATION DECLINE

During broodfish collections in the early 1980s, GA-DNR biologists noted a precipitous decline in adult catch per unit effort (CPUE). From 1980 to 1988, CPUE of adult striped bass (including large broodfish > 9.0 kg) declined by 97%. (Figure 3-2). Out of fear of exacerbating the population decline, GA-DNR abandoned the estuary as a broodfish source and focused on the nearby Ogeechee River. That population was not large enough to support the total collection needs of the program, and GA-DNR used other Georgia rivers and reservoirs that had been stocked with striped bass as a source of broodstock.

Concurrent with the decline in adult striped bass, egg production declined as well. Larson (1985) noted that striped bass eggs occurred in the same locations (primarily Back River) as in years past, but densities were considerably lower (Figure 3-3a). Striped bass egg production continued to be monitored throughout the 1980s, and patterns of salinity distribution and flow dynamics were also investigated (Van Den Avyle et al. 1990). During this period, egg production declined by 96% (Figure 3-3a). The hypothesized cause of the decline was increased salinity on spawning grounds and accelerated seaward transport of eggs and larvae to areas of lethal salinity, all of which resulted from tide gate operation and the attendant channel modifications (Van Den Avyle and Maynard 1994). Winger and Lasier (1994) found that Savannah River striped bass eggs perished in salinity greater than 18 0, and 50% of 48-h posthatch larvae perished at 10 0. Based on exposure probabilities in the estuary, the critical threshold of salinity for eggs and larvae was estimated to be 9 0.

TIDE GATE INFLUENCES

During operation of the tide gate, harmful and lethal salinities were common in areas previously suitable for striped bass spawning and rearing (Van Den Avyle and Maynard 1994). The tide gate also had a marked influence on salinity in the upper reaches of the Back River. During operation, a measurable salt wedge (measured as the 0.5 0 halocline) was displaced 3-10 km upstream and as far upriver as rkm 42 in the Back River during low discharge periods (see Figure 3-1; Pearlstine et al. 1993). A U.S. Geological Survey (USGS) gauging station located at the Savannah National Wildlife Refuge dock (rkm 37.5 in the Back River and 14.6 km from the tide gate) measured salinity (as specific conductance) during tide gate operation (Figure 3-4). Salinity during periods of operation often approached 8 0 at the gaging station, but conditions when the gate was not operating were fresh (<0.5 0) or nearly so.

Behavioral compensation by adult striped bass in response to changing conditions for ichthyoplankton is unlikely (Ulanowicz and Polgar 1980) and was investigated in the Savannah River Estuary. Upriver egg sampling detected little or no shift in spawning locations by striped bass in response to the increased salinity on spawning grounds (Van Den Avyle and Maynard 1994). Adults may have found areas within the estuary suitable for spawning, however nursery areas for eggs and larvae became less suitable, and even lethal, during tide gate operation.

The tide gate and diversion canal also affected egg transport pathways. Altered hydrodynamics in the Back River forced river flow into the Front River via the diversion canal and Middle River (see Figure 3-1). The channelized and deepened Front River has higher velocities and greater salinity (14-26 0) than other areas of the estuary (Van

Den Avyle and Maynard 1994). Eggs that typically would have stayed in the Back River were transported to the Front River and potentially more rapidly to areas of hamful or lethal salinity. This accelerated downstream transport of late-stage embryos and/or recently hatched larvae to areas of high salinity may have been the most immediate and important factor responsible for reproductive failure of striped bass in the lower Savannah River Estuary (Van Den Avyle and Maynard 1994).

MITIGATION AND MONITORING

In response to the dramatic decline in striped bass adults and striped bass reproduction, resource managers implemented several restoration actions. The states of Georgia and South Carolina instituted fishing moratoriums for striped bass in 1988 and 1990, respectively. The moratorium affected the entire free-flowing portion of the river up to the New Savannah Bluff Lock and Dam, near Augusta, Georgia (approximately rkm 312). In 1990, GA-DNR began a stock-enhancement program aimed at restoring a self-sustaining population of striped bass to the river. To mitigate environmental effects, operation of the tide gate ceased in 1991, and the diversion canal was filled in 1992. These actions were aimed at restoring the salinity and flow regimes common to the estuary prior to modification and the subsequent population decline.

Environmental mitigation efforts attempted to re-establish the salinity patterns and channel morphology that existed prior to the population decline. Cessation of tide gate operation resulted in spawning ground salinity levels similar to those prior to tide gate implementation (see Figure 3-4). Following tide gate decommissioning, marsh

interstitial salinity declined immediately by as much as 80 (Pearlstine et al. 1993). Salinity levels continue to remain suitable for striped bass spawning and rearing in the Back River spawning area (Reinert et al. 1998a; Will et al. 2000). Additionally, closure of the diversion canal has restored channel configuration and flow patterns to those that existed prior to tide gate construction. However, years of tide gate operation increased siltation in the area immediately upstream of the tide gate; hence, flow rates may not be representative of those prior to tide gate operation (ATM 2000).

The stocking program was initiated at the GA-DNR Richmond Hill Fish Hatchery, near Savannah, Georgia. Survival studies indicated that larger fish (175 mm TL) stocked in freshwater had the highest long-term survival (Wallin and Van Den Avyle 1995b). Effects of handling, transportation, and release on the stress-response in stocked fish also were investigated (Hendrickx Jr. 1996). GA-DNR adopted recommendations from these studies, and annual stocking continued through 2003 with over 1.6 million fish stocked since 1990 (Table 3-1). All hatchery-produced fish were marked, either by coded-wire tag, internal anchor tag, or oxytetracycline (OTC) immersion-marking (labeling calcified structures with a fluorescent chemical mark). Each marking procedure was evaluated for efficiency and mark retention (Wallin and Van Den Avyle 1994; Reinert et al. 1998b; Van Den Avyle and Wallin 2001), and eventually OTC-marking was selected as the primary marking method. A series of electrofishing stations was established and systematically sampled just prior to and during the striped bass spawning season (February-April). From 1990-1995, the Georgia Cooperative Fish and Wildlife Research Unit (GCFWRU) conducted the electrofishing surveys until GA-DNR assumed the annual monitoring program.

From 1990-1994, GCFWRU conducted juvenile trawl sampling to monitor juvenile abundances in the estuary. Implementation of a juvenile monitoring program also would provide an effective way of evaluating the success of the stocking program. Similar programs have provided decades of recruitment information in the Chesapeake Bay (Goodyear 1985; Dorazio et al. 1991). Seining, the primary collection method in the Chesapeake Bay, cannot be conducted in the Savannah River Estuary because of soft substrates, swift currents, and the presence of alligators (Wallin et al. 1995). Electrofishing was found to be ineffective for young-of-year (YOY) striped bass. Instead, otter trawls were performed during summer months, the period when YOY striped bass abundance peaks. During this period, 87% of the juveniles captured were stocked individuals and most (78%) were captured in the Back River. Unfortunately, precision indices indicated that trawling was not an effective measure of year-class strength and the number of trawls required to achieve acceptable precision (coefficient of variation = 0.2) was not practical (Wallin et al. 1995). As such, electrofishing for age classes 2+ currently is the only effective index of striped bass abundance.

Sub-adult striped bass (< 600 mm) CPUE increased sharply immediately following implementation of the stocking program (Figure 3-5). Information on sub-adults prior to 1990 is unreliable, as GA-DNR biologists concentrated on capturing broodfish and often did not record captures of immature fish. The dramatic increase in CPUE is almost entirely the result of the contribution of stocked fish, which made up approximately 70% of the catch annually (GA-DNR, unpublished data). The abundance of large females (individuals 9.0 kg) is still low compared to that of the late 1970s; however, larger fish do appear to be increasing in number (Figure 3-3).

With increased abundance of large striped bass in the river, egg production was expected to increase as well. Monitoring continued through the 2000 spawning season and egg production remained relatively low. Egg density in the estuary rose to 0.95/100 m³ in 2000, but this was still just 10% that of levels reported in the late 1970s (see Figure 3-3a). However, over the last 3 years of sampling, egg abundances appear to have increased (Figure 3-3b).

Additional evidence of increased spawning success comes from capture of larvae and wild juvenile striped bass, even though striped bass larvae are rarely captured in our egg sampling efforts. From 1986-1989, 192 striped bass larvae were captured (Van Den Avyle et al. 1990), and in the following nine sampling years (1990-1991 and 1994-2000), only 26 larvae were caught (Wallin and Van Den Avyle 1995a; Reinert et al. 1998a; Will et al. 2000, 2001). Recently however, in 2001 and 2002, 48 larvae were captured during an ichthyofaunal survey of the estuary. Notably, these larvae were captured under a sampling regime that sampled about 1/3 as frequently as previous studies (Jennings and Weyers 2003). Collins et al. (2003) reported 66 juvenile striped bass captured in trawl and gill net sampling in the lower estuary. Nine of those captured were smaller than striped bass stocked by GA-DNR and thus presumably of wild origin.

NEW INVESTIGATIONS

Since the 1970s, research efforts to determine striped bass spawning locations have consistently identified the Back River as the primary spawning ground (Smith 1970; Dudley and Black 1978; Larson 1985; Van Den Avyle 1990). The evidence for this conclusion has been consistently higher egg densities at Back River sampling

stations than at Front River sampling stations. However, recent studies have shown that sampling efficiency is greater in the shallow, narrow reaches of the Back River than in the deeper, wider channel of the Front River (Reinert et al. 2004). Thus, past conclusions about striped bass spawning activity may have underestimated the importance of the Front River as a spawning area. Additionally, egg surrogates moved throughout the entire channel system following releases in either the upper estuary or the upper Back River, indicating that eggs spawned in these areas may contribute to eggs captured in other reaches of the estuary. These results suggest that the importance of the Front River for striped bass spawning may have been underestimated in years past; however, the Back River has supported known spawning aggregations of striped bass in the past, and its importance should not be discounted by these results. Clearly, as far as potential striped bass recruitment is concemed, the SRE must be considered as a whole system.

Aspects of the reproductive status and age distribution of striped bass in the estuary may help explain continued low egg abundance despite an apparently increasing adult population. Although adult striped bass were present and apparently increasing in abundance, the maturational status of adult females was unknown. Will et al. (2002) used ultrasonograpy to assess the reproductive status of Savannah River striped bass, providing a non-lethal measure of fecundity and maturational status. Histological samples indicated normal inter-uterine development of oocytes, and ultrasonography indicated fecundity/size relationships similar to other striped bass populations. Striped bass appeared to be maturing normally and compared favorably to other healthy, reproductive populations. Hence, the low abundance of eggs in the

estuary cannot be attributed to delayed or abnormal maturity of striped bass adults. Continued low egg numbers in the estuary likely are the result of too few large individuals in the population to effectively contribute to annual reproduction. As the adult population continues to grow (both in number and in age), egg production should begin increasing to levels that support self-sustainability (Will et al. 2002).

CONCLUSIONS

Over the last 30 years, many striped bass stocks have suffered population declines. Reasons for these declines have varied, but often habitat quality has been identified as a primary factor. Poor water quality (primarily because of nutrient enrichment and pollution) in the Chesapeake Bay likely contributed to that noted decline (Price et al. 1985) and was the primary culprit in the decline of the Delaware River stock (Chittenden Jr. 1971). In the Sacramento/San Joaquin delta, loss of freshwater habitat (primarily a result of agricultural water withdrawals) was implicated in the striped bass decline there (Stevens et al. 1985), and insufficient flows from upstream dams precipitated the decline in the Roanoke River (Rulifson and Manooch 1990). Similarly, the striped bass population of the Savannah River Estuary has been affected by decreased habitat quality. Loss of freshwater habitat for spawning and rearing was not caused by withdrawls or insufficient flows, but by altering tidal flow for the purposes of harbor maintenance. Freshwater flow, as well as eggs and larvae, were shunted to the Front River to areas of salinity detrimental to normal striped bass development. Additionally, saltwater intrusion into spawning and nursery areas made them unsuitable for either purpose.

Efforts to restore the Savannah River striped bass population have taken a twofaceted approach: habitat restoration and stock enhancement. The modifications that caused habitat degradation have been removed; the tide gate no longer operates, and the diversion canal has been filled. Salinity in historic spawning and nursery grounds is now similar to that prior to the decline. Since 1990, stocking of juvenile striped bass has placed over 1.5 million juvenile striped bass into the river. Adult striped bass CPUE appears to be increasing, and egg production, although still low compared to pre-tide gate levels, also appears to be increasing. Most age 2 fish continue to be of hatchery origin, validating the success of the stocking program yet also demonstrating the continued lack of natural recruitment. However, recent captures of larvae and wild juvenile striped bass indicate an increased level of spawning success. Although Savannah River striped bass appear to be maturing normally and on schedule, too few large adults may be present to sufficiently resume reproduction at the level required for a self-sustaining population. Each year, increasing numbers of stocked individuals enter the reproductive age classes, and because of the continued fishing moratorium, current adults freed from harvest pressure will continue growing and spawning year after year. Hopefully reproductive output will increase to self-sustaining levels, but this may yet be several years away. Eventually, if current trends continue, the Savannah River population of striped bass will join such locales as the Chesapeake Bay and Roanoke River in the catalog of successful striped bass recovery efforts.

FUTURE CONCERNS

Increased salinity on spawning and nursery grounds was the primary cause of the striped bass population decline in the 1980s and may once again pose a problem for this population. Currently, environmental resource agencies are reviewing a proposal to deepen the Savannah Harbor by up to 2 m. This deepening would directly affect the Front River channel up to rkm 32 and saltwater would once again encroach further upriver than under present conditions (see Figure 3-1). If the Front River is indeed more important than previously suspected, major spawning and nursery grounds are directly upstream of the proposed harbor deepening. Additionally, if saltwater progresses past river kilometer 43, then the ebb tide in the upper Back River will contain saltwater harmful to the freshwater marsh and likely preclude any recovery of Back River striped bass spawning and nursery habitat. Use of egg surrogates indicated that eggs likely distribute across all reaches of the estuary and the system must be managed as an integrated unit; selective restoration attempts in the historically productive Back River at the expense of increasing development of the Front River is not a viable mitigation alternative.

LITERATURE CITED

- Applied Technology and Management, Inc. (ATM). 2000. Evaluation of existing and historic velocities and salinities in Back River for striped bass restoration study. Final report. Georgia Ports Authority, Savannah.
- Chittenden, M. E. Jr. 1971. Status of striped bass, *Morone saxatilis*, in the Delaware River. Chesapeake Science 12:131-136.
- Collins, M. R., A. R. Rourk, C. K. Way, and W. C. Post. 2003. Temporal and spatial distribution of estuarine-dependent species in the Savannah River Estuary. Final Report. Georgia Ports Authority. Savannah, Georgia.
- Dorazio, R. M., B. M. Florence, and C. M. Wooley. 1991. Stocking of hatchery-reared striped bass in the Patuxent River, Maryland: Survival, relative abundance, and cost-effectiveness. North American Journal of Fisheries Management 11:435-442.
- Dudley, R. G. and K. N. Black. 1978. Distribution of striped bass eggs and larvae in the Savannah River estuary. Proceedings of the Annual Conference Southeastern Association of Fish and Wildlife Agencies 32:561-570.
- Dudley, R. G., A. W. Mullis, and J. W. Terrell. 1977. Movements of adult striped bass (*Morone saxatilis*) in the Savannah River, Georgia. Transactions of the American Fisheries Society 106:314-322.
- Goodyear, C. P. 1985. Relationship between reported commercial landings and abundance of young striped bass in Chesapeake Bay, Maryland. Transactions of the American Fisheries Society 114:92-96.

- Hendrickx, E. J. Jr. 1996. Physiological stress in cultured striped bass: quantifying the effects of routine handling and stocking procedures. Master's thesis. University of Georgia, Athens.
- Hill, J., J. W. Evans, and M. J. Van Den Avyle. 1989. Species profiles: Life histories and environmental requirements of coastal fishes and invertebrates (South Atlantic)-Striped Bass. U.S. Fish and Wildlife Service Biological Report 82(11.118):35.
- Jennings, C. A. and R. S. Weyers. 2003. Temporal and spatial distribution of estuarine-dependent species in the Savannah River Estuary. Final Report.
 Georgia Ports Authority. Savannah, Georgia.
- Larson, S. C. 1985. The distribution and abundance of striped bass eggs in the lower Savannah River. Master's thesis. University of Georgia, Athens.
- Pearlstine, L. G., W. M. Kitchens, P. J. Latham, and R. D. Bartleson. 1993. Tide gate influences on a tidal marsh. Water Resources Bulletin 29:1009-1019.
- Price, K. S., D. A. Flemer, J. L. Taft, G. B. Mackiernan, W. Nehlsen, R. B. Biggs, N. H. Burger, and D. A. Blaylock. 1985. Nutrient enhancement of Chesapeake Bay and its impact on the habitat of striped bass: a speculative hypothesis. Transactions of the American Fisheries Society 114:97-106.
- Reinert, T. R., K. L. Jefferson, and C. A. Jennings. 1998a. Abundance and distribution of striped bass eggs and larvae in the Savannah River Estuary - Implications for channel dredging window. Final Report, U.S. Army Corps of Engineers Savannah District, Savannah, Georgia.
- Reinert, T. R., J. Wallin, M. C. Griffin, M. J. Conroy, and M. J. Van Den Avyle. 1998b. Long-term retention and detection of oxytetracycline marks applied to

hatchery-reared larval striped bass, *Morone saxatilis*. Canadian Journal of Fisheries and Aquatic Sciences 55:539-543.

- Reinert, T. R., T. A. Will, and C. A. Jennings. 2004. Use of egg surrogates to estimate sampling efficiency of striped bass eggs in the Savannah River. North American Journal of Fisheries Management 24:704-710.
- Rulifson, R. A., M. T. Huish and R. W. Thoesen. 1982. Anadromous fish in the southeastern United States and recommendations for development of a management plan. U.S. Fish and Wildlife Service, Fishery Resources, Region IV, Atlanta, Georgia.
- Rulifson, R. A. and C. S. Manooch. 1990. Recruitment of juvenile striped bass in the Roanoke River, North Carolina, as related to reservoir discharge. North American Journal of Fisheries Management 10:397-407.
- Smith, L. D. 1970. Life history studies of striped bass. Final Report, Project A.F.2-2. Georgia Department of Natural Resources, Atlanta, Georgia.
- Stevens, D. E., D. W. Kohlhorst, L. W. Miller, and D. W. Kelley. 1985. The decline of striped bass in the Sacramento-San Joaquin Estuary, California. Transactions of the American Fisheries Society 114:12-30.
- Surber, E. W. 1957. Results of striped bass (*Roccus saxatilis*) introductions into freshwater impoundments. Proceedings of the Annual Conference Southeastern Association of Fish and Wildlife Agencies 11:273-276.
- Ulanowicz, R. E. and T. T. Polgar. 1980. Influences of anadromous spawning behavior and optimal environmental conditions upon striped bass (*Morone saxatilis*)

year-class strength. Canadian Journal of Fisheries and Aquatic Sciences 37:143-154.

- U.S. Department of the Interior (U.S. DOI), Fish and Wildlife Service and the U.S. Department of Commerce, Bureau of the Census. 1998. 1996 Survey of Fishing, Hunting, and Wildlife-Associated Recreation -- Georgia. U.S. Fish and Wildlife Service Report FHW/96-GA.
- Van Den Avyle, M. J. and M. A. Maynard. 1994. Effects of saltwater intrusion and flow diversion on reproductive success of striped bass in the Savannah River estuary.
 Transactions of the American Fisheries Society 123:886-903.
- Van Den Avyle, M. J. and J. E. Wallin. 2001. Retention of internal anchor tags by juvenile striped bass. North American Journal of Fisheries Management 21: 656-659.
- Van Den Avyle, M. J., M. A. Maynard, R. C. Klinger, and V. S. Blazer. 1990. Effects of Savannah Harbor development on fishery resources associated with the Savannah National Wildlife Refuge. Final Report. U.S. Fish and Wildlife Service. Atlanta, Georgia.
- Wallin, J. E. and M. J. Van Den Avyle. 1994. Retention of coded wire tags by juvenile striped bass. Proceedings of the Annual Conference Southeastern Association of Fish and Wildlife Agencies 48:550-554.
- -----. 1995a. Annual trends and spatial patterns of striped bass egg abundance in the Savannah River. Final Report. Georgia Department of Natural Resources. Social Circle, Georgia.

- ----. 1995b. Evaluation of the Savannah River striped bass stocking program,
 1990-1994. Final Report. Georgia Department of Natural Resources. Social Circle, Georgia.
- Wallin, J. E., M. J. Van Den Avyle, and T. B. Sinclair Jr. 1995. Juvenile striped bass nursery habitat and abundance index in the lower Savannah River. Final Report.
 Georgia Department of Natural Resources. Social Circle, Georgia.
- Will, T. A., T. R. Reinert, and C. A. Jennings. 2000. Spatial assessment of current and historic spawning sites of striped bass, *Morone saxatilis*, in the Savannah River estuary. Final Report. U.S. Army Corps of Engineers, Savannah District. Savannah, Georgia.
- -----. 2001. Assessment of spawning sites and reproductive status of striped bass, *Morone saxatilis*, in the Savannah River Estuary. Final Report. Georgia Ports Authority. Savannah, Georgia.
- -----. 2002. Maturation and fecundity of a stock-enhanced population of striped bass in the Savannah River Estuary, U.S.A. Journal of Fish Biology 60:532-544.
- Winger, P. V. and P. J. Lasier. 1994. Effects of salinity on striped bass eggs and larvae from the Savannah River, Georgia. Transactions of the American Fisheries Society 123:904-912.

	Numbers (in 1000s) of striped bass stocked by size class		
Year	15-25 mm	60-90 mm	121-225 mm
1990	0	96	21
1991	0	95	27
1992	250	150	44
1993	250	99	63
1994	146	84	51
1995	0	0	23
1996	0	0	40
1997	0	0	42
1998	0	0	47
1999	0	0	33
2000	0	0	30
2001	0	0	41
2002	0	0	13
2003	0	0	40
Total	646	524	475

Table 3-1. Numbers of striped bass stocked into the Savannah River Estuary, 1990-2003, as part of the Georgia Department of Natural Resources (GA-DNR) stock enhancement program (1990-1994 data, Wallin and Van Den Avyle, 1995b; 1995-2003 data, GA-DNR, unpublished data).



Figure 3-1. Map of the Savannah River Estuary, Georgia-South Carolina, showing three major highways, the tide gate, diversion canal, and the Savannah National Wildlife Refuge (shaded area). United States Geological Survey conductivity station at U.S. Fish and Wildlife Refuge Dock is noted (*****).



Figure 3-2. Catch-per-unit effort (#/hr) of adult striped bass in the Savannah River Estuary, Georgia-South Carolina, 1977-2003. All adult striped bass (> 600 mm total length, grey bars) and adult striped bass > 9.0 kg (black bars) are shown. Unpublished data courtesy Georgia Cooperative Fish & Wildlife Research Unit and Georgia Department of Natural Resources.



Figure 3-3. Striped bass egg density (number/100 m³) in the Savannah River Estuary, Georgia-South Carolina. Egg density was not measured 1979-1983,1985, or 1992-93. Where available, error bars are standard deviations. Where error bars disappear, end points are denoted. A) 1977-1989. B) 1990-2000. Note differences in scale between graphs. Data sources: 1977-1978, Dudley and Black (1978); 1984, Larson (1985); 1986-1989, Van Den Avyle et al. (1990); 1990-1991, Wallin and Van Den Avyle (1995a); 1994-1996, Reinert et al. (1996); 1997-1998, Reinert et al. (1998a); 1999, Will et al. (2000); 2000, Will et al. (2001).



Figure 3-4. Salinity levels in the Back River, Savannah River Estuary, Georgia-South Carolina, 1990-1991. The gage was located at the U.S. Fish & Wildlife Service Refuge Dock, approximately river kilometer 37.3 of the Back River (see Figure 3-1). Periods when the tide gate was not operational are noted. Data courtesy of U.S. Geological Survey and Applied Technology and Management, Inc.



Figure 3-5. Catch per unit effort (#/hr of electrofishing) of sub-adult striped bass (< 600 mm total length) in the Savannah River Estuary, Georgia-South Carolina, 1990-2003. The stock enhancement program began in 1990. Unpublished data courtesy Georgia Cooperative Fish & Wildlife Research Unit and Georgia Department of Natural Resources.

CHAPTER 4

ESTIMATING HISTORIC STRIPED BASS *MORONE SAXATILIS* REPRODUCTIVE EFFORT IN THE SAVANNAH RIVER ESTUARY, GEORGIA-SOUTH CAROLINA²

²Reinert, T. R. and C. A. Jennings. To be submitted to *Estuaries*.

INTRODUCTION

The Savannah River Estuary hosted Georgia s most popular sport fishery for striped bass *Morone saxatilis* during the 1960s and 1970s and was the source of broodstock for the Georgia Department of Natural Resources (GA-DNR) state-wide stocking program. However, subsequent declines in adult catch-per-unit-effort (CPUE) alerted the resource agency to potential recruitment problems. From 1980 to 1988, total CPUE of adult striped bass declined by 97% (Chapter 3). Egg sampling from 1986-1989 was used as an index of reproductive effort and confirmed a concomitant 96% decline in striped bass egg CPUE (number per 100 m³). The population decline was linked to operation of a tide gate that increased salinity on spawning and nursery grounds and altered egg transport pathways, shunting eggs to areas of harmful or lethal salinity (Van Den Avyle and Maynard 1994).

Stock recovery efforts for striped bass began in 1988 with a fishing moratorium and continued with the inception of the stock-enhancement program in 1990. As a result of stocking, striped bass CPUE has increased to levels near those reported prior to the decline. The Savannah River divides into three channels below river kilometer (rkm) 45 the Front, Middle, and Back rivers (Figure 4-1) and the Back River was considered the primary striped bass spawning and nursery grounds (Smith 1970; Dudley and Black 1978). Habitat restoration focused on restoring habitat quality to the Back River area, yet development continued in the Front River, most recently with a deepening in 1993-1994. Remediation of Back River spawning and nursery habitats included cessation of tide gate operation (1991) and filling of a diversion canal (1992). Back River salinity levels and flow pathways recovered almost immediately (Pearlstine
et al. 1993). However, despite an increased abundance of adults, egg CPUE has not increased substantially and is still far below that of the late 1970s, especially in the historically productive Back River (Chapter 3).

Egg sampling has been used in the Savannah River as an index to determine the location and relative amount of striped bass spawning since the 1960s, but most intensively since the mid-1980s (Larson 1985; Van Den Avyle et al. 1990; Wallin and Van Den Avyle 1995; Reinert et al. 1996, 1998; Will et al. 2000). The methods employed calculated CPUE for striped bass eggs, but these estimates are relative and dependent on the assumption that capture efficiency between stations and between years is constant. If CPUE increased or decreased relative to previous years, the assumption is that egg abundance has increased or decreased as well. However, a recent study (Reinert et al. 2004) suggested that sampling efficiency is different in the separate reaches of the estuary, which would result in biased conclusions about egg abundance if CPUE is used as the informative index. Egg abundances historically may have been higher in the Front River than previously suspected, and selective restoration of Back River habitats (potentially at the expense of Front River areas to increased development) may not be a viable mitigation option.

Reinert et al. (2004) used egg surrogates to investigate the sampling efficiency of the standardized egg sampling procedures. Egg surrogates (beads) released in the upper estuary (rkm 50; henceforward, Savannah River releases) were recovered in all 3 river channels. An unknown portion of the released beads traveled into the Middle and Back rivers affecting our ability to estimate sampling efficiency separately for the Front River. In the Back River, however, sampling efficiencies were discernable

because beads released in the upper Back River remained in the Back River. Back River sampling efficiency was an order of magnitude greater than the efficiency calculated for the estuary as a whole (from Savannah River releases). These differences were attributed to the narrower and shallower channel of the Back River as compared to the Front River. Thus, Reinert et al. (2004) reported sampling efficiencies for the whole system and an efficiency specific to the Back River. These differences in sampling efficiency between reaches suggested that previous conclusions about where striped bass preferentially spawned need to be revisited.

To investigate historical abundances of striped bass eggs, we employed sampling efficiency estimates developed by Reinert et al. (2004) for our egg sampling methods. Our objectives for this study were to: 1) refine those sampling efficiency estimates to discern individual sampling efficiencies at two of the historically most productive sampling stations in the Front and Back rivers, and 2) use the more precise estimates of sampling efficiency to back-calculate egg abundances at those two stations from egg sampling studies dating as far back as 1978. These previously unavailable estimates of egg abundance will allow for a better understanding of historic trends in striped bass egg distribution within the estuary and provide a better comparative index of striped bass reproductive effort.

METHODS

Egg sampling in the estuary traditionally consisted of bow-mounted 0.5 m diameter plankton nets with 505- m mesh. Until 1990, a sampling event consisted of a single tow of paired nets (Dudley and Black 1978; Van Den Avyle et al. 1990; Wallin and Van

Den Avyle 1995). Beginning in 1991, samples were standardized to one net fished 3 consecutive times (considered replicates) during each sampling event. Tows were conducted primarily during the ebb tide, 1 m below the surface (see Figure 4-1 for sampling stations). A General Oceanics flow meter in the mouth of each net measured the exact volume sampled, and captured eggs were standardized to number per 100 m³. Stations typically were sampled daily or every other day from about mid-March through mid-May.

To improve sampling efficiency estimates, we revisited sampling efficiency at two historically productive stations, one each in the Front and Back rivers. We examined Savannah River bead releases that coincided with separate Back River releases (n=3) to estimate individual sampling efficiencies at these stations. Different color beads distinguished each release location (see Reinert et al. 2004 for complete description of bead characteristics). We followed our normal egg sampling protocol following each bead release. All stations were sampled on the two days following each release. To estimate the number of Savannah-River released beads that traveled into the Back and Middle rivers, we applied the Back River capture efficiency (from Reinert et al. 2004) to the total number of Savannah River-released beads captured in the Back and Middle rivers (Figure 4-1). Middle River captures were included with Back River captures because the Middle River is hydrographically and hydrologically similar to the Back River, and we assumed sampling efficiency to be similar along these two reaches of the estuary. The estimated number of Savannah River-released beads that traveled into the Back and Middle rivers was calculated as:

$$\hat{\mathbf{N}}_{\scriptscriptstyle B} = \frac{(\mathbf{C}_{\scriptscriptstyle B} + \mathbf{C}_{\scriptscriptstyle M})}{\mathbf{E}_{\scriptscriptstyle B}} \tag{1}$$

where E_B is the sampling efficiency for Back and Middle rivers (from Reinert et al. 2004), and C_B and C_M are Savannah River-released beads captured in the Back and Middle rivers, respectively. We subtracted the estimated number of beads in the Back and Middle rivers (\hat{N}_B) from the total number of beads released in the Savannah River to obtain the amount of Savannah River-released beads available for capture at the historic Front River station (rkm 40; see Figure 4-1). Sampling efficiency for the Front River station was calculated as,

$$E_{\rm F} = \frac{C_{\rm F}}{\hat{\rm N}_{\rm F}} \tag{2}$$

where C_F = total number of Savannah River-released beads captured at the Front River station. Sampling efficiency for that station was estimated as the mean of the three bead-releases. Standard deviation from the mean sampling efficiency was used to calculate the confidence intervals around the extrapolated estimate of egg abundance. Sampling efficiency for the Back River station (rkm 35; see Figure 4-1) was calculated in the same fashion, based on beads released in the Back River (rkm 43.3) and captured at the Back River station. Our calculated efficiencies were applied to historic captures of striped bass eggs at these two stations. Because of potential independence problems with the paired-net samples (1977-1990) and high variability with the 3-net replicate samples (1991-2000), we summed egg captures throughout each season rather than treating each sample or replicate independently.

RESULTS

The estimated number of beads that traveled from the Savannah River release location into the Back and Middle rivers ranged from about 90000 to over 500000. Adjusting the number of beads available for capture at the Front River station yielded an adjusted sampling efficiency of 0.00022% (± 0.00017% SD; Table 4-1). Sampling efficiency at the Back River station averaged 0.0058% (± 0.0036% SD; Table 4-2).

Estimated egg abundances at the two stations differed greatly, but consistently, over time. In all years, estimated egg abundance at the Front River station was at least an order of magnitude greater than the estimated abundance at the Back River station (Table 4-3). Unfortunately, the Front River station was only partially sampled in 1978 and not sampled at all in 1986. For those two years, we used egg captures at a nearby station (rkm 43.3) with the efficiency developed for the station at rkm 40. Estimated Front River abundance ranged from 127000 (in 1998) to over 460 million eggs (1986), whereas estimated Back River abundance ranged from 0 (in 1991) to about 23 million (in 1986). Because our efficiencies were based only on three sampling events, our mean efficiency estimates had large variances. However, a general trend for declining egg abundance is evident at both reference stations. Additionally, an apparent increase in egg abundance occurred in 1999 and 2000 (Figure 4-2).

April river discharge was highly variable (402±209 cms) during the historic study period (1978-2000), but was low and stable (198±38 cms) during the period we

established sampling efficiencies (1999-2000). River discharge may have an effect on sampling efficiency by increasing dispersion or more rapidly moving eggs through the system, although we were unable to evaluate this effect during our study. However, several years throughout the span of our back-calculations had mean April discharges similar to 1999-2000. Examining only years of similar discharge (within about 100 cms of the 2000 April average), the same declining trend in egg abundances over time is apparent (Figure 4-2).

DISCUSSION

Previous estimates of striped bass egg abundance were limited to reporting average CPUE for stations and years and provided a relative index of striped bass reproduction in the estuary. Historic CPUE data show that Back River densities appeared to be higher than those in the Front River during 1978, 1984 and 1986 (Figure 4-3). However, because of differences in sampling efficiencies between reaches of the Savannah River Estuary, CPUE is not a valid index for comparing egg catches between reaches. Areas (or years) that compare favorably based on CPUE may not be similar at all, if sampling efficiency is vastly different. Efficiency at our Front River station was much lower than that of the Back River station which resulted in abundance estimates for those stations that contradict interpretations from CPUE comparison. By determining sampling efficiencies for our egg sampling methods, we have been able to translate annual egg captures into estimates of egg abundance at these stations. These estimates are comparable between reaches and across years. Estimating the number of eggs present at a given station may be more meaningful to

managers and decision makers than estimating average number per unit volume (CPUE).

Because calculation of our sampling efficiencies was based on relatively few egg surrogate releases, the precision of our estimates is low (note rather larger confidence intervals, Figure 4-2). Additionally, these estimates were calculated under relatively low discharges (<225 cms) and may not be applicable to all years and discharge levels. Discharge may negatively affect efficiency through increased dispersion or flushing. During years of especially high discharge, we may be overestimating sampling efficiency, and hence, underestimating egg abundance. For example, one such year was 1998, when average April discharge was 922 cms. This also was the year of lowest estimated egg abundance at the Front River station (127000 eggs). However, the previous (1997) and following (1999) years also had relatively low production and much lower discharges (342 and 222 cms, respectively), indicating that our estimate was at least relatively accurate (Figure 4-2). However, even when comparing only years of similar discharge, the overall trend in declining egg abundances is evident at both stations, and a recent increase in abundance is evident at the Front River station (Figure 4-2). Conducting additional egg surrogate studies under a variety of flows (e.g., normal and high flow periods) would reduce the high variance in our predictions and better decipher the relationship between discharge and sampling efficiency.

The importance of the Front River as a spawning and nursery ground may have been underestimated in years past. Abundance estimates indicate that the vast majority of striped bass eggs occurred in the Front River. Previous studies found that egg CPUE was highest in the Back River and thus concluded that the Back River area

was the primary spawning location for striped bass (Smith 1970; Dudley and Black 1978; Larson 1985). Under this interpretation, managers previously have suggested that habitat restoration efforts should concentrate on the Back River, potentially at the expense of the Front River (i.e., if the Back River could be restored and historic spawning levels returned, additional development could be allowed in the Front River). Our study suggests that sampling efficiency is an order of magnitude greater in the Back River than in the Front River and may have created the apparently-false conclusion that more eggs occur there than in the Front River. Egg surrogates released above where the estuary divides into separate reaches traveled into both Front and Back river areas, and presumably striped bass eggs would do the same. Additionally, striped bass larvae are rarely captured in our egg samples, but when they have occurred, they primarily have been captured in upper Front River areas (Van Den Avyle et al. 1990; Jennings and Weyers 2003). Thus, the upper estuary may be more important to striped bass recruitment than previously considered. However, the Back River has supported known spawning aggregations of striped bass in the past, and its importance should not be diminished by these results. Clearly, as far as potential striped bass recruitment is concerned, the Savannah River Estuary must be considered as a whole system.

Recovery efforts for the striped bass population have taken a two-faceted approach, environmental restoration and stock-enhancement, with the ultimate goal of restoring a self-sustaining population. To rectify the environmental issues thought to be responsible for the collapse, the tide gate was removed from operation and the diversion canal was filled (1991 and 1992, respectively). Salinity has since decreased

in the areas thought to be important striped bass spawning and nursery areas (Pearlstine et al .1993), and original pathways for egg distribution have been restored. The stock-enhancement program also has been successful, as indicated by increasing adult CPUE (Chapter 3). With increased adult abundance, reproductive effort also was expected to increase. Ideally, the population would reach a level that would be selfsustaining and again support a recreational fishery. By using egg abundance at historically productive stations as an index of striped bass reproduction (as opposed to relative CPUE), we may be better able to understand levels necessary for selfsustainability and be better able to set recovery goals. Based on our estimates, striped bass egg abundance in these areas was over 200 million eggs in 1978 and was as high as 450 million in 1986. A reasonable recovery goal would be to approach that level of reproduction for several consecutive years. Reproductive effort at our two reference stations in 2000 was estimated at 36 million eggs, thus recovery still may be several years away. Striped bass have been shown to be year-class dependent, and high egg production in any given year will not guarantee a successful year class (Ulanowicz and Polgar 1980; Boreman and Austin 1985; Secor and Houde 1995). Thus, if the adult population increases to a point where such reproductive output can be maintained over several years, at least one successful year-class might be ensured, giving the population a good chance of regaining self-sustainability.

LITERATURE CITED

- Boreman, J. and H. M. Austin. 1985. Production and harvest of anadromous striped bass stocks along the Atlantic coast. Trans. Am. Fish. Soc. 114:3-7.
- Dudley, R. and K. Black. 1978. Distribution of striped bass eggs and larvae in the Savannah River estuary. Proceedings of the Annual Conference Southeastern Association of Fish and Wildlife Agencies 32:561-570.
- Jennings, C. A. and R. S. Weyers. 2003. Temporal and spatial distribution of estuarine-dependent species in the Savannah River Estuary. Final Report.Georgia Ports Authority. Savannah, Georgia.
- Larson, S. C. 1985. The distribution and abundance of striped bass eggs in the lower Savannah River. Master's thesis. University of Georgia, Athens.
- Olsen, E. J. and R. A. Rulifson. 1992. Maturation and fecundity of Roanoke River-Albemarke Sound striped bass. Trans. Am. Fish. Soc. 121: 524-537.
- Pearlstine, L. G., W. M. Kitchens, P. J. Latham, and R. D. Bartleson. 1993. Tide gate influences on a tidal marsh. Water Resources Bulletin 29:1009-1019.
- Reinert, T. R., K. L. Jefferson, and C. A Jennings. 1998. Abundance and distribution of striped bass eggs and larvae in the Savannah River Estuary - Implications for channel dredging window. Final Report, U.S. Army Corps of Engineers Savannah District, Savannah, GA.
- Reinert, T. R., J. Wallin, and M. J. Van Den Avyle. 1996. Abundance and distribution of striped bass eggs and larvae in the Savannah River Estuary - Implications for channel dredging window, 1994 - 1996. Final Report, U.S. Army Corps of Engineers Savannah District, Savannah, GA.

- Reinert, T. R., T. A. Will, and C. A. Jennings. 2004. Use of egg surrogates to estimate sampling efficiency of striped bass eggs in the Savannah River. North American Journal of Fisheries Management 24:704-710.
- Secor, D. H. and E. D. Houde. 1995. Temperature effects on the timing of striped bass egg production, larval viability, and recruitment potential in the Patuxent River (Chesapeake Bay). Estuaries 18:527-544.
- Smith, L. D. 1970. Life history studies of striped bass. Final Report. Game and Fish Division, Georgia Department of Natural Resources. Atlanta, Georgia.
- Van Den Avyle, M. J. and M. A. Maynard. 1994. Effects of saltwater intrusion and flow diversion on reproductive success of striped bass in the Savannah River estuary.
 Transactions of the American Fisheries Society 123:886-903.
- Van Den Avyle, M. J., M. A. Maynard, R. C. Klinger, and V. S. Blazer. 1990. Effects of Savannah Harbor development on fishery resources associated with the Savannah National Wildlife Refuge. Final Report. U.S. Fish and Wildlife Service. Atlanta, GA.
- Wallin, J. and M. J. Van Den Avyle. 1995. Annual trends and spatial patterns of striped bass egg abundance in the Savannah River. Final report. Georgia Department of Natural Resources, Atlanta, GA.
- Will, T. A., T. R. Reinert, and C. A. Jennings. 2000. Spatial assessment of current and historic spawning sites of striped bass, *Morone saxatilis*, in the Savannah River Estuary. Final report. Georgia Department of Natural Resources, Atlanta, GA.

- -----. 2001. Assessment of spawning sites and reproductive status of striped bass, *Morone saxatilis*, in the Savannah River Estuary. Final Report. Georgia Ports Authority, Savannah, Georgia.
- -----. 2002. Maturation and fecundity of a stock-enhanced population of striped bass in the Savannah River Estuary, U.S.A. J. Fish Biol. 60:532-544.

Table 4-1. Releases and captures of striped bass egg surrogates (gellan beads) in the Savannah River Estuary, 1999-2000. Beads captured in the Back River originated from the Savannah River release station (SR; river kilometer 50). The estimated number of beads in the Back (BR) and Middle (MR) rivers is used to adjust the remaining number of beads in the Front River (FR) available for capture, and to calculate an adjusted sampling efficiency specifically for the Front River sampling station (river kilometer 40).

	#released	Bead captures	Efficiency	Estimated # beads	Adjusted # beads	Bead captures	Adjusted efficiency
Date	SR	BR+MR	BR*	BR+MR	FR	FR station	FR station
5/19/99	2.1x10 ⁶	10	0.0018%	562500	1.54x10 ⁶	3	0.00020%
3/27/00	3.5x10 ⁶	23	0.0070%	328571	3.17x10 ⁶	2	0.00006%
3/31/00	7.0x10 ⁶	8	0.0088%	90688	6.91x10 ⁶	28	0.00041%

* Back River sampling efficiency is from Reinert et al. (2004).

Table 4-2. Estimated sampling efficiency at the historic egg sampling station in the Back River (river kilometer 35), Savannah River Estuary, 1999-2000. Striped bass egg surrogates (beads) were released in the Back River, river kilometer 43.3.

Date	number released	number captured	station efficiency
5/19/99	1.8 x 10 ⁶	32	0.0018%
3/29/00	9.0 x 10⁵	63	0.0070%
3/31/00	2.8 x 10 ⁶	241	0.0086%

Table 4-3. Estimated egg abundance at the Front River (FR; river kilometer [rkm] 40) and Back River (BR; rkm 35) reference stations of the Savannah River Estuary, 1978-2000. Number of eggs captured were standardized to number/100 m³ and totaled for each season. Range is ± one standard deviation (SD). <u>Note</u>: Front River egg captures in 1978 and 1986 (denoted by *) are from rkm 43.3 because the reference station (rkm 40) was either partially or not sampled at all those years.

Year	number of eggs FR	Est. FR abundance	Range (±1 SD)	number ofnumbe eggs BR	er œfst. BR abundance	Range (±1 SD)
1978	455*	2.06 x 10 ⁸	1.16 x 10 ⁸ - 9.37 x 10 ⁸	844	1.46 x 10 ⁷	9.02 x 10 ⁶ - 3.80 x 10 ⁷
1984	100*	4.48 x 10 ⁷	2.50 x 10 ⁷ - 2.12 x 10 ⁸	1259	2.17 x 10 ⁷	1.36 x 10 ⁷ - 5.50 x 10 ⁷
1986	1023*	4.63 x 10 ⁸	2.60 x 10 ⁸ - 2.11 x 10 ⁹	1345	2.32 x 10 ⁷	1.44 x 10 ⁷ - 6.05 x 10 ⁷
1987	315	1.42 x 10 ⁸	8.00 x 10 ⁷ - 6.49 x 10 ⁸	31	5.38 x 10⁵	3.33 x 10⁵ - 1.40 x 10 ⁶
1988	66	2.98 x 10 ⁷	1.68 x 10 ⁷ - 1.36 x 10 ⁸	179	3.08 x 10 ⁶	1.91 x 10 ⁶ - 8.03 x 10 ⁶
1989	240	1.09 x 10 ⁸	6.10 x 10 ⁷ - 4.94 x 10 ⁸	42	7.20 x 10⁵	4.45 x 10⁵ - 1.87 x 10 ⁶
1990	126	5.70 x 10 ⁷	3.20 x 10 ⁷ - 2.59 x 10 ⁸	32	5.50 x 10⁵	3.41 x 10⁵ - 1.43 x 10 ⁶
1991	11	5.20 x 10 ⁷	2.92 x 10 ⁷ - 2.37 x 10 ⁸	0	0	0 - 0
1994	119	5.38 x 10 ⁷	3.02 x 10 ⁷ - 2.45 x 10 ⁸	4	7.08 x 10 ⁴	4.38 x 10 ⁴ - 1.84 x 10 ⁵
1995	61	2.76 x 10 ⁷	1.55 x 10 ⁷ - 1.26 x 10 ⁸	16	2.67 x 10⁵	1.65 x 10⁵ - 6.97 x 10⁵
1996	68	3.07 x 10 ⁷	1.73 x 10 ⁷ - 1.40 x 10 ⁸	2	3.23 x 10 ⁴	2.00 x 10 ⁴ - 8.41 x 10 ⁴
1997	16	7.24 x 10 ⁶	4.06 x 10 ⁶ - 3.29 x 10 ⁷	3	5.00 x 10 ⁴	3.10 x 10 ⁴ - 1.30 x 10 ⁵
1998	10	4.52 x 10 ⁶	2.54 x 10 ⁶ - 2.06 x 10 ⁷	1	2.30 x 10 ⁴	1.42 x 10 ⁴ - 5.98 x 10 ⁴
1999	132	5.97 x 10 ⁷	3.35 x 10 ⁷ - 2.72 x 10 ⁸	32	5.50 x 10⁵	3.41 x 10⁵ - 1.43 x 10 ⁶
2000	139	6.29 x 10 ⁷	3.53 x 10 ⁷ - 2.86 x 10 ⁸	14	2.40 x 10⁵	1.48 x 10⁵ - 6.25 x 10⁵



Figure 4-1. Map of the Savannah River Estuary including Front, Middle, and Back river channels, major highways, tide gate, and diversion canal. Gellan bead (striped bass egg surrogate) release locations (\clubsuit) and sampling stations (\bullet) are shown. Historic sampling stations where individual efficiencies were calculated denoted by (\blacklozenge). RKM = river kilometer.



Figure 4-2. Estimated striped bass egg abundance in the Savannah River Estuary, 1978-2000. A) Abundance (in 1000s) at the Back River reference station (river kilometer [rkm] 35). B) Abundance (in millions) at the Front River reference station (rkm 40). Note: abundances from 1978, 1984 and 1986 (denoted by •) are from rkm 43.3 because the reference station was not fully sampled those years. Asterisks (*****) denote years of comparable river discharge (± 100 cms) to 1999-2000, when sampling efficiencies were developed. Error bars are ± one standard deviation. Where error bars disappear, end points are denoted.



Figure 4-3. Historic egg densities (number/100 m³) in the Savannah River Estuary, 1978-2000. Front River egg densities (black bars) are from river kilometer (rkm) 43.3 in 1978, 1984, and 1986 and from the reference station (rkm 40) for the remaining sample years. Back River egg densities (grey bars) are from the Back River reference station (rkm 35). Error bars (where available) are standard deviations. Where error bars disappear, end points are denoted. Data are from Dudley and Black (1978), Larson (1985), Van Den Avyle et al. (1990), Wallin and Van Den Avyle (1995), Reinert et al. (1996, 1998), and Will et al. (2000, 2001).

CHAPTER 5

MODELING THE EFFECTS OF HARBOR DEEPENING ALTERNATIVES ON THE RECOVERY OF STRIPED BASS IN THE SAVANNAH RIVER ESTUARY, GEORGIA-SOUTH CAROLINA, U.S.A. ³

³Reinert, T.R. and J. T. Peterson. To be submitted to: *River Research and Applications.*

INTRODUCTION

The Savannah River Estuary (SRE), Georgia-South Carolina, U.S.A., once hosted the largest and most popular striped bass *Morone saxatilis* fishery in Georgia. This population also served as the source of broodstock for a state-sponsored aquaculture program during the 1960s-1970s that focused on stocking reservoirs and riverways throughout the state (and occasionally other states) with striped bass and striped bass-white bass (*M. chrysops*) hybrids. Historically, striped bass spawning aggregations occurred in the upper estuary reaches of the lower Savannah River, between river kilometer (rkm) 40 and 50, and upper Back River (Figure 5-1), from mid-March through early-May. During this time, Georgia Department of Natural Resources (GA-DNR) performed annual broodstock collections by electrofishing the upper estuary areas, particularly the Back River. In the early 1980s, GA-DNR biologists noted declines in the catch per unit effort (CPUE) of large, 9.0 kg striped bass; those declines eventually made broodfish collections in the SRE impractical. By 1989, CPUE of adults had declined by 97% and egg production had declined by 96% (Chapter 3).

Striped bass adults typically spawn in freshwater habitats within or just above the tidally influenced sections of estuaries (Setzler et al. 1980). Because striped bass are broadcast spawners (i.e., gametes are released into the water column and float for a brief period before hatching), early life history stages are susceptible to downstream changes in habitat and water quality. Loss of tidal-freshwater spawning and nursery habitat brought about by increases in salinity and accelerated seaward transport of eggs and larvæ were cited as the primary causes of the decline in the SRE striped bass population (Van Den Avyle and Maynard 1994). These altered conditions were

caused by the implementation of a tide gate on the Back River and a diversion canal that enhanced flushing of sediments from Savannah Harbor (see Figure 5-1). Flood tides were captured by the tide gate and forced through the diversion canal during ebb flow. Entrapment of the flood tide increased salinity in important spawning and nursery areas, and transport through the diversion canal exposed eggs and larvae to harmful or lethal salinity levels in the industrial harbor. During tide gate operation, the saltwater wedge moved 3.33 - 10 km upstream, depending on tidal and discharge conditions (Pearlstine et al. 1993).

Efforts to restore the population began with a fishing moratorium in 1988 and the inception of a state-sponsored stocking program in 1990. Environmental remediation included decommissioning of the tide gate (1991) and filling of the diversion canal (1992). To date, the stocking program has released almost 2 million fish into the SRE. In recent years, egg production and CPUE of large striped bass both appear to be increasing (Chapter 3). Adults are maturing properly and in a timely fashion (W ill et al. 2002), and salinity levels in historic spawning and nursery habitats are similar to those prior to the decline (Chapter 3). Additionally, recent captures of wild-spawned larvae and juveniles indicate that natural reproduction is occurring and is successful (Collins et al. 2003; Jennings and W eyers 2003). The increasing abundance of larger fish should result in continued increases in egg production and continued recruitment. However, current efforts to deepen the Savannah Harbor may preclude striped bass recovery by allowing saltwater intrusion into spawning and nursery habitats.

In 1996, the Georgia Ports Authority (GPA) began investigations into the feasibility of deepening the Savannah Harbor (see Figure 5-1). At present, harbor depth is 12.8 m

at mean low water (MLW), and GPA is sponsoring investigations examining deepening alternatives of 0.6, 1.2, and 1.8 m. A consulting firm, Applied Technology and Management (ATM), is constructing a three-dimensional hydrodynamic model to assess the environmental effects of these alternatives. Eventually this model should be able to predict potential changes in salinity, among other variables, under a variety of deepening scenarios, river flows, and mitigation options (Bo Ellis, ATM, personal communication).

The proposed harbor deepening will directly affect the Front River channel to rkm 32 (Figure 5-1) and may have indirect effects further upstream if additional saltwater is conveyed into the estuary via the deeper channel. Recent studies indicate that a majority of striped bass eggs are captured in the upper Front River (Chapter 4). To evaluate effects on striped bass recruitment potential in the SRE, we developed a decision model (Reckhow 1999; Varis and Kuikka 1999) to investigate effects of upriver shifts in the salinity regime on striped bass recruitment potential. We used published studies of striped bass early life history survival and unpublished data characterizing the salinity conditions in the SRE. Once the three-dimensional hydrodynamic model is completed, our decision model may be used to assess the environmental effects of the deepening project on current striped bass recruitment potential. Because our model is based on a salinity shift and not a specific decision (e.g., a 1.2 m deepening), it may be applied to a variety of deepening and mitigation scenarios. Specifically, our objectives were to: 1) develop a predictive relationship between present salinity conditions and survival of early-life history stages of striped bass in the SRE, and 2) develop a decision model incorporating these parameters to evaluate upstream shifts in salinity as a result of harbor deepening and potential effects on striped bass recruitment potential.

METHODS

To evaluate the effects of management decisions (e.g., deepening options) for the SRE on the early life history stages of striped bass, we developed a stochastic recruitment model to estimate striped bass recruitment potential. This model is composed of environmental factors (e.g., river discharge, tidal phase, and salinity), striped bass egg and larval survival, egg distribution, and salinity movement components (Figure 5-2). The model is spatially explicit and operates as a single time step during a hypothetical striped bass spawning season (in the SRE, typically during the month of April). Surface water salinity at specific locations (see Figure 5-1) is modeled as a function of river discharge and tidal phase. Egg and larval survival at each location are modeled as a function of salinity concentration. Egg distribution among historic egg sampling stations (see Figure 5-1) is estimated as a function of river discharge. Striped bass recruitment potential is modeled as the product of egg survival, larval survival, and egg distribution summed across sampling stations. Stochasticity is imposed in a multi-step process (Lee and Rieman 1997; Peterson and Evans 2003) by randomly generating values for the variables of interest. Parameter estimates were generated by specific models to address: (1) salinity, as a function of river discharge and tidal phase; (2) survival rates of eggs and larvae as a function of salinity; and (3) egg distribution as a function of discharge.

Salinity Model

To evaluate effects of increased salinity on survival of striped bass early life history stages, we modeled the current salinity regime of the SRE. This model incorporated tidal phase and river discharge. ATM made observations of salinity in 1997 and 1999 for the purposes of calibrating the three-dimensional hydrodynamic model that will be used for evaluating environmental effects of harbor management decisions. ATM provided surface salinity data from continuous monitoring stations within the SRE, and we used data from stations located between rkm 18.3 and 35.8 (see Figure 5-1). Data were obtained from 15 July 1997 through 26 September 1997, and from 3 additional stations (for a total of 6) from 26 July 1999 through 6 October 1999. Data were recorded at 15 minute intervals in 1997 and 5 minute intervals in 1999.

Because river discharge affects salinity in the SRE (Alber and Sheldon 1999), we incorporated it into our salinity models. Daily means for river discharge were measured at a United States Geological Survey (USGS) gaging station, located at rkm 103 (station ID: 02198500, Clyo, Georgia). Daily discharge was lagged by 4 days, reflecting the amount of time a water mass takes to reach the upper estuary (roughly rkm 50; Bo Ellis, ATM, personal communication). During the salinity study periods, discharge ranged from 154-326 cms. We divided discharge into two categories: low (<225 cms), and average (225-326 cms). Historically (1929-2003), discharge in April, the primary spawning month for striped bass, has averaged 484 (±276 SD) cms. Low flows (<225 cms) have occurred 8.7% of the time, and average flows (225-326 cms; within 1 SD of the long-term mean) have occurred 28% of the time (USGS 2003). Dividing discharge into the aforementioned categories of average and low captured fairly common

(average) and relatively uncommon (low) flows, although we were unable to evaluate higher flows during this study. Additionally, this designation allowed us to typify drought flows (low), which occurred in April during 1999-2002 (USGS 2003).

Each sampling day during the study period also was assigned a value for tidal phase . Daily tidal amplitude was calculated from tidal heights as measured at a National Oceanographic and Atmospheric Administration (NOAA) gaging station (Ft. Pulaski; station ID: 8670870). Mean tidal amplitude for each month was calculated, and days that exceeded 1 SD of the mean were considered spring tides and those below 1 SD of the mean were considered neap . All other days were assigned average . Assignment of tidal phase also was cross-validated with lunar phase for each day. Spring tides occur during full and new moons, whereas neap tides occur during first and last quarter phases (Pond and Pickard 1983). During the study period (which included partial months), neap tides occurred about 16% of the time, spring tides occurred 17% of the time, and average tides occurred 67% of the time (NOAA 2003).

To model salinity patterns in the SRE, salinity measurements from each station were grouped by lagged discharge and tidal phase, for a total of 6 groups per station. For example, for the station at rkm 18.3, the 6 groupings were: 1) average discharge, average tide; 2) average discharge, neap tide; 3) average discharge, spring tide; 4) low discharge, average tide; 5) low discharge, neap tide; 6) low discharge, spring tide; etc. Three distributions (normal, log-normal, and gamma) were fit to each combination of station, discharge, and tidal phase (for examples, see Figure 5-3). We selected the optimal distribution for each grouping based on lowest chi-square score. The best fitting statistical distribution and associated fit parameters (i.e., mean, standard

deviation, shape, scale) were used to characterize the salinity pattern associated with each station under each discharge and tidal phase (Table 5-1). By using a statistical distribution to represent each station/discharge/tidal phase scenario, we implicitly incorporated uncertainty into our models (Peterson and Evans 2003). Thus, we created 36 distributions that described salinity in the SRE (6 distributions for each combination of discharge and tidal phase for each of the 6 salinity stations).

Striped Bass Early Life History Survival Models

To estimate the probability of hatching success and larval survival as a function of salinity for SRE striped bass, we used data from Winger and Lasier (1994) to model this relationship. Winger and Lasier (1994) performed hatching and survival trials on SRE striped bass eggs and larvae to determine salinity tolerances and growth effects. Eggs and larvae were exposed to serial dilutions of saltwater ranging from 0 - 33 0 in 3 0 increments. Percent mortality 72 h post-fertilization for eggs and percent mortality over a 10 d exposure for larvae were calculated. Using their data, we used logistic regression to generate hatching and survival models for striped bass eggs and larvae at salinities ranging from 0 - 24 0. The following relationships were developed:

$$\mathsf{P}_{(egg \ surviva \ l)} = 1/(1 + \mathbf{e}^{(-0.6 \ 664 \ + 0.0 \ 969 \ * sal)}) \tag{1}$$

$$P_{(larval survival)} = 1/(1 + e^{(-0.5069 + 0.1193 * sal)})$$
(2)

where sal = salinity (0).

Egg Distribution Model

Because striped bass eggs are not evenly distributed throughout the SRE, we needed to account for this unequal distribution in the calculation of striped bass

recruitment potential. Certain areas of the SRE may be completely unsuitable for striped bass eggs and larvae, but if the probability of eggs and larvae actually occurring there is extremely low, changes in salinity in that area should not affect the overall striped bass recruitment potential. Typically, the majority of striped bass eggs in the Front River are captured between rkm 35-45 (Wallin and Van Den Avyle 1995a; Reinert et al. 1996, 1998; Will et al. 2000, 2001). However, an exception occurred in 1998 when discharge during April was abnormally high (922 cms) and in 1997, when more eggs were captured at the upper most sampling station (rkm 52; Figure 5-4). To predict the probability of eggs occurring at given locations in the SRE under varying river discharges, we used a discrete multinomial logistic regression on SRE egg capture data (1990-1991: Wallin and Van Den Avyle 1995a; 1994-1996: Reinert et al. 1996; 1997-1998: Reinert et al. 1998; 1999-2000: Will et al. 2000, 2001). Egg sampling stations in the SRE during this period (n=7) ranged from rkm 15 to 52 (Figure 5-1). Not all stations were sampled each year, but 5 of the stations were sampled every year. Discharge during sampling dates ranged from 171 - 922 cms. Using the results of the multinomial regression (Table 5-2), we simulated egg occurrence under two discharge conditions: low (150-225 cms), and average (225-326 cms), to coincide with those used in the salinity model. A value for discharge was randomly chosen and applied to the regression models for each egg sampling station and repeated for 10000 iterations under each discharge condition. Based on these simulations, we calculated the probability of egg occurrence (in 10th percentiles) at each egg sampling station. Probability of egg occurrence was estimated at 1.67 km increments from rkm 18.3 to 35 (to correspond with the salinity model empirical data range). The probability of egg

occurrence consistently was in the 10^{th} percentile for all stations (n = 4) at or downstream of rkm 35, regardless of discharge level (i.e., <10% of eggs occurred at these locations 100% of the time). Therefore, we constrained those stations and modeling increments to the 10^{th} percentile, 100% of the time.

Estimation of Egg and Larval Survival in the SRE

We estimated egg and larval survival at each salinity station under each tidal and discharge combination. To do this, we randomly selected a salinity value from one of the generated distributions in the salinity model, applied this value to the egg survival model (1) and the larval survival model (2) and repeated for 10000 iterations. We did this for each of the 36 discharge/tidal phase salinity distributions described above. From this simulation, we developed conditional survival probability tables segregated into 10th percentiles for each salinity station. To generate survival probabilities between salinity stations, we linearly extrapolated survival at 1.67 km intervals between the stations (over a maximum distance of 5 km), up to the most upstream salinity station (rkm 35). The difference in survival probability between stations under each scenario was divided by the distance between stations in 1.67 km segments. Thus, we generated salinity-based survival probabilities for each 1.67 km increment from rkm 18.3 to 35 (see Table 5-3 for a portion of the conditional survival probability table). Three egg sampling stations (rkm 40, 43.3, and 51.7) included in the egg distribution model were upstream of the predicted salinity distribution model range. Historic salinity data taken in conjunction with egg sampling efforts indicated that surface salinity at each of these locations never exceeded 0.5 0 and was frequently 0.0 0 (Reinert et al. 1996, 1998; Will et al. 2000, 2001). Based on the egg and larval survival models,

salinity at these stations would result in survival probabilities that would occur in the 70th percentile 100% of the time for both larvae and eggs.

Bayesian Belief Network Creation

To evaluate the combined distributions of salinity distribution in the estuary, salinity-based egg and larval survival, and the distribution of eggs in the system, we created a Bayesian belief network (BBN; Charniak 1991). BBNs may be represented graphically (Figure 5-5) and calculated with user-friendly software (in this case, Netica[™]; Norsys Software Corporation 1998), facilitating computation and explanation (Peterson and Evans 2003). Discharge and tidal phase were included as state-specific probabilities based on typical April conditions (Table 5-4). Predictions from BBNs are probabilistic (rather than point estimates with confidence intervals, common in traditional statistical modeling) and explicitly incorporate uncertainty Because uncertainty is expressed probabilistically, results are more meaningful and applicable for decision makers and managers (Reckhow 1999).

To predict changes in striped bass recruitment potential following a given management decision, egg and larval survivals were estimated in response to 1.67 km upstream shifts in salinity. Because behavioral compensation by adult fish in response to changing conditions for ichthyoplankton is unlikely in striped bass (Ulanowicz and Polgar 1980), the egg distribution function in the BBN remained unchanged for the upstream salinity shift simulations. The conditional survival probabilities we estimated for the SRE were sequentially shifted upstream in 1.67 km increments. The furthest downstream location (rkm 18.3) remained at baseline (no change) conditions across all simulations because we did not estimate salinity distribution downstream of that

location. Similarly, the location at rkm 20 changed with the initial 1.67 km shift (adopting the baseline conditions of rkm 18.3) and then remained constant for the following 4 shifts. For the three stations above the range of the salinity model (the three upstream egg sam pling stations), conditional survival probabilities remained at baseline until a projected shift reached the respective station. The station at rkm 40 was affected by shifts of 5 km and greater, when the baseline conditions of rkm 35 reached rkm 40, and the station at rkm 43.3 was affected only by the 8.33 km shift, when the baseline conditions of rkm 51.7) was not affected by salinity shifts and remained at baseline conditions under all scenarios.

RESULTS

Striped bass recruitment potential was highest under the current (no change) salinity regime and decreased with increasing upstream shifts (shown by decreasing utility value; Figure 5-5). We estimate that striped bass recruitment potential decreased 6% under a 1.67 km shift and continued to decline with increasing severity of salinity shifts. A 3.33 km shift resulted in a 13% decrease in utility, whereas 5.0 and 6.67 km shifts resulted in 17.0% and 22% decreases, respectfully. An 8.33 km shift would decrease recruitment potential by 25% (Figure 5-6).

Sensitivity analysis (Clemen 1996) indicated that our estimates of striped bass recruitment potential were most sensitive to egg distribution in the estuary. The egg and larval survival model components had less influence, and tidal phase and discharge had almost no influence at all (Figure 5-7). The range of flows examined was limited, however, and this factor may increase in importance if additional modeling on the effect of discharge on salinity is performed for this system. The response profile of egg occurrence showed that the greatest difference in utility value was in areas representing higher proportions of total egg abundance. Specifically, if more eggs occur in an area, changes in the salinity regime will have a greater effect in that area, because increasing salinity increases the negative effect (Figure 5-8). For this reason, maintaining baseline conditions at the lowest station (rkm 18.3) throughout the simulation and having that condition progress upstream with increasing salinity shift, although conservative, probably had little effect on our estimation of recruitment potential, as striped bass eggs rarely occur at those downstream locations. Additionally, the optimal decision did not change with increasing values of egg occurrence in the estuary (i.e., lines in the response curve do not cross; Figure 5-8).

DISCUSSION

Predicted upstream shifts in salinity had a marked effect on our calculation of striped bass recruitment potential. The relative difference between decisions that would result in an upstream shift in salinity increased with increasing severity of the shift. A 1.67 km shift only resulted in a 6% decrease in recruitment potential, whereas shifts greater than 3.33 km resulted in an almost 20% or greater decrease. A 8.33 km shift would result in a 25% decrease in striped bass recruitment potential. Previously, operation of the tide gate resulted in an average upstream shift of 3.8 km in the Front River and a 5 km upstream shift in the Back River (Pearlstine et al. 1993). Presumably, these salinity shifts contributed to the drastic decline of striped bass reproductive effort and the eventual decline of the total population (Van Den Avyle and Maynard 1994).

Although the salinity regime that existed in the Back River prior to tide gate operation has been mostly restored (Chapter 3), additional harbor development resulting in further salinity intrusion into the Front River could again affect the striped bass population. Based on models developed here, salinity increases in spawning and nursery grounds could result in a perpetual reduction in the number of eggs and larvae that would be available for recruitment. A 20% loss in recruitment potential is severe and would likely greatly hinder the recovery of the striped bass population in the SRE. Fewer spawners would produce fewer eggs, further delaying population restoration. Adult striped bass females in the SRE produce 0.4-1.0 million eggs per female (Will et al. 2002). A 20% reduction in the number of adults could potentially mean a loss of 10s or 100s of millions of eggs. Currently, an adequate population estimate does not exist for SRE striped bass; therefore, projections into the future based on known fecundity and predicted recruitment potential differences are not feasible. Based on these concerns, an optimal decision for future striped bass recovery efforts would be one that ensures little or no upstream shift (1.67 km or less) in the current salinity regime.

Before adopting any policy, decision models should be examined by sensitivity analysis (Clemen 1996). This process identifies the components that have the greatest influence on the decision. Each model component is allowed to vary to determine its relative influence on the expected value of the decision, while all other components are held at baseline values. Of the 5 components in our model, our estimates of egg distribution had the most influence, whereas egg and larval survival components had less influence (Figure 5-7). Tidal phase had very little influence. Perhaps surprisingly, river discharge also had little influence; however, the actual range of flows examined

was limited. For purposes of this model, 91.3% of the flows occurred between 225-326 cms. In reality, this range only represents about 23% of flows that historically occur in April. Flows are typically higher than this and may have a stronger effect than predicted here, by decreasing salinity and by altering egg distribution. Only very high discharge periods appear to affect the distribution of eggs in the SRE (see Figure 5-4). Eggs tended to be captured in the same area, above rkm 35, between discharges of 171-516 cms. We limited our model to the range of flows over which the salinity measurements were taken (154-326 cms) and could not extrapolate beyond the bounds of the data.

Our model was most sensitive to our estimates of egg distribution. In areas where eggs are unlikely to occur, e.g., where < 20% of eggs historically have occurred, the difference in utility between decisions was quite low. The greatest difference in utility was in areas where eggs are most likely to occur, e.g., areas where 50-70% of eggs occur in any given year. Over the range of proportional distribution of eggs in the SRE, the optimal decision to avoid decreased egg and larval survival was always the no change option (Figure 5-8). Striped bass eggs in the SRE tend to occur in the same place, year-after-year, with occasional exceptions (see Figure 5-4). Because these areas are directly upstream of the proposed harbor deepening, they would be particularly vulnerable to upstream shifts in salinity. To increase the value of our information and the precision of our model, continued estimates of where eggs occur in the estuary will add the most value during model updating.

Our model provides an example of how biological and environmental data may be used to evaluate effects of management decisions; however, the current structure of the model is somewhat limited in scope. We did not consider other environmental factors

that may contribute to or limit egg and larval survival. In this system, such variables as dissolved oxygen and current velocity, which also are likely to be affected by changes in harbor depth, may have significant effects on survival of striped bass early life history stages. Additionally, we have not considered survival of later life stages, such as young-of-year (YOY), that may be important to recruitment. While striped bass year-class strength in other systems is thought to be primarily structured by density independent mechanisms during early life history periods (Polgar 1982; Rutherford and Houde 1995; Secor and Houde 1995; North and Houde 2001), such a relationship has not been conclusively investigated in the SRE.

Currently, little is known about striped bass YOY survival in the SRE. Survival studies of stocked individuals in the SRE suggest that long-term survival is higher for larger individuals (150 -250 mm total length) than for smaller ones (15 - 90 mm; Wallin and Van Den Avyle 1995b). Recent captures of known-wild juvenile striped bass suggest that natural recruitment currently is taking place (Collins et al. 2003), but whether there is a survival bottle-neck for wild spawned YOY in the SRE remains to be investigated. Incorporating additional environmental variables and expanding the striped bass recruitment potential metric to include YOY survival likely would create a more robust model. However, this would require additional data, such as survival of YOY, that are not currently available. Despite this, we believe that we have provided a model that incorporates an environmental variable of demonstrated importance (salinity) and life-history stages (eggs and larvae) that have been shown to be crucial to establishment of year-class strength in other systems. Our model serves as an initial

guide for evaluating the potential effects of harbor deepening and may serve as a building bock for additional and more comprehensive modeling in the future.

Decision networks provide managers and decision makers with tools that address the concerns of multiple user-groups and that can integrate research and management goals across disciplines. However, managers and decision makers must be in agreement over the means (the science behind the models) and the ends (preferred outcome). Often total agreement over these objectives is difficult and consensus must be achieved in order to move forward in the decision making process (Lee 1993). In this case, use of a Bayesian belief network allowed us to develop a predictive model that incorporated uncertainty and natural variability, facilitating the creation of a potentially useful tool for managers and decision makers. For example, multiple management decisions may be examined simultaneously and evaluated empirically (Peterson and Evans 2003). In addition, decision networks such as the one developed here can be used to update current information and add additional information used to develop the utility function (Clemen 1996). We hope that the managers and decision makers involved in the Savannah Harbor deepening project can agree that restoration of the striped bass population is a common objective and they find this tool useful in their decision making process.

LITERATURE CITED

- Alber, M. and J. E. Sheldon. 1999. Use of a date-specific method to examine variability in the flushing times of Georgia estuaries. Estuarine and Coastal Shelf Science 49:469-482.
- Charniak, E. 1991. Bayesian networks without tears. Artificial Intelligence Magazine 12(4):50-63.
- Clemen, R. T. 1996. Making hard decisions, second edition. Duxbury Press, Belmont, California.
- Collins, M. R., A. R. Rourk, C. K. Way, and W. C. Post. 2003. Temporal and spatial distribution of estuarine-dependent species in the Savannah River Estuary. Final Report. Georgia Ports Authority. Savannah, Georgia.
- Jennings, C. A. and R. S. Weyers. 2003. Temporal and spatial distribution of estuarine-dependent species in the Savannah River Estuary. Final Report.Georgia Ports Authority. Savannah, Georgia.
- Lee, D. C. and B. E. Rieman. 1997. Population viability assessment of salmonids using probabilistic networks. North American Journal of Fisheries Management 17:1144-1157.
- Lee, K. N. 1993. Compass and gyroscope: integrating science and politics for the environment. Island Press, Washington, D.C.

National Oceanographic and Atmospheric Administration (NOAA). 2003. Retrieve Observed Water Levels and Associated Ancillary Data. http://www.co-ops.nos.noaa.gov/data_res.html. Last accessed 07 November 2003.
Norsys Software Corporation. 1998. Netica 1.12. www.norsys.com.

- North, E. W. and E. D. Houde. 2001. Retention of white perch and striped bass larvae: biological-physical interactions in Chesapeake Bay Estuarine Turbidity Maximum. Estuaries 24:756-769.
- Pearlstine, L. G., W. M. Kitchens, P. J. Latham, and R. D. Bartleson. 1993. Tide gate influences on a tidal marsh. Water Resources Bulletin 29:1009-1019.
- Peterson, J. T. and J. W. Evans. 2003. Quantitative decision analysis for sport fisheries management. Fisheries 28(1):10-21.
- Polgar, T. T. 1982. Factors affecting recruitment of Potomac River striped bass and resulting implications for management. Pages 427-442 in: Kennedy, V. S. ed.,
 Estuarine Comparisons: Proceedings of the 6th Biennial International Estuarine Research Federation Conference, Academic Press.
- Pond, S. and G. L. Pickard. 1983. Introductory dynamical oceanography, second edition. Pergamon Press, New York.
- Reckhow, K. H. 1999. Water quality prediction and probability network models Canadian Journal of Fisheries and Aquatic Sciences 56:1150-1158.
- Reinert, T. R., J. Wallin, and M. J. Van Den Avyle. 1996. Abundance and distribution of striped bass eggs and larvae in the Savannah River Estuary - Implications for channel dredging window, 1994 - 1996. Final Report, U.S. Army Corps of Engineers Savannah District, Savannah, Georgia.
- Reinert, T. R., K. L. Jefferson, and C. A. Jennings. 1998. Abundance and distribution of striped bass eggs and larvae in the Savannah River Estuary Implications for

channel dredging window. Final Report, U.S. Army Corps of Engineers Savannah District, Savannah, Georgia.

- Rutherford, E. S. and E. D. Houde. 1995. The influence of temperature on cohortspecific growth, survival, and recruitment of striped bass, Morone saxatilis, larvae in Chesapeake Bay. Fishery Bulletin U.S. 93:315-332.
- Secor, D. H. and E. D. Houde. 1995. Temperature effects on the timing of striped bass egg production, larval viability, and recruitment potential in the Patuxent River (Chesapeake Bay). Estuaries 18:527-544.
- Setzler, E. M., W. R., Boynton, K. V. Wood, H. H. Zion, L. Lubbers, N. K. Mountford, P.
 Frere, L. Tucker, and J. A. Mihursky. 1980. Synopsis of biological data on striped bass, *Morone saxatilis* (Walbaum). National Oceanic and Atmospheric
 Administration (NOAA) Technical Report, National Marine Fisheries Service (NMFS) Circular 433: Food and Agriculture Organization (FAO) Synopsis No. 121.
- Ulanowicz, R. E. and T. T. Polgar. 1980. Influences of anadromous spawning behavior and optimal environmental conditions upon striped bass (*Morone saxatilis*) year-class strength. Canadian Journal of Fisheries and Aquatic Sciences 37:143-154.
- United States Geological Survey (USGS). 2003. Water Resources of Georgia. http://ga.water.usgs.gov/. Last accessed 07 November 2003.
- Van Den Avyle, M. J. and M. A. Maynard. 1994. Effects of saltwater intrusion and flow diversion on reproductive success of striped bass in the Savannah River estuary.
 Transactions of the American Fisheries Society 123:886-903.

- Varis, O. and S. Kuikka. 1999. Learning Bayesian decision analysis by doing: lessons from environmental and natural resources management. Ecological Modeling 119:177-195.
- Wallin, J. E. and M. J. Van Den Avyle. 1995a. Annual trends and spatial patterns of striped bass egg abundance in the Savannah River. Final Report. Georgia
 Department of Natural Resources. Social Circle, Georgia.
- -----. 1995b. Evaluation of the Savannah River striped bass stocking program, 1990-1994. Final Report. Georgia Department of Natural Resources. Social Circle, Georgia.
- Will, T. A., T. R. Reinert, and C. A. Jennings. 2000. Spatial assessment of current and historic spawning sites of striped bass, *Morone saxatilis*, in the Savannah River estuary. Final Report. U.S. Army Corps of Engineers, Savannah District. Savannah, Georgia.
- -----. 2001. Assessment of spawning sites and reproductive status of striped bass, *Morone saxatilis*, in the Savannah River Estuary. Final Report. Georgia Ports Authority. Savannah, Georgia.
- -----. 2002. Maturation and fecundity of a stock-enhanced population of striped bass in the Savannah River Estuary, U.S.A. Journal of Fish Biology 60:532-544.
- Winger, P. V. and P. J. Lasier. 1994. Effects of salinity on striped bass eggs and larvae from the Savannah River, Georgia. Transactions of the American Fisheries Society 123:904-912.

Table 5-1. Selected distribution (N: Normal; LN: Log-normal; or G: Gamma) and associated scale and shape (mean and standard deviation for N distributions, scale and shape for LN and G) parameters for each station, discharge, and tidal phase combination. Salinity data for each station, denoted by river kilometer, were fit with all three distributions and the best fitting model (based on lowest Chi-square score) was selected. Discharge: Average = 225-326 cms, Low = <225 cms.

Station (rkm)	Discharge	Tidal Phase	Distribution, Scale, Shape
18.3	Average	Average	N, 10.8, 3.5
		Neap	N, 9.8, 1.6
		Spring	G, 1.4, 7.4
	Low	Average	LN, 2.5, 0.3
		Neap	N, 11.8, 2.5
		Spring	G, 1.0, 12.9
23.3	Average	Average	G, 0.5, 14.4
		Neap	LN, 1.9, 0.2
		Spring	G, 0.7, 10.2
	Low	Average	LN, 2.0, 0.4
		Neap	N, 8.8, 2.5
		Spring	G, 1.2, 7.5
26.7	Average	Average	N, 5.5, 2.4
		Neap	G, 0.4, 12.0
		Spring	N, 4.1, 2.2
	Low	Average	LN, 1.8, 0.5
		Neap	LN, 1.8, 0.3
		Spring	G, 1.2, 5.2

Station (rkm)	Discharge	Tidal Phase	Distribution, Scale, Shape
30.8	Average	Average	G, 1.3, 1.9
		Neap	G, 1.6, 2.1
		Spring	G, 1.4, 1.5
	Low	Average	G, 2.1, 1.5
		Neap	N, 4.6, 2.5
		Spring	G, 1.5, 2.1
33.3	Average	Average	G, 2.4, 0.6
		Neap	LN, -1.1, 1.5
		Spring	G, 1.3, 0.7
	Low	Average	G, 3.5, 0.7
		Neap	G, 6.0, 0.5
		Spring	G, 1.8, 0.9
35.0	Average	Average	G, 2.9, 0.6
		Neap	G, 4.1, 0.6
		Spring	G, 1.7, 0.6
	Low	Average	G, 3.8, 0.5
		Neap	G, 5.0, 0.6
		Spring	G, 2.6, 0.7

Table 5-1continued.

Table 5-2. Multinomial logit model of striped bass egg abundance by river kilometer (rkm) versus river discharge (cms) in the Savannah River Estuary (SRE) during sampling seasons 1990-91, 1994-2000. Estimated coefficients should be interpreted relative to station 15.0 rkm (the baseline). Components of this model were used in simulations to predict egg distribution in the SRE based on 2 discharge conditions, Average (225-326 cms) and Low (<225 cms). Egg capture and discharge data are from W allin and Van Den Avyle (1995a); Reinert et al. (1996, 1998); and Will et al. (2000, 2001).

Sampling Location	Model Parameter	Estimated coefficient	Standard Error	Upper 95% CI	Lower 95% CI
rkm 20.0	Intercept	2.212	1.647	5.440	-1.015
	Discharge	-0.003	0.003	0.003	-0.008
rkm 31.7	Intercept	4.245	1.414	7.017	1.472
	Discharge	-0.003	0.002	0.002	-0.007
rkm 35.0	Intercept	4.583	1.401	7.328	1.838
	Discharge	-0.002	0.002	0.002	-0.007
rkm 40.0	Intercept	9.220	1.394	11.953	6.487
	Discharge	-0.009	0.002	-0.004	-0.013
rkm 43.3	Intercept	10.692	1.395	13.427	7.957
	Discharge	-0.012	0.002	-0.007	-0.016
rkm 51.7	Intercept	8.878	1.398	11.618	6.138
	Discharge	-0.009	0.002	-0.005	-0.014

Table 5-3. Example of conditional survival probabilities for striped bass larvae in the Savannah River Estuary based on estimated salinity levels. River kilometers (rkm) in **bold** are stations where salinity was measured. Survival probabilities between stations with measured salinity were linearly extrapolated. Survival probabilities are presented only for baseline (no change) conditions in the lower 5 rkm in the study region. Discharge: Average = 225-326 cms, Low = <225 cms. Probabilities were never in the 90 or 100th percentiles and thus are not shown.

						Percent	Percentiles			
Location (rkm)	Discharge	Tidal Phase	10th	20th	30th	40th	50th	60th	70th	80th
18.3	Average	Average	0.00	0.08	0.38	0.36	0.15	0.02	0.01	0.00
		Neap	0.00	0.00	0.16	0.68	0.15	0.01	0.00	0.00
		Spring	0.00	0.06	0.33	0.38	0.18	0.04	0.00	0.01
	Low	Average	0.00	0.08	0.40	0.45	0.06	0.01	0.00	0.00
		Neap	0.00	0.05	0.46	0.40	0.08	0.01	0.00	0.00
		Spring	0.18	0.13	0.12	0.15	0.17	0.20	0.05	0.00
20.0	Average	Average	0.03	0.08	0.28	0.27	0.14	0.11	0.09	0.00
		Neap	0.00	0.00	0.11	0.54	0.33	0.02	0.00	0.00
		Spring	0.00	0.04	0.23	0.35	0.32	0.05	0.00	0.01
20.0 Lo	Low	Average	0.02	0.08	0.29	0.34	0.09	0.11	0.07	0.00
		Neap	0.00	0.03	0.35	0.43	0.17	0.02	0.00	0.00
		Spring	0.14	0.12	0.12	0.16	0.19	0.22	0.05	0.00

Table 5-3	continued.
-----------	------------

						Percentiles				
Station	Discharge	Tidal Phase	10th	20th	30th	40th	50th	60th	70th	80th
21.7	Average	Average	0.05	0.07	0.18	0.19	0.14	0.19	0.18	0.00
		Neap	0.00	0.00	0.06	0.40	0.51	0.03	0.00	0.00
		Spring	0.00	0.02	0.14	0.33	0.45	0.06	0.00	0.00
	Low	Average	0.03	0.07	0.19	0.22	0.13	0.21	0.15	0.00
		Neap	0.00	0.02	0.23	0.45	0.25	0.04	0.01	0.00
		Spring	0.11	0.12	0.13	0.17	0.20	0.23	0.04	0.00
23.3	Average	Average	0.08	0.07	0.08	0.10	0.13	0.28	0.26	0.00
		Neap	0.00	0.00	0.01	0.26	0.69	0.04	0.00	0.00
		Spring	0.00	0.00	0.04	0.30	0.59	0.07	0.00	0.00
	Low	Average	0.05	0.07	0.08	0.11	0.16	0.31	0.22	0.00
		Neap	0.00	0.00	0.12	0.48	0.34	0.05	0.01	0.00
		Spring	0.07	0.11	0.13	0.18	0.22	0.25	0.04	0.00

Table 5-4. Categorical model parameters, prior probability used in model process, and source/rationale of how each was selected for root nodes in the Bayesian belief network used to evaluate harbor management decisions on striped bass recruitment potential in the Savannah River Estuary.

Parameter	Category	Prior Probability	Source/rationale
Tidal Phase	Average	0.67	based on April tidal phase frequency,
	Neap	0.16	1999-2003; NOAA (2003)
	Spring	0.17	
Discharge	Average	0.91	based on mean April river discharge
	Low	0.09	1929-2003, USGS (2003)



Figure 5-1. Map of Savannah River Estuary, Georgia-South Carolina, showing maintained river channel, major highways, tide gate, and diversion canal (filled). Salinity measurement stations denoted by (). Egg sampling stations denoted by (). Dark grey channel depth is 12.8 m, mean low water (MLW). Light grey channel depth is 11.6 m MLW. The proposed deepening will occur only along the current 12.8 m channel. rkm = river kilometer.



Figure 5-2. Influence diagram representing how deepening options for the Savannah Harbor may affect striped bass recruitment potential. The decision node is square, probabilistic variables are ovals, and objective functions are represented as rounded rectangles (Varis and Kuikka 1999). Directional arrows indicate a functional dependence (e.g., salinity is dependent upon the deepening option, tidal phase, and river discharge).



Figure 5-3. Examples of statistical distributions fit to salinity data collected in the Savannah River Estuary, Georgia-South Carolina, 1997 and 1999. Distributions included normal (black), log-normal (red) and gamma (green). Scenarios included combinations of discharge ('A' = average, 'L' = low) and tide phase ('A' = average, 'N' = neap, and 'S' = spring). Average discharge = 225-326 cms and low discharge <225 cms. Data courtesy of Applied Technology and Management, Inc. Station location is noted by river kilometer (rkm). Overall, 6 scenarios were modeled for each station.



Figure 5-4. Percent of striped bass eggs captured by river kilometer (rkm) in the Front River, Savannah River Estuary, 1994-2000. Numbers in boxes represent average April discharge (cms) during sampling as reported at the U.S. Geological Service gauging station near Clyo, Georgia. Annually, most eggs were captured between rkm 35 and 45. The two atypical years are represented by dashed lines. In 1998 (\blacksquare), discharge was abnormally high (922 cms) and eggs were shifted downstream. In 1997 (\blacklozenge), most eggs were captured at the upper most sampling station. The grey lines represent 1999 (\bullet) and 2000 (\blacklozenge), when egg sampling did not occur at the most downstream station, rkm 15. Data are from Reinert et al. (1996, 1998) and Will et al. (2000, 2001).



Figure 5-5. Bayesian Belief Network (from the program NeticaTM) depicting joint probability distribution of salinity-based survival of striped bass eggs and larvae and predicted egg distribution in the Savannah River Estuary (SRE). Survival probabilities and egg distribution are given in 10th percentiles. Discharge (A = 'average' and 'L' = 'low) and tidal phase ('A' = average, 'N' = neap, and 'S' = spring) are included as state-specific probabilities based on mean April conditions, the primary spawning month for SRE striped bass. SBRP = striped bass recruitment potential, the utility value for this network. Utility scores for respective salinity shifts are given in the 'saltshift' box (the decision node).



Figure 5-6. Estimated relative change in striped bass recruitment potential if decisions regarding Savannah Harbor deepening and mitigation options result in 1.67 km upstream shifts in the prevailing salinity regime. Percentage decreases are relative to no change in salinity.



Figure 5-7. Tornado diagram for one-way sensitivity analysis with model components listed from greatest (top) to least influential for the Savannah Harbor deepening scenarios that result in shifts in the prevailing salinity regime. For each component, the bar length represents the extent to which striped bass recruitment potential varies in response to changes in the value of that component, with all other components held at base values.



Figure 5-8. Response profile of striped bass recruitment potential with proportion of striped bass egg occurrence. Difference in utility value is greatest in areas representing higher proportions of total egg abundance (i.e., if more eggs occur in an area, changes in the salinity regime will have a greater effect in that area). In this case, decision lines never cross, indicating the optimal decision does not change with changes in how eggs are distributed in the estuary.

CHAPTER 6

CONCLUSIONS

Since the arrival of the first colonists to the lower Savannah River Estuary, a primary focus has been on altering and maintaining the Savannah River to enhance transportation and commerce. Currently, the port of Savannah is the fifth busiest container port in the United States, with over 1 million TEUs (20-foot equivalent units) passing through the port facilities in 2003 (U.S. DOT 2004). The drive to maintain this important economic industry has resulted in a series of recent and proposed alterations to the river channel. Beginning with the 1977 installation of the tide gate and followed by a deepening in 1994, the Georgia Ports Authority (GPA) is pursuing an investigation into an additional deepening of up to 2 m. Previous alterations for harbor imporvement have not been without unintended environmental consequences, and the lessons learned from the past should be considered when evaluating additional harbor development.

Increased salinity intrusion into upper reaches of the estuary has had multiple negative effects on the ecosystem. Operation of the tide gate and attendant diversion canal significantly increased upstream salinity (Pearlstine et al. 1993). The Savannah National Wildlife Refuge suffered a 74% loss of the tidal-freshwater marsh community through conversion to saline and brackish marsh species (Pearlstine et al. 1990). Striped bass spawning and nursery grounds were affected, and altered pathways of egg and larval transport resulted in a 96% reduction in egg production (Van Den Avyle

et al. 1990). Concurrent with the decline in egg production was a decline in overall striped bass abundance, evidenced by a 97% decline in adult catch per unit effort (Chapter 3).

Habitat restoration and mitigation plans have been effective at correcting some of the problems associated with altered freshwater flow and salinity intrusion. Decommissioning the tide gate (1991) and filling the diversion canal (1992) had immediate effects on the distribution of saltwater in the National Wildlife Refuge (Chapter 3). Interstitial marsh salinities decreased and freshwater marsh plants recolonized areas previously converted to brackish marsh (Latham and Kitchens 1996). Stock enhancement has increased the number of adult striped bass in the river, and the number of eggs appears to be increasing as well (Chapter 3). Although previously rare or absent in samples, wild larval and juvenile striped bass are starting to appear in the system, demonstrating successful natural reproduction and recruitment (Collins et al. 2003; Jennings and Weyers 2003).

The importance of striped bass in the Savannah River is reflected both economically and ecologically. Savannah River striped bass have and continue to represent an economically important component of the recreational fishing industry in Georgia (U.S. DOI 1998). Additionally, striped bass are a major component of the Savannah River Estuary and of most estuarine systems along the Atlantic coast, and serve in the top-predator echelon of estuarine food webs (Setzler et al. 1980). Further, striped bass in the Savannah and Ogeechee rivers are genetically distinguishable from neighboring systems (I. Wirgin, New York University Medical Center, personal communication). Because striped bass south of the Roanoke River (NC) are riverine

and rarely venture into the ocean or other rivers, they may be forming distinct subpopulations. Differences in egg characteristics found among these populations may represent population adaptations to native watersheds, thus increasing the need to conserve the genetic identity of these groups (Bergey et al. 2003).

Historically, Savannah River striped bass have been thought to use the Back River area as the primary spawning location (Smith 1970; Dudley and Black 1978; Larson 1985; Van Den Avyle 1990). As such, harbor development proponents have suggested that if conditions in the Back River could be restored for striped bass reproduction, additional development of the Front River harbor may be pursued. However, recent investigations have found biases in the sampling methodology that led to the conclusion that striped bass eggs were more numerous in the Back River (Reinert et al. 2004). Back-calculating egg abundances in the estuary to 1978, Front River egg abundance typically has been at least an order of magnitude greater than in the Back River (Chapter 4). Additionally, eggs spawned in the Front River may contribute to captures in the Back River and vice versa (Reinert et al. 2004). The Front River may be more important to striped bass recruitment than previously considered. This is not to suggest that the Back River is any less important. Indeed, the population decline of the 1980s primarily was blamed on the operation of the tide gate, which increased salinity in Back River areas (Van Den Avyle et al. 1990). This suggests that the Back River is important to striped bass recruitment in the Savannah River Estuary. Any Front River-spawned eggs traveling down the Back River also would have encountered harmful salinities and been shunted into the harbor via the diversion canal. The importance of the upper Front River may also be evidenced by the occasional

capture of larvae. Although rare in egg sampling efforts, the few captures of larvae predominantly have been found in the upper Front River (Van Den Avyle et al. 1990). Recently, during an ich thyofaunal survey of the estuary, striped bass larvae were captured only in the upper Front River (Jennings and Weyers 2003). Clearly, the importance of the Front River has been underestimated in the past, and the entire estuary must be viewed as a whole, inter-connected system. Restoration of one area, at the expense of another, is not a viable mitigation alternative.

Future efforts to improve the Savannah Harbor for perceived shipping needs are likely to include harbor deepening. GPA currently is evaluating the feasibility and the environmental impact of 0.6, 1.2, and 1.8 m deepenings of the maintained shipping channel. Salinity in the estuary above the harbor probably will increase as a result of a deeper channel. Models of how increased salinity will affect striped bass egg and larval survival suggest that shifts in the current salinity regime greater than 2 km will have significant and detrimental effects on striped bass recruitment potential (Chapter 5). The area where the majority of eggs are found and the only area to have produced larvae in recent years is directly upstream of the proposed deepening. Interestingly, a deeper harbor may not be the best way to maintain or improve the competitive ability of Savan nah Harbor. In a recent study, harbor depth was not a significant variable explaining the success of ports in the U.S. South (Witters and Ivy 2002). Connectivity to inland markets and berthing space were the primary factors associated with port competitiveness; in 1999, Savannah ranked first in connectivity and third in berthing space in the region. If Savannah Harbor could increase its berthing space (perhaps by using more of Hutchinson's Island or areas further downstream) and the infrastructure

surrounding that space, it may be able to increase its competitiveness without further altering the depth of the river channel.

Throughout this dissertation. I have attempted to present a case history of the striped bass population in the Savannah River Estuary, provide a re-analysis of historic egg-production data, and forecast the potential consequences of additional harbor development on striped bass reproductive potential in the estuary. Hopefully, this dissertation provides some much needed synthesis of the amount of work that has been done over the last 2 decades regarding striped bass in the Savannah River, presents new insights into how striped bass use the estuary to reproduce, and demonstrates what factors may contribute to their continued success or potential lapse back into decline. However, this work does not investigate all of the possible sources of uncertainty regarding the recovery of Savannah River striped bass. One critical component is still unknown: the fate and survival of wild young-of-year (YOY) striped bass. In years past, this component has not been effectively sampled or investigated. Recent captures of known wild larvae and juvenile striped bass in the estuary provide evidence that recruitment is occurring, a phenomenon which warrants further investigation. Additionally, the relationship between river discharge and egg sampling efficiency is unclear. Sampling efficiencies were only calculated over a small range of discharges and may not be robust for other flows, particularly much higher ones. Future studies should focus on further refining sampling efficiency estimates and investigating the fate of wild striped bass YOY in the Savannah River Estuary. I hope that this dissertation provides useful information regarding the past, present, and potential future of striped bass in the Savannah River, and that any conclusions derived

from this work will assist resource managers and policy makers as they attempt to accommodate the sometimes conflicting goals of economic development and natural resource conservation and protection. LITERATURE CITED

- Bergey, L. L., R. A. Rulifson, M. L. Gallagher, and A. S. Overton. 2003. Variability of Atlantic Coast striped bass egg characteristics. North American Journal of Fisheries Management 23:558-572.
- Collins, M. R., A. R. Rourk, C. K. Way, and W. C. Post. 2003. Temporal and spatial distribution of estuarine-dependent species in the Savannah River Estuary. Final Report. Georgia Ports Authority. Savannah, Georgia.
- Dudley, R. G. and K. N. Black. 1978. Distribution of striped bass eggs and larvae in the Savannah River estuary. Proceedings of the Annual Conference Southeastern Association of Fish and Wildlife Agencies 32:561-570.
- Jennings, C. A. and R. S. Weyers. 2003. Temporal and spatial distribution of estuarinedependent species in the Savannah River Estuary. Final Report. Georgia Ports Authority. Savannah, Georgia.
- Larson, S. C. 1985. The distribution and abundance of striped bass eggs in the lower Savannah River. Master's thesis. University of Georgia, Athens.
- Latham, P. J. and W. M. Kitchens. 1996. Changes in vegetation and interstitial salinities on the lower Savannah River: 1986-1994. Final Report. U.S. Fish and Wildlife Service. Atlanta, Georgia.
- Pearlstine, L. G., W. M. Kitchens, P. J. Latham, and R. D. Bartleson. 1990. Application of a habitat succession model for the wetlands complex of the Savannah National Wildlife Refuge. Final Report. U.S. Fish and Wildlife Service. Atlanta, Georgia.

- -----. 1993. Tide gate influences on a tidal marsh. Water Resources Bulletin 29:1009-1019.
- Reinert, T. R., T. A. Will, and C. A. Jennings. 2004. Use of egg surrogates to estimate sampling efficiency of striped bass eggs in the Savannah River. North American Journal of Fisheries Management 24:704-710.
- Setzler, E. M., W. R., Boynton, K. V. Wood, H. H. Zion, L. Lubbers, N. K. Mountford, P.
 Frere, L. Tucker, and J. A. Mihursky. 1980. Synopsis of biological data on striped bass, *Morone saxatilis* (Walbaum). National Oceanic and Atmospheric Administration Technical Report, National Marine Fisheries Service Circular 433: Food and Agriculture Organization Synopsis No. 121.
- Smith, L. D. 1970. Life history studies of striped bass. Final Report, Project A.F.2-2. Georgia Department of Natural Resources, Atlanta, Georgia.
- U.S. Department of the Interior (U.S. DOI), Fish and Wildlife Service and the U.S. Department of Commerce, Bureau of the Census. 1998. 1996 Survey of Fishing, Hunting, and Wildlife-Associated Recreation -- Georgia. U.S. Fish and Wildlife Service Report FHW/96-GA.
- United States Department of Transportation, Maritime Administration (U.S. DOT). 2004.
 U.S. Waterborne Foreign Trade, Containerized Cargo: Top 30 U.S. Ports
 Calendar year 2003. http://www.marad.dot.gov/Marad_Statistics/index.html. Last
 accessed: 19 March 2004.
- Van Den Avyle, M. J., M. A. Maynard, R. C. Klinger, and V. S. Blazer. 1990. Effects of Savannah Harbor development on fishery resources associated with the

Savannah National Wildlife Refuge. Final Report. U.S. Fish and Wildlife Service. Atlanta, Georgia.

Witters, R. L. and R. I. ky. 2002. Port competition for cargo tonnage in the U. S. South. Southeastern Geographer 42:65-80.