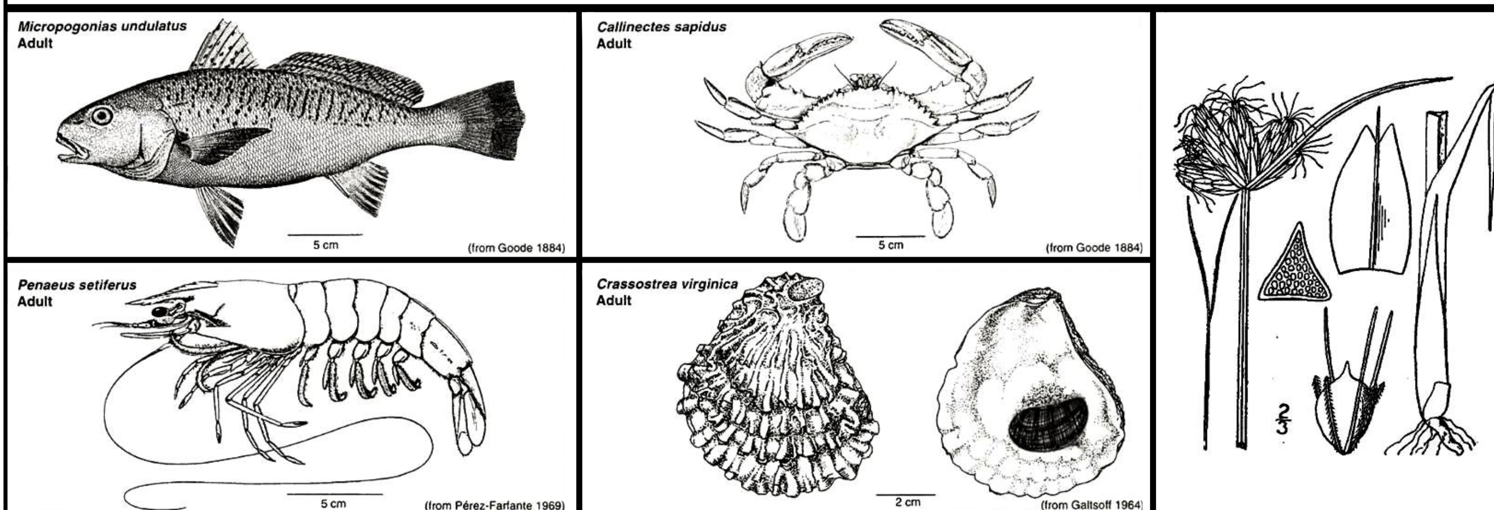
Estuarine Focal Species Summary Report

For the

Sabine/Neches BBEST

Ecological Information to Support Environmental Flow Recommendations



(Patillo et al. 1997; USDA 2009)

Submitted to:

Sabine/Neches BBEST

Prepared by:

BIO-WEST, Inc.

1812 Central Commerce Court
Round Rock, Texas 78664

August 2009

Estuarine Focal Species Summary Report

For the

Sabine/Neches BBEST

Ecological Information to Support Environmental Flow Recommendations

Submitted to:

Sabine/Neches BBEST

Prepared by:

BIO-WEST, Inc.
1812 Central Commerce Court
Round Rock, Texas 78664

August 2009

TABLE OF CONTENTS

TABLES & FIGURES

Tables

Figures

1.0 INTRODUCTION

Freshwater inflows have long been known to play a key role in the functioning of bays and estuaries. In 2007, the Texas Legislature passed Senate Bill 3, directing the development of environmental flow recommendations to protect a "sound ecological environment" and to maintain the productivity, extent, and persistence of key aquatic habitats in bays and estuaries (SAC 2009).

This document provides a summary of ecological information on focal plant and animal species within the Sabine-Neches Estuary (Sabine Lake) to support environmental flow recommendations by the Sabine/Neches Basin and Bay Expert Science Team (BBEST). As noted in SAC (2009), aquatic organisms in estuaries are influenced by the effects of inflow, notably on salinity, nutrients, and sediments rather than by the inflow itself. This differs from the response of riverine organisms, which do respond directly to velocity associated with river flow as an important ecological determinant.

The purpose of this report is to:

- Summarize the dependencies of focal species with regard to habitat conditions, especially as affected by freshwater inflow variation, salinity patterns and seasonality
- Provide graphical or tabular summaries of population abundance or biodiversity trends within the estuary
- Describe key relationships between inflow and salinity variation and the ecology of focal species at the individual or population level

Several previous reports on freshwater inflow to Sabine Lake were reviewed in addition to a large collection of scientific literature on Gulf of Mexico (GOM) estuaries and the focal species identified in this report. Relative to other major Texas estuaries, biological data for the Sabine Lake system has been collected for a shorter period of time. However, information regarding the life history and habitat requirements of many of the focal species was abundant in the literature. Range, abundance and biodiversity trend information specifically within Sabine Lake was less ample, but enough information was available to describe the freshwater inflow-ecology relationship for at least one life stage of these estuarine-dependent focal species.

Sabine Lake

Sabine Lake is a relatively large, shallow, brackish-water estuary located on the Louisiana-Texas state line that receives freshwater inflow from the Sabine and Neches Rivers. Sabine Lake is connected to the GOM by Sabine Pass, which is very long and narrow compared to other Texas tidal passes. The tidal range in Sabine Lake is generally in the range of 0.5 to 0.75 feet, and tides are generally minor except when amplified by wind. The maximum depth in Sabine Lake is less than 10 feet, although dredged portions of the rivers, canals and pass may be over 40 feet deep.

Sabine Lake is roughly divisible into three general environments that TDWR (1981) identified based on composition and nature of bottom sediments, salinity and faunal composition. The upper part of the lake includes the river-influenced environment, characterized by low salinity (generally less than 10 parts per thousand [ppt]), lower species diversity (mainly mollusks and crustaceans) and generally firm mud bottom sediments. The middle part of Sabine Lake has slightly higher salinities than the upper estuary and bottom sediment is largely bioturbated mud. The lower part of Sabine Lake is an open bay that is influenced by tidal interchange, with salinity ranging from 10 to 20 ppt, bioturbated mud bottom sediments, and relatively high species diversity (TDWR 1981).

2.0 SABINE-NECHES ESTUARY FOCAL SPECIES

Ten estuarine focal species were chosen to support environmental flow recommendations to the Sabine/Neches BBEST. The list of focal species were collectively identified by BIO-WEST, Inc. (BIO-WEST) in collaboration and coordination with the Biological Subcommittee of the Sabine/Neches BBEST, state agencies involved in the Texas Bays and Estuary Study Program, Louisiana Department of Wildlife and Fisheries (LDWF), and local universities. The Biological Subcommittee provided the initial guidance with regard to focal species, including those species that are sensitive to salinity and freshwater inflow, serve as valuable ecosystem indicators, or that have been identified as focal species in other studies within the northwestern Gulf of Mexico region.

A preliminary review was made of the Texas Parks and Wildlife Department's (TPWD) 2005 publication, *Freshwater Inflow Recommendation for the Sabine Lake Estuary of Texas and Louisiana*, in which eight commercially and recreationally important fish and crustacean species were chosen, including Atlantic croaker (*Micropogonias undulatus*), spot (*Leiostomus xanthurus*), Gulf menhaden (*Brevoortia patronus*), white shrimp (*Litopenaeus setiferus*), blue crab (*Callinectes sapidus*), brown shrimp (*Farfantepenaeus aztecus*), as well as two other species in which analysis was not provided due to low catch rates, spotted seatrout (*Cynoscion nebulosus*) and red drum (*Sciaenops ocellatus*). Several other species suggested by TPWD staff included sand seatrout (*Cynoscion arenarius*), hardhead catfish (*Ariopsis felis*), threadfin shad (*Dorosoma petenense*), oysters (*Crassostrea virginica*), Atlantic rangia (*Rangia cuneata*), bald cypress (*Taxodium distichum*), water tupelo (*Nyssa aquatic*), overcup oak (*Quercus lyrata*), river birch (*Betula nigra*), olney bulrush (*Schoenoplectus americanus*) and bulltongue (*Sagittaria lancifolia*).

Ultimately, ten focal species were chosen to include two wetland plants, two mollusks, three crustaceans, and three fish species (**Table 1**). This list of species was compiled with consideration of representing: a diversity of estuarine-dependent species across a number of taxa and trophic levels; species that "enjoy some prominence" (SAC 2009) or those that are economically important; species that are abundant in Sabine Lake or that utilize the estuary during a particular life stage; and species that are a key ecological component to the ecosystem. No state or federally threatened and endangered fish, crustacean, molluscan, or wetland plant species occur in Sabine Lake and therefore were not considered. Lastly, our focus for the estuarine focal species selection and freshwater inflow-ecology relationship summary was concentrated on aquatic species within Sabine Lake itself and its fringing marshes. Therefore, additional wildlife species associated with wetlands surrounding Sabine Lake were not included in this summary document. In a separate report (Fluvial Focal Species Summary [BIO-WEST 2009]), a number of recommended species more closely associated with the Sabine and Neches river basins were evaluated.

Table 1. Estuarine-dependent focal species identified to support environmental flow recommendations of the Sabine/Neches BBEST.

Wetland Plants	Bivalve Mollusks
Olney bulrush (*Schoenoplectus americanus*)	Atlantic rangia (*Rangia cuneata*)
Saltmeadow cordgrass (*Spartina patens*)	American oyster (*Crassostrea virginica*)
Crustaceans	**Fish**
White shrimp (*Litopenaeus setiferus*)	Atlantic croaker (*Micropogonias undulatus*)
Brown shrimp (*Farfantepenaeus aztecus*)	Spot (*Leiostomus xanthurus*)
Blue crab (*Callinectes sapidus*)	Gulf menhaden (*Brevoortia patronus*)

3.0 FOCAL SPECIES SUMMARIES

3.1 Wetland Plant Focal Species

Estuarine wetlands provide shelter, foraging and nursery habitat for many wading and migratory bird species as well as small mammals, fish, shrimp, crabs, and invertebrates. As described in TDWR (1981), the periodic inundation of deltaic and tidal marshes also provides a method for nutrient exchange processes and allows for the movement of detritus from the marshes into the open estuary. The plant communities themselves are structured by both ambient salinity levels and the degree of flooding stress, determined to a large extent by marsh elevation, river flood events and tidal inundation rates (Bertness and Ellison 1987; Flynn et al. 1995) and vary both regionally and over the course of the growing season.

While plant species dominance patterns within wetland communities are not well understood, they are likely related to gradients in salinity and hydrology (Mitsch and Gosselink 2000). Landscape patterns of species dominance are influenced over long time periods, whereas annual gross and net primary productivity of wetland plants can vary seasonally and between years as a result of short-term changes in hydrology (Mitsch and Gosselink 2000). These changes in seasonal and annual productivity may be attributed to individual plants' adaptations to the stressors of salinity and inundation.

Most of the estuarine or tidal fringe wetlands along the GOM formed around the bays that resulted from the flooding and filling of ancient river valleys. The Chenier Plain is a unique salt marsh area on the eastern edge of Texas into Louisiana, formed over the last 3,000 years by sediment input from the shifting of the Mississippi River mouth. Extensive wetlands less than five feet above sea level stretch inland four to fifteen miles along the entire GOM shoreline and a narrower discontinuous band of marsh borders Sabine Lake. Marshes cover most of the lower fifteen miles of the Neches valley, and extensive swamps extend another ten miles up the valley. Swamp and wetlands are also common in the lower fifteen miles of the Sabine valley.

Nearly 35,000 acres of vegetated intermediate, brackish, and salt marshes dominated by cordgrass (*Spartina* spp.) and saltgrass (*Distichlis spicata*) border Sabine Lake (**Figure 1**). Saltmeadow cordgrass (*Spartina patens*) is one of the dominant wetland plant species in brackish marshes around Sabine Lake, with areas dominated by the less salt-tolerant olney bulrush (*Schoenoplectus americanus*) also present (TPWD, *pers. comm*., July 2009). The Texas Point National Wildlife Refuge, the largest salt marsh bordering the estuary, is to the west of the Sabine Pass Ship Channel. Smaller marshes occur along the Sabine and Neches Rivers at the head of the estuary (Armstrong 1987). Most of the salt marsh to the east of the estuary has been designated a National Wildlife Refuge (USFWS 2009).

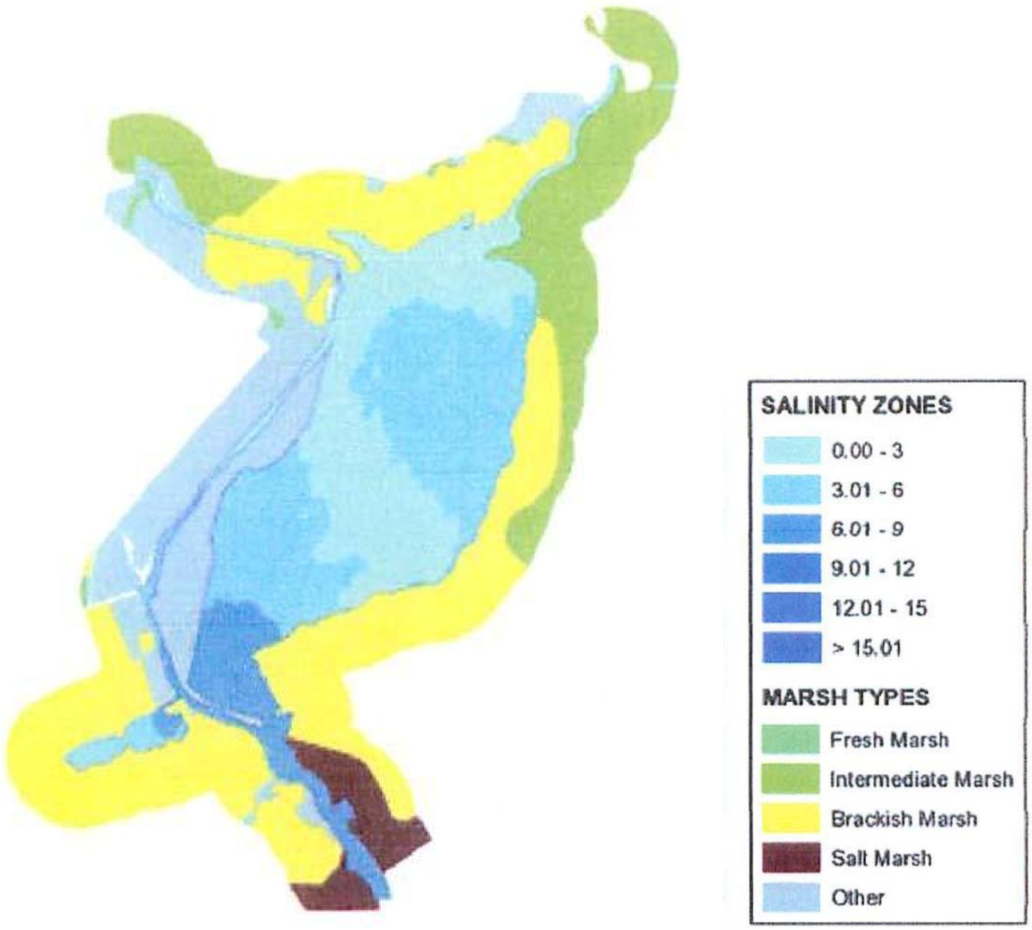


Figure 1. Wetland communities around Sabine Lake relative to a typical April salinity gradient (Source: TPWD 2005).

3.1.1 Olney bulrush (*Schoenoplectus americanus*)

General Description

Olney bulrush *Schoenoplectus americanus* is a member of the sedge family Cyperaceae. Common synonyms of this species that appear in the wetland literature are olney's three-square bulrush, chairmaker's sedge, *Schoenoplectus olneyi*, *Scirpus americanus*, and *Scirpus olneyi*. *S. americanus* is a medium height to tall, native herbaceous plant, that can grow as high as seven feet (Tiner 1987). The seeds, basal portions and rhizomes are eaten by wildlife including ducks, snow geese, nutria and muskrats. *S. americanus* is the single most important food source for muskrats along the Gulf Coast (Stutzenbaker 1999).

Marshes dominated by *S. americanus* occur along the Gulf Coast of Texas, the Chenier Plain of Louisiana, and the mid-Atlantic coast of Maryland and Delaware. It occurs in both low and high marsh habitats, but is most abundant on the high marsh (Ikegami 2006). It also occurs near ponds, lakes, sloughs, swamps, beach pools and sandy flats, often in shallow water up to about one to 2.5 feet (Voss 1972). In mixed plant communities, *S. americanus* is most commonly mixed with *S. patens*. Other species associated with *S. americanus* vegetation communities can include *Spartina alterniflora*, *Spartina cynosuroides*, *Phragmites australis*, *Juncus roemerianus*, *Typha domingensis*, *Pluchea odorata*, *Distichlis spicata*, and *Limonium carolinianum*.

Ecological Relationship with Freshwater Inflow and Salinity

S. americanus can occur in fresh, intermediate and brackish marshes, surviving in salinities from 0 to 12 ppt (Howard & Mendelssohn 1999). However, *S. americanus* reaches its maximum productivity in intermediate marshes where salinities are generally below 3.5 ppt (Stutzenbaker 1999). The aboveground vegetation biomass of *S. americanus* is dependent on the presence of standing water, with biomass being greater during periods of standing water (Bhattacharje et al. 2009). *S. americanus* functions as a stress tolerator, being able to withstand temporary increases in salinity and inundation duration (Howard and Mendelssohn 2000). *S. americanus* tolerance exceeds that of *E. palustris* and *S. lancifolia* (Howard and Mendelssohn 1999).

Life History

S. americanus is a perennial sedge from long stout rhizomes, with single triangular stems that are in small groups. The ability of *S. americanus* to successfully colonize a wide range of habitats is the result of plasticity in clonal architectures. An individual *S. americanus* plant can send out one to three new ramets (consisting of a shoot, roots and a tuber) throughout the growing season.

Green shoots appear aboveground at the beginning of the growing season (generally around April along the Gulf coast) and green shoot production may persist into the winter (Ikegami 2006). Flowering occurs around May and June, although not all shoots flower. Seeds mature and are shed around September. The seeds remain dormant as long as they are submerged in water and thus become a component of the marsh seed bank. Germination and seedling establishment potentially occurs on exposed mudflats following marsh drawdown. The seed germination of this species is strongly regulated by salinity. At a salinity of 4 ppt, germination is reduced by 50 percent, and above 13 ppt no germination occurs (Palmisano and Newsom 1968). Thus, due to high salinity, seed germination is rare in salt marshes.

3.1.2 Salt meadow cordgrass (*Spartina patens*)

General Description

Saltmeadow cordgrass *Spartina patens*, also known as wiregrass or marshhay cordgrass, is a characteristic species of high salt marsh, typically occurring on slightly elevated surfaces where tides may be less regular and where soils may concentrate salts. *Spartina* is a relatively small genus consisting of approximately 14 species, geographically centered along the east coast of North and South America, with outliers on the west coast of North America and Europe. Members of the genus occur primarily in wetlands, especially estuaries (Partridge 1987).

S. patens is an important coastal grass species, occurring along the Atlantic coast from Canada to the Caribbean and Central America, and along the Gulf of Mexico coast into south Texas (Silander 1984). It can also be found along the shores of the Great Lakes. *S. patens* grows in all marsh types but reaches greatest abundance in intermediate to brackish marshes where it often forms meadow-like communities over large expanses (Stutzenbaker 1999).

Ecological Relationship with Freshwater Inflow and Salinity

S. patens is a halophyte with a high salinity tolerance that has the ability to secrete salts out of the plant and onto the leaf surfaces through salt glands, although growth reduction does occur at salinities above 12 ppt (Anastasiou and Brooks 2003). It is limited to high salt marshes because of its inability to tolerate the lower oxygen conditions at lower tidal elevations. The species lacks aerenchyma tissue that would allow it to oxygenate its rhizosphere in anoxic soils (Bertness 1991). Along the Atlantic and Gulf coasts, *S. patens* and *S. alterniflora* often occupy the same tidal marshes. *S. alterniflora* dominates the regularly flooded seaward margins of the marshes, while *S. patens* inhabits higher, less flooded areas (Gleason and Zieman 1981). Unlike *S. patens*, *S. alterniflora* can survive in either high or low salt marshes; however, it is restricted to low salt marshes by competitive displacement by *S. patens* (Bertness 1991).

Life History

S. patens is a rhizomatous grass with dark green stems, 0.3 to 1.2 meters tall, often forming dense, single species stands (Pfauth and Sytsma 1998). *S. patens* is commonly found growing in saline to brackish marshes, sandy beaches and low dunes, tidal flats and marsh ridges from normal high tide to about 4 meters above sea level. *S. patens* typically occurs from mean high water to approximately 0.5 meters above mean high water (Raupp and Denno 1979). A study in Connecticut found that 72 percent of *S. patens* occurred above mean high water (Lefor et al. 1987). This grass is adapted to a wide range of soils from coarse sands to silty clay sediments with pHs ranging from 3.7 to 7.9. *S. patens* will tolerate irregular inundations with salinities from 0 to 35 ppt (USDA 2009).

S. patens culms first appear in the spring, when they emerge through the thick, dead horizon of the previous year's growth (Denno 1980). The major production of roots, rhizomes, stolons, and upright culms occurs under the higher temperature and longer day lengths of the growing season. The highest standing crop occurs from July to October (Seneca 1974).

S. patens flowers from June to September. Seedlings emerge in May, but they do not appear to flower during their first season and produce limited flowers during their second season (Seneca 1974). Seedlings often colonize low sand flats where moisture is adequate for germination and growth (Seneca 1974). Although *S. patens* does produce viable seed, it reproduces primarily via rhizomes (Seneca 1974).

3.2 Bivalve Focal Species

Similar to crustaceans, bivalves play an important role in energy transfer in the estuarine food web. Additionally, adult bivalves are sessile organisms in the estuary and are therefore regarded as integrators of ecological conditions over time. They are filter-feeders and feed on phytoplankton and detritus in the water column by pumping water across the gills and trapping food particles that are then moved to the mouth. Estuarine bivalve species typically spawn in response to environmental conditions, and their free-swimming larvae stay within the estuary until they find adequate substrate to settle on and become sessile (Nelson et al. 1991; Patillo et al. 1997).

Estuary-dependent species occurring within Sabine Lake include Atlantic rangia (*Rangia cuneata*) and eastern oyster (*Crassostrea virginica*). *R. cuneata* is by far the most common bivalve in Sabine Lake (TDWR 1981).

Variability in physicochemical parameters such as temperature, salinity and dissolved oxygen, as well as the availability of food in the water column, and available substrate for recruitment are important in determining the size and location of bivalve populations in an estuary. To the extent available, the life history, physicochemical preference of specific life stages, and spatiotemporal abundance of focal bivalve species are described below.

3.2.1 Atlantic rangia (*Rangia cuneata*)

General Description

Atlantic rangia *Rangia cuneata* (Gray), also known as common rangia, is a small brackish water clam of the family Mactridae (marine bivalve clams) that is an important component of estuarine ecosystems. In low salinity estuarine areas, *R. cuneata* functions as a link between primary producers and secondary consumers. As a non-selective filter feeder, this species transforms large quantities of plant detritus and phytoplankton into clam biomass. *R. cuneata* was a food item of prehistoric Indians and it is still occasionally canned and eaten. Economically, it is more important as a source of shells for road building and industrial products.

R. cuneata is found along the GOM coast from Florida to Mexico and along the Atlantic coast as far north as Maryland and New Jersey (LaSalle and de la Cruz 1985). The highest concentration of clams along the Gulf coast has been associated with shallow water areas less than 6 meters deep, where they are common in a wide range of soft substrates.

This species occupies the fresher portion of Sabine Lake, and are usually scattered throughout the sediments rather than forming reef-like masses (Kane 1961; Harrel 1993). A distribution of *R. cuneata* within the Neches River and a portion of Sabine Lake was established by Harrel (1993). However, the overall distribution of *R. cuneata* in Sabine Lake is not well understood. The National Wildlife Federation (NWF) has a project underway to assess the distribution of Atlantic rangia colonies in Sabine Lake. Maps from previously collected sonar imagery along with a remote sensing survey using side scan sonar will be used to map the estuary bottom and identify rangia colonies throughout Sabine Lake (**Figure 2**).

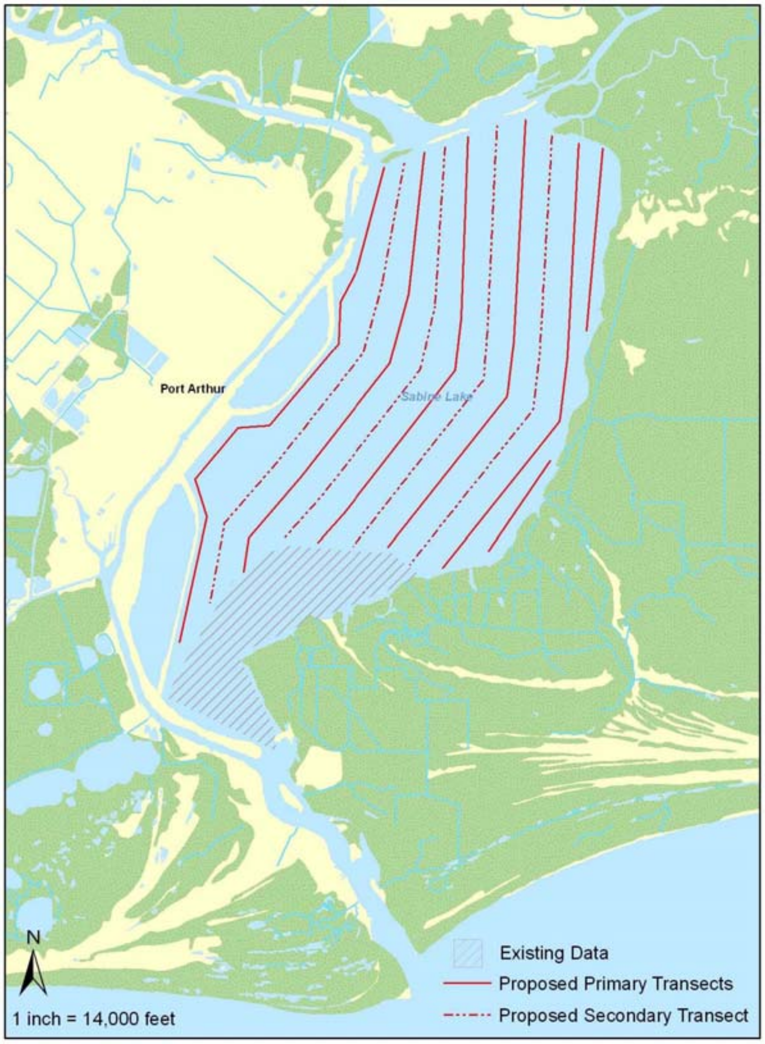


Figure 2. Transect locations for a proposed Atlantic rangia survey in Sabine Lake.

Ecological Relationship with Freshwater Inflow and Salinity

This species is a permanent resident in low salinity (0 to 18 ppt) regions of estuaries (Cain 1975), with populations most abundant in areas of 5 to 15 ppt. The distribution of *R. cuneata* in an estuary overlaps that of *C. virginica*, but *R. cuneata* becomes much more abundant farther up the estuary where the salinities are too low for oysters and for almost all other estuarine competitors or influents (Hopkins and Andrews 1970). A population of *R. cuneata* 40 to 50 kilometers above the mouth of the Neches River was found living in fresh water (salinity below 0.3 ppt) for at least 7 months of the year, and in salinity up to 13 ppt during low river periods, without apparent mortality (Hopkins and Andrews 1970).

Although adults are euryhaline, embryos are much more sensitive to salinity. Spawning at salinities between 2 to 10 ppt allows for the survival of the sensitive stages to the more eurytopic later larval stages (Cain 1973). Once the larvae have developed past the swimming stage and settled to the bottom as juvenile clams, salinity is probably not as critical (Cain 1976). The increased tolerance of the larvae permits good survival during its more stressful pelagic existence.

Life History

The life span of *R. cuneata* has not been confirmed, although it has been estimated between 4 and 15 years (LaSalle and de la Cruz 1985). Annual growth increments of *R. cuneata* in the GOM are reported to range between 0 and 20 mm per year (Fairbanks 1963). Adults range from 2.5 to 6 centimeters in length. *R. cuneata* possess both extracellular (blood and body fluid) and intracellular mechanisms of osmoregulation that enable them to respond to sudden salinity changes in many estuaries (Bedford and Anderson 1972). However, studies indicate the long-term welfare of a *Rangia* population is not the physiology of the adult individuals, but reproduction and recruitment (Hopkins et al. 1973; Cain 1975).

Although spawning may be continuous, peak spawning periods have been documented from March to May and from late summer to November in Louisiana (LaSalle and de la Cruz 1985). Spawning may be triggered by an increase in temperature and salinity. Cain (1975) and Jovanovich and Marion (1989) indicated that an increase in water temperature to 15 °C appeared to be important in the initiation of spawning. During spawning, gametes are released directly into the water and shelled larvae have been documented within 24 hours of fertilization (Chanley 1965). Although common in a wide range of soft substrates, Fairbanks (1963) reported that larvae were capable of selecting substrate for setting and preferred substrates high in organic content.

R. cuneata can be an important species in the low salinity zones of estuaries along the GOM and may comprise a large portion of the benthic macroinvertebrate biomass in these areas (Cain 1976; Brammer et al. 2007). A combination of low salinity, high turbidity, and a substrate of sand, mud, and vegetation appears to be the most favorable habitat for *R. cuneata* (Tarver 1972). *R. cuneata* are concentrated in areas where salinity seldom exceeds 18 ppt (LaSalle and de la Cruz 1985). Studies indicate optimum conditions for embryo development are water temperatures of 18 to 29 °C and salinities of 6 to 10 ppt. Embryos did not develop at 0 ppt salinity (Cain 1973, 1974). On the Gulf coast, *R. cuneata* tolerates water temperatures as low as 3 °C for at least a few hours, and as high as 32 °C for months, without conspicuous mortality (Hopkins and Andrews 1970).

Parasites and Predators

R. cuneata are parasitized by larvae of Fellodistomatid trematodes (Fairbanks 1963), although only large clams are infected. *R. cuneata* are preyed upon by fish, crustaceans, mollusks and ducks. Moon shell snails, *Polinices* spp., may be predators as suggested by drill holes in *R. cuneata* shells (Hoese 1973). *R. cuneata* are abundant in the diets of blue catfish, freshwater drum, spot, black drum, river shrimp, and blue crab in Louisiana (Darnell 1958, 1961). Ctenophores are also potential predators of *R. cuneata*, which sometime appear in high abundance in certain times of the year. Ctenophores can cause mass mortality of *R. cuneata* larvae.

3.2.2 American oyster (*Crassostrea virginica*)

General Description

The American oyster is a species of oyster that is native to the eastern and GOM coastlines of North America. This species is also referred to as the Eastern oyster, Atlantic oyster, and Virginia oyster. As extremely popular seafood, oysters are of vital economic and cultural importance to the GOM region. Additionally, oysters provide a number of key ecosystem functions: oyster spawn and larvae comprise a large proportion of the planktonic biomass in Texas bays providing a vital food source for many planktivores; oyster reefs provide an important physical habitat for a diverse group of benthic organisms; and oyster filter feeding plays a key role in maintaining water clarity (Kennedy et al. 1996).

Oysters are filter feeders, feeding primarily on phytoplankton and suspended detritus (Langdon and Newell 1996). Oyster reefs are also highly utilized habitats in the estuarine environment, exploited by different species than those utilizing the marsh habitats (Zimmerman 1989). Many animals including fish, crabs, worms and meiofauna use oyster reefs as both a foraging and shelter resource.

Although oysters are present in a few areas, oyster reefs are not as well developed in the Sabine Lake and do not support a commercial fishery as in the other estuaries on the Texas coast. The American oyster occurs singly or as reefs, typically in the more saline part of the lake (**Figure 3**). One large reef is located along the Louisiana shoreline near Blue Buck Point, with another reef along the Texas shoreline approximately opposite the point (Kane 1961).

Ecological Relationship with Freshwater Inflow and Salinity

The oyster has a complex ecological relationship with freshwater inflow and salinity. While adult oysters are euryhaline (5 to 40 ppt salinities), oyster populations are dependent on estuaries for their food supply and in regulating the predator and parasite populations that prey on oysters (Buzan et al. 2009). Prolonged exposure to very low salinities or freshwater floods will cause mortality of oysters (Kennedy 1996). Larvae life stages require salinities that are not too high or low to settle, generally in the range of 10 to 27.5 ppt (Kennedy 1996). Optimal salinity conditions for oyster growth are 10-28 ppt, and freshet events that significantly lower salinities are extremely important to decrease predators and parasite infections that can decimate oyster reefs, including the oyster drill (*Stramonita haemastoma*) and dermo (*Perkinsus marinus*) (La Peyre et al. 2003).

Life History

American oysters have a lifespan of up to 20 years (Buroker 1983) growing to 100 to 115 millimeters in length in two years. Individuals can reach sexual maturity at four months. Spawning is initiated by a combination of factors including water temperature, salinity, and physiochemical interactions (Galtsoff 1964, Hofstetter 1977, Hofstetter 1983).

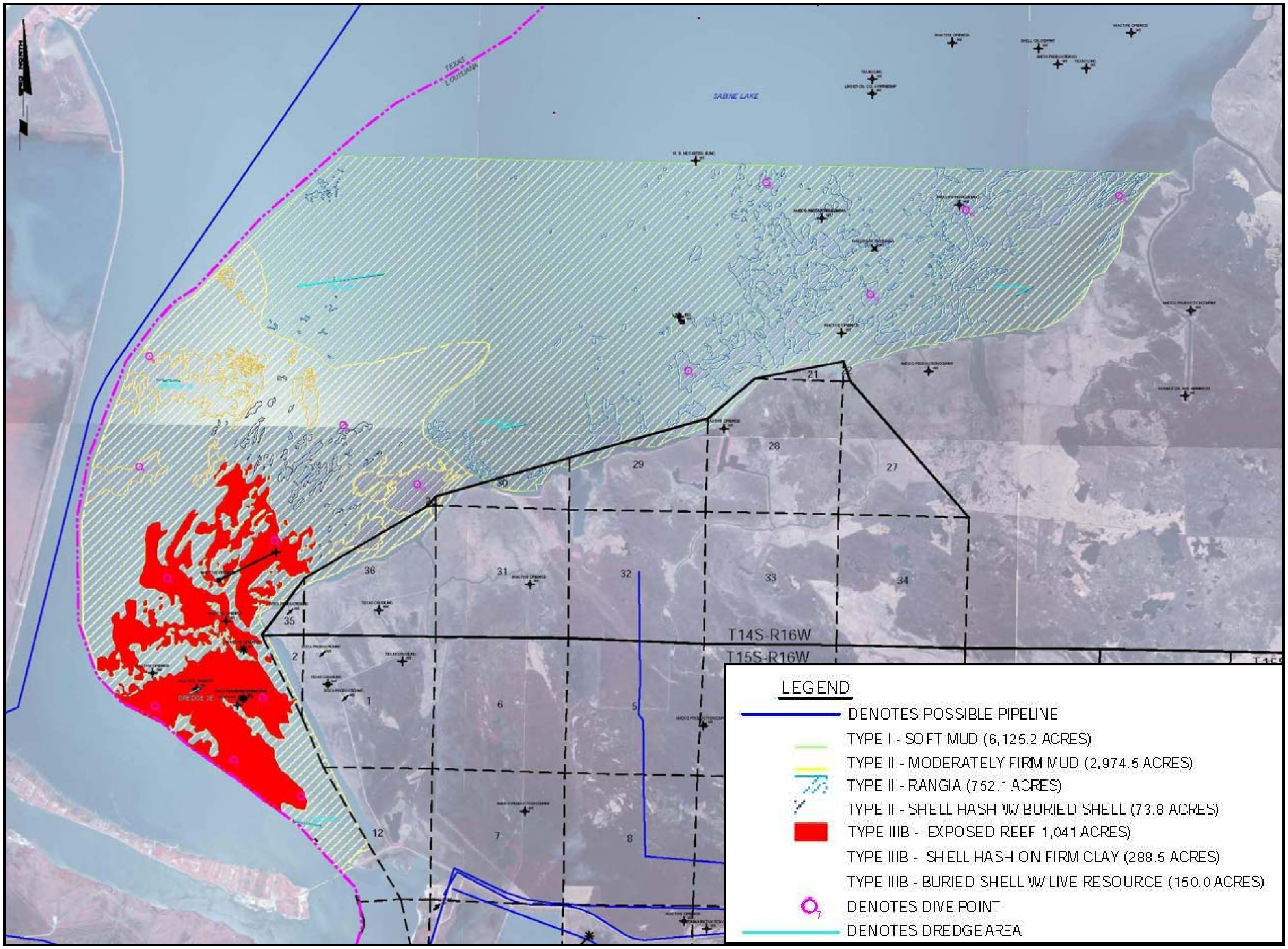


Figure 3. Oyster reef locations in Sabine Lake based on a side scan sonar survey in 2008. (Source: Shackelford 2008).

In southern waters, spawning occurs in all but the coldest months (Berrigan et al. 1991). Conditions generally required for spawning include water temperatures at or above 20°C and salinity higher than 10 ppt. When these conditions persist, spawning can continue year-round (Breuer 1962). The optimal salinity for growth and reproduction is 10-28 ppt (Wilson et al. 2005). Larvae will not settle and metamorphose into spat when salinity is less than 6 ppt (Wilson et al. 2005), while adults can live in salinities up to 35 ppt (Buroker 1983). After fertilization, oysters develop through several free-swimming larval stages before attaching to a hard substrate and becoming sessile. The rate of development through these stages is temperature dependent (Shumway 1996).

Larval oysters are induced to settle by the presence of hard substrate, such as shells, and by chemicals produced by adult conspecifics, so oyster reefs tend to be self-perpetuating. Unlike some regions, such as the Chesapeake Bay, oysters in Texas bays are almost always harvested in the reefs where they settle rather than moved post-settlement to designated growing locations. As a result, the entire post-larval life of these oysters will depend on specific conditions at the reefs.

Oysters can survive in salinities ranging from about 5 to 40 ppt, but growth is stunted below 7.5 ppt (Kennedy et al.. 1996). Oyster reefs which are subjected chronically or episodically to salinities that are too low due to excessive freshwater runoff may have problems ranging from complete or partial population mortality to stunted growth. Oysters grow optimally from approximately 10 to 25 ppt (Cake 1983). Salinities of greater than 25 ppt are not only suboptimal physiologically, but reefs that are located in regions of chronic or seasonally high salinities (>25 ppt) will have a greater mortality due to predation and to dermo, a protozoan parasite infection caused by *Perkinsus marinus* (Kennedy et al. 1996).

Temperatures in the GOM do not get low enough to cause oyster mortality, but oyster growth rate is slower in colder temperatures. In fact, the combination of physiological effects of low temperature and limited food supply, in general, can cause individual oysters to lose biomass in winter months (Hofmann et al 1992). Optimal temperature for oysters is approximately 25 °C and temperatures over 30 °C can cause cessation of filter feeding (Kennedy et al. 1996).

The timing and amount of food supply in the form of phytoplankton and other organisms that can be utilized by filter-feeding oysters may have strong impacts on both oyster productivity and size structure (Hofmann et al. 1992, 1995; Powell et al. 1995, 1997; Dekshenieks et al. 2000).

Because adult oysters are sessile, their distribution depends on where the larvae set and on subsequent survival of the young spat oysters (Stanley and Seller 1986). Oysters are capable of surviving in a wide range of habitat conditions, but they are more abundant under preferred habitat (general range) conditions. These habitat conditions include estuarine areas with oxygenated waters that are less than 4 meters deep with a tidal range of 0.5-2.7 meters (Stanley and Seller 1986).

Optimum temperatures for settlement and growth of larvae are ~20°C to 32.5°C (Calabrese and Davis 1970), while adult optimum temperatures range from 20 to 30ºC (Stanley and Sellers 1986). Larvae prefer to settle on clean hard or shell substrate, and adult oysters do well on various substrates, including mud that supports the growing community weight (Jenkins et al. 1997).

Disease/Parasites

Two major parasites impact *C. virginica* populations in the United States, *Haplosporidium nelsoni* (also known as MSX) and *Perkinsus. marinus* (also known as dermo) (Kennedy et al. 1996). However, only dermo is a problem in the Western GOM (Soniat, *pers. comm.*, 2005). It is known that dermo prefers high salinity waters (>15 ppt). Infection from this parasite usually occurs in the warmer months between an oyster's first and second year, then intensifies during the second year, killing the oyster before it reaches market size.

Dermo infections may be strongly affected by temperature and salinity regimes. The division rate of dermo cells within oysters is related to both temperature and salinity of the surrounding water (Hoffman et al. 1995). At salinities greater than 10 ppt, dermo cell division is primarily affected by and increases with temperature. Below 10 ppt salinity, dermo cell growth decreases sharply with salinity (Hofmann et al. 1995). In bays in the western GOM, oyster populations on reefs closer to freshwater inflow sources typically have lower dermo infection intensities than reefs farther down bay (closer to the seawater source at the bay's mouth), and episodes of salinity below 10 ppt are often associated with a reduction of dermo levels on reefs (see data on oystersentinel.org; MBHE 2005). However, salinities low enough to harm dermo populations can also stress oysters, so the ideal salinity regime to control dermo is one with episodic freshwater inflows that reduce salinity below 10 ppt, rather than continuously low salinities (Hofmann et al. 1995, Kennedy et al. 1996).

Dermo infestations tend to be most intense in summer, when temperatures are highest. Temperatures above 25 °C are associated with high oyster mortality from dermo, and the persistence of high intensity dermo infestations is dependent on extended periods of high temperature (Kennedy et al. 1996). Such periods are common during summers in Texas bays.

In Sabine Lake, dermo infection and intensity data is collected routinely at one Oyster Sentinel station in the southern portion of the Lake (**Figure 4**). Oyster Sentinel is a web-based scientific community which uses the American oyster as a bioindicator of estuarine health (http://www.oystersentinel.org/). On this website, temperature, salinity, and dermo infection data for juvenile and commercial sized oysters in Sabine Lake is reported from January 2006 through the spring 2009.

Figure 4. Dermo assessment location in Sabine Lake for the Oyster Sentinel program (http://www.oystersentinel.org).

Predators

Many important oyster predators are limited by low salinities (Kennedy et al. 1996). The most severe predation impact on oysters in the western GOM is from the oyster drill, *Thais haemastoma* (Soniat and Kortright 1998). Drill predation rates on oysters are limited by both low salinity and low temperature. Lower tolerance levels for drills (7.5 ppt, 12.5 °C) also constitute poor conditions for oysters (Kennedy et al. 1996), but drill predation is also reduced in moderate salinities in the range where oysters prosper. In the western GOM, significant losses to drills increase on reefs farther from freshwater sources (Soniat 2005).

A number of other oyster predators are also limited by low or moderate salinities (Longley 1994; Kennedy et al. 1996). In general, extended periods of salinities greater than 25 ppt allow predator populations to build up and are associated with high predation rates on oyster populations (Kennedy et al. 1996).

3.3 Crustacean Focal Species

As food for fishes and larger invertebrates, crustaceans play a major role in the transfer of food energy to higher trophic levels within coastal waters. Crustaceans are an important link in the estuary food chain between benthic and pelagic organisms (Turner and Brody 1983). Crustaceans are also a dominant food item in the diet of a variety of fish species. As with many fishes, the life histories of many Gulf crustaceans can be characterized as estuarine-dependent. These species typically spawn in the GOM, and their larvae are then carried inshore by currents. Juveniles generally remain in these estuarine nurseries for about a year, taking advantage of the greater availability of food and protection that estuarine habitats afford. Upon reaching maturity, individuals migrate from the shallow estuaries to the deeper GOM.

Estuary-dependent crustaceans occurring within the intertidal brackish marsh habitats within Sabine Lake include, but are not limited to, hermit crab (*Clibanarius vittatus*), mud crabs (*Rhithropanopeus harrisii*, *Neopanope texana*, and *Panopeus herbstii*), white shrimp, brown shrimp, pink shrimp (*Farfantapenaeus duorarum*), spiny lobster (*Panulirus argus*), blue crab, Gulf stone crab (*Menippe adina*), and stone crab (*M. mercenaria*) (Nelson 1992). Up to 15 species of penaeid shrimp can be expected to use the coastal and estuarine areas in the GOM; brown, white, and pink shrimp are the most numerous and comprise a substantial shrimp fishery. About eight species of portunid (swimming) crabs use the coastal and estuarine areas in the GOM. Blue crabs are the only species, however, that is located throughout the Gulf and comprises a substantial fishery. All of these species occur in a variety of habitat types in fresh, estuarine and shallow offshore waters.

Variability in physicochemical parameters, such as temperature, salinity, and dissolved oxygen, affect the suitability and selection of habitat by estuarine fish, crustaceans, and other organisms in their various life stages (Peterson et al. 2004). Therefore, for the purposes of this Summary Report and when available, life histories, physicochemical preferences of specific life stages, spatiotemporal abundance, and value are described below.

Based on the National Oceanic and Atmospheric Administration's (NOAA) Estuarine Living Marine Resources (ELMR) Program, relative abundance is defined using the following categories (Nelson 1992; Patillo et al. 1997):

- High abundant – species is numerically dominant relative to other species.
- Abundant – species is often encountered in substantial number relative to other species.
- Common – species is generally encountered but not in large numbers; does not imply an even distribution over a specific salinity zone.
- Rare – species is present but not frequently encountered.
- Not present – species or life stage not found, questionable data as to identification of the species, or recent loss of habitat or environmental degradation suggests absence.

When relevant, essential fish habitat (EFH) is described for particular species. EFH is defined as "those waters and substrate necessary to fish for spawning, breeding, feeding, or growth to maturity" (16 U.S.C. 1802(10)). The Gulf of Mexico Fisheries Management Council (GMFMC) designated EFH for adult and juvenile life stages of the following two focal species: white shrimp and brown shrimp.

3.3.1 White shrimp (*Litopenaeus setiferus*)

General Description

White shrimp (*Litopenaeus setiferus*), previously in the genus *Penaeus*, along with other penaeid species comprise a commercially important shrimp fishery in the GOM (Cook and Murphy 1971), the second most valuable commercial fishery in the U.S. (Patillo et al. 1997). Up until the 1930's, white shrimp were the major commercial shrimp in the GOM (Muncy 1984).

White shrimp range from the Atlantic Coast as far north as New York, down to Florida, along the coast of the GOM and down to Mexico (Perez-Farfante 1969). In the GOM, highest abundance of white shrimp occur off the coast of Louisiana in waters less than 9 meters deep (Muncy 1984) and are well established throughout Texas, Louisiana, and Mississippi bays and estuaries (Patillo et al. 1997). White shrimp have been found in the Sabine Lake system year round with peak abundances from July to December (TPWD 2005).

Morphology

Morphologically similar to brown shrimp, a few key characteristics help to differentiate between the two species. In white shrimp, the antennal flagella are 2.5 to 3 times the length of the body length (Perez-Farfante 1969), much longer than those of brown shrimp. Additionally, the adrostral sulcus is much shorter extending only to the epigastric tooth on the rostrum, versus the hind margin of the carapace in brown shrimp (Muncy 1984).

Ecological Relationship with Freshwater Inflow and Salinity

White shrimp are tolerant to a wide range of salinities and can be considered euryhaline (Zein-Eldin and Griffith 1969). However, they are generally found in lower salinity waters than brown shrimp (Turner and Brody 1983). **Table 2** provides the relative abundance by month of white shrimp in Sabine Lake during each life stage (adult, eggs, juveniles, larvae, and spawners) in five salinity zones. White shrimp have been shown to have a preference for low salinity nursery grounds, with postlarval shrimp most abundant at 5 to 10 ppt in Texas (Muncy 1984, cited from Gunter 1967), though they have been collected in salinities as low as 0.42 ppt (Perez-Farfante 1969) and as high as 37.4 ppt. In Texas, postlarvae enter nursery areas from April to November (Kilma et al. 1982). Juveniles appear to tolerate lower salinities ranges, less than 10 ppt (Zein-Eldin and Renaud 1986) and have been found upstream in rivers and tributaries (Patillo et al. 1997), as far as 160 kilometers in Louisiana (Perez-Farfante 1969).

NOAA (1998c) has documented adult white shrimp as being highly abundant in the high and decreasing salinity season (August through February) in Sabine Lake (**Figure 5**) and also being found offshore in salinities greater than 27 ppt (Muncy 1984).. Juveniles in Sabine Lake are highly abundant in lower salinities, ranging from 0.0 to 0.5 ppt, particularly around April through December (Nelson 1992), though NOAA (1998d) NMFS Galveston Lab has documented juveniles as highly abundant throughout the year (**Figure 6**).

White shrimp are also tolerant to a wide range of temperatures, from 7 to 38 °C (Patillo et al 1997). Postlarval shrimp have been recorded in temperature ranging from 13 to 30 °C and juveniles ranging from 6.5 to 39 °C, with peaks of abundance around 15 and 33 °C (Zein-Eldin and Renaud 1986).

Life History

Adults inhabit both estuarine and coastal waters; however, adults spawn offshore at depths ranging from 8 to 30 meters from spring to early fall (Perez-Farfante 1969; Patillo et al. 1997) preferring salinities to be at least 27 ppt (Cook and Murphy 1969). Spawning also coincides with increasing temperatures in the spring time and ending with declining temperatures in the fall (Muncy 1984). White shrimp spawn offshore where they hatch and pass through a series of metamorphoses as planktonic larvae. After a period of about 2 to 3 weeks, postlarvae are transported by favorable currents and tides to estuary nursery grounds, around May to November (Perez-Farfante 1969; Muncy 1984). In nursery grounds that provide habitat and protection (Turner and Brody 1983), juveniles appear to tolerate lower salinities ranges moving farther upstream than brown shrimp (Muncy 1984). Juveniles approaching adulthood move out of estuaries back into coastal waters.

Depending on the life stage, white shrimp are neritic to estuarine and pelagic to demersal. Eggs and early planktonic larvae are found in nearshore marine waters, and postlarvae are later found in estuarine nursery grounds. Postlarvae seek areas of shallow water with muddy or sandy bottoms or marsh grass (Patillo et al. 1997) connected by passes to adjacent offshore, higher salinity areas with mud or clay bottoms (Anderson 1956). Juveniles prefer sandy and muddy habitats and adults prefer sand-silt-clay areas of high detrital content (Zein-Eldin and Renaud 1986).

Feeding Preferences and Predators

White shrimp tend to be omnivorous through their life stages, even as postlarve. Juveniles feed on organic-inorganic detrital matter, diatoms, and polychaetes, and the diet of adults is composed of much of the same (Zein-Eldin and Renaud 1986).

Finfish prey heavily on white shrimp, which serve as an important food source, link and integrator of the environment (Muncy 1984; Patillo et al. 1997). A number of predators feed on white shrimp, including tiger sharks (*Galeocerdo cuvier*), Atlantic sharpnose shark (*Rhizoprionodon terraenovae*), ladyfish, hardhead catfish, red snapper (*Lutjanus campechanus*), southern kingfish (*Menticirrhus americanus*), seatrout, red drum, and flounder (Patillo et al. 1997).

Table 2. Relative abundance of different life stages of white shrimp in Sabine Lake within selected salinity zones (CCMA, no date).

White Shrimp | Sabine Lake

SALINITY ZONE	LIFESTAGE	Relative Abundance by Month											
		J	F	M	A	M	J	J	A	S	O	N	D
0-0.5 ppt.	ADULTS	3	3	3	2	2	2	3	3	4	4	4	3
	EGGS	0	0	0	0	0	0	0	0	0	0	0	0
	JUVENILES	2	2	2	2	4	4	5	5	5	5	5	5
	LARVAE	0	0	0	0	0	0	0	0	0	0	0	0
	SPAWNERS	0	0	0	0	0	0	0	0	0	0	0	0
0.5-5 ppt.	ADULTS	3	3	3	2	2	2	3	3	5	5	5	4
	EGGS	0	0	0	0	0	0	0	0	0	0	0	0
	JUVENILES	2	2	2	2	5	5	5	5	5	5	5	5
	LARVAE	0	0	0	0	0	0	0	0	0	0	0	0
	SPAWNERS	0	0	0	0	0	0	0	0	0	0	0	0
5-15 ppt.	ADULTS	3	3	3	2	2	2	3	3	5	5	5	4
	EGGS	0	0	0	0	0	0	0	0	0	0	0	0
	JUVENILES	2	2	2	2	5	5	5	5	5	5	5	5
	LARVAE	0	0	0	0	0	0	0	0	0	0	0	0
	SPAWNERS	0	0	0	0	0	0	0	0	0	0	0	0
15-25 ppt.	ADULTS	3	3	3	2	2	2	3	3	5	5	5	4
	EGGS	0	0	0	0	0	0	0	0	0	0	0	0
	JUVENILES	2	2	2	0	5	5	5	5	5	5	5	5
	LARVAE	0	0	0	0	0	0	0	0	0	0	0	0
	SPAWNERS	0	0	0	0	0	0	0	0	0	0	0	0
>25 ppt.	ADULTS	•	•	•	•	•	•	•	•	•	•	•	•
	EGGS	•	•	•	•	•	•	•	•	•	•	•	•
	JUVENILES	•	•	•	•	•	•	•	•	•	•	•	•
	LARVAE	•	•	•	•	•	•	•	•	•	•	•	•
	SPAWNERS	•	•	•	•	•	•	•	•	•	•	•	•

Legend: Relative Abundance

NI	No Information	2	Rare
•	Zone Not Present	3	Common
0	Not Present	4	Abundant
		5	Highly Abundant

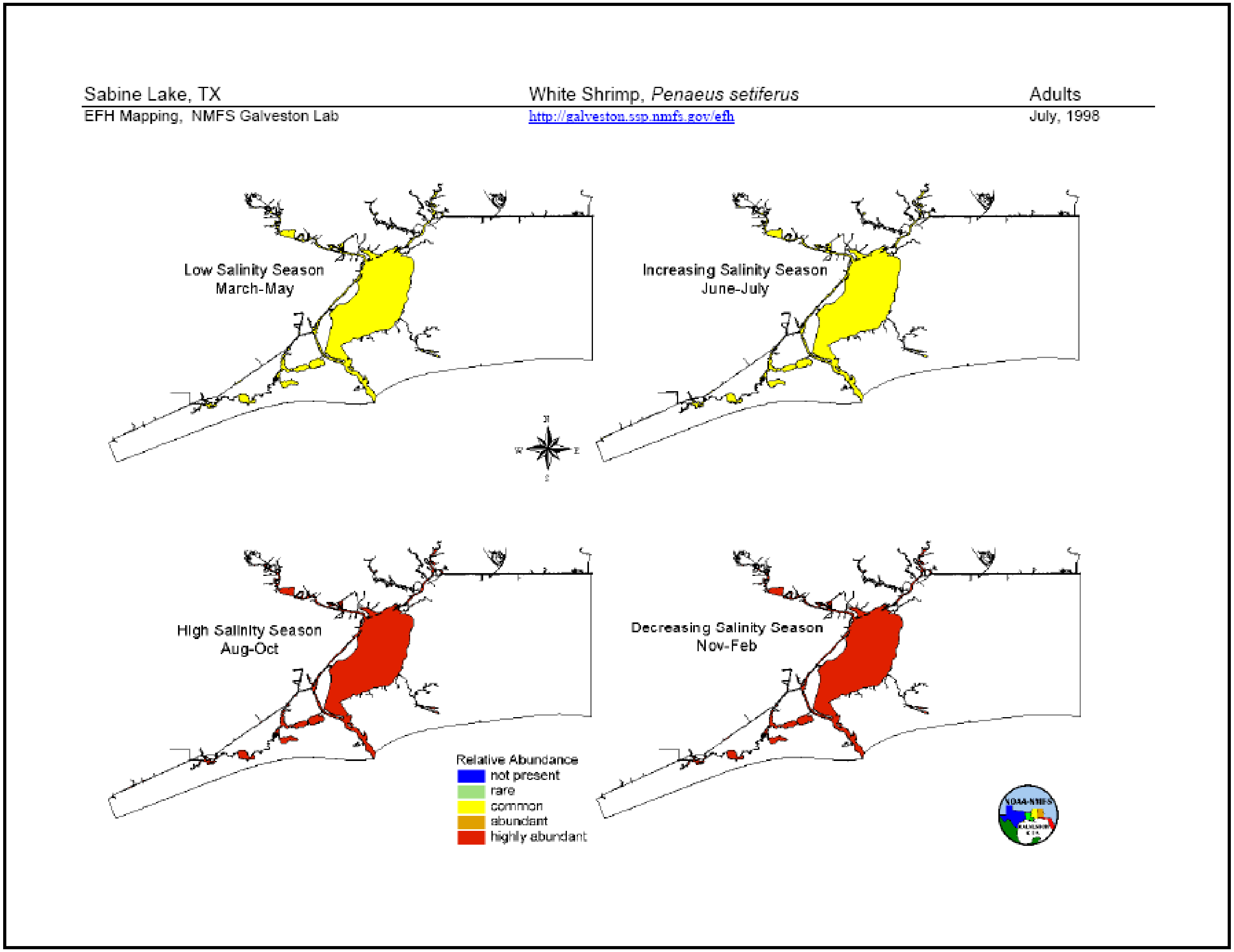


Figure 5. The seasonal relative abundance of white shrimp adults in Sabine Lake (NOAA 1998c).

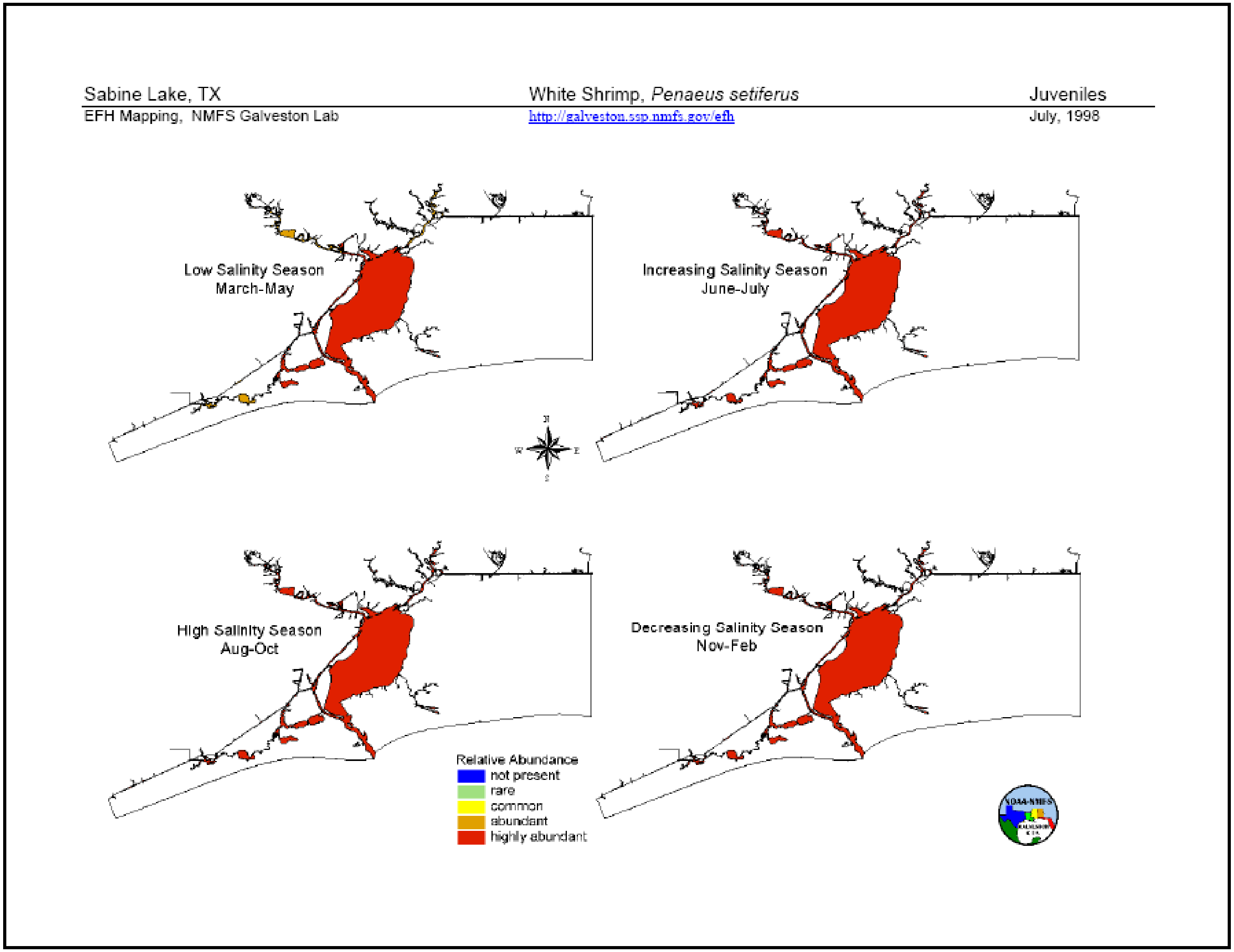


Figure 6. The seasonal relative abundance of white shrimp juveniles in Sabine Lake (NOAA 1998d).

3.3.2 Brown shrimp (*Farfantepenaeus aztecus*)

General Description

Brown shrimp, previously in the genus *Penaeus*, is an estuarine-dependent (Hass et al. 2004) shrimp species and member of the family Penaeidae. Brown shrimp, along with other penaeid species such as pink shrimp and white shrimp, comprise a commercially important shrimp fishery in the GOM (Cook and Murphy 1971), the second most valuable commercial fishery in the U.S. (Patillo et al. 1997). Brown shrimp extend from Massachusetts, around the tip of Florida, throughout the whole of the GOM, and south to the Yucatan Peninsula. In the GOM, brown shrimp are widespread throughout the bays and estuaries with centers of abundance in Texas, Louisiana, and Mississippi (Allen et al. 1980; Patillo et al. 1997). **Table 3** provides the relative abundance by month of brown shrimp in Sabine Lake during each life stage (adult, eggs, juveniles, larvae, and spawners) in five salinity zones.

Morphology

Brown shrimp are morphologically similar to white shrimp. Brown shrimp are characterized by the adrostral groove and crests extending almost to the hind margin of the carapace; well developed postrostral crest as far back as adrostral grooves; presence of gastrofrontal crests; and the absence of a dark, lateral spot between the third and fourth abdominal segment (Lassuy 1983b).

Ecological Relationship with Freshwater Inflow and Salinity

Adult brown shrimp are common within Sabine Lake at salinity zones between 5 to 25 ppt (Nelson 1992; CCMA, no date) during April to July. NOAA (1998a) also characterizes adult brown shrimp as common in Sabine Lake during the late spring and summer months when salinities are generally increasing (**Figure 7**). Juveniles are more abundant than adults in Sabine Lake, using the estuary as nursery habitat in salinities up to 25.0 ppt throughout the summer and fall and decreasing in abundance in late fall as the shrimp move out into the GOM (Nelson 1992; NOAA 1998b; CCMA, no date) (**Figure 8**). Brown shrimp are abundant in Sabine Lake during the larval life stage during April and May (Nelson 1992).

Life History

Adult brown shrimp reproduce and spawn offshore, usually between depths of 46 to 91 meters, but have been recorded as deep as 137 meters. Spawning occurs throughout the year, but primarily from September through May (Patillo et al. 1997; Haas et al. 2004). Planktonic larvae hatch after several hours and pass through a series of metamorphoses over a period of weeks, moving shoreward towards estuarine nursery grounds where postlarvae then settle (Baxter and Renfro 1967; Haas et al. 2004). Postlarve have been documented to move inshore primarily at night on incoming tides, taking on demersal habits in soft-bottom areas of estuaries (Lassuy 1983b). Postlarvae transform into juveniles around 25 millimeters total length (TL) in about four to six weeks (Perez-Farfante 1969) and spend about three months in nursery grounds (Cook and Murphy 1971) which provide protection from predation and feeding habitat (Lassuy 1983b). As they reach sizes of 90 to 110 millimeters, they begin migrating offshore (Patillo et al. 1997; Haas et al. 2004) from May through August, with peak months between June and July (Lassuy 1983b).

Adults then return to spawning depths offshore. The postlarvae that reach inshore waters and estuaries represent successful recruitment of the spawning season and will make up the bulk of the commercial fishery for a given year (Baxter and Renfro 1967); therefore survival within nursery grounds is extremely important (Haas et al. 2004).

Juveniles and subadults select shallow marsh areas and vegetation habitats within estuarine or nearshore areas over muddy and sandy substrates. Adults occur in the offshore neritic zone, associated with silty, sandy substrates (Lassuy 1983b; Patillo et al. 1997). Environmental conditions, habitat alteration, food availability, and substrate type affect brown shrimp abundance and distribution. The brown shrimp's habitat preference for vegetated areas may be affected by physicochemical parameters such as salinity, turbidity, and light; occasionally causing brown shrimp to inhabit areas with less coverage and food resources and making it more vulnerable to predation (Minello et al. 1989; Patillo et al. 1997).

Feeding Preferences and Predators

Larval stages of brown shrimp are planktivores, consuming both phytoplankton and zooplankton in the water column. Demersal postlarvae in estuarine nursery grounds feed at the vegetation-water interface, indiscriminately feeding on detritus, comprised primarily of *Spartina* (Jones 1973, cited by Lassuy 1983b). Juveniles and adults feed on a number of prey items, such as polychaetes, amphipods, and chironomid larvae, in addition to detritus and algae (Patillo et al. 1997).

Minello et al. (1989) describes predation as the most usual direct cause of brown shrimp mortality in estuarine nursery grounds in the GOM. As described above, brown shrimp prefer vegetated habitats for protection from predation. A number of predators feed on brown shrimp, including ladyfish (*Elops saurus*), hardhead catfish, sheepshead (*Archosargus probatocephalus*), pinfish, spot, and Atlantic croaker among many other fish as well as crustaceans (Patillo et al. 1997). In estuarine habitats, southern flounder are considered the major predator of juvenile brown shrimp as well as seatrout (Minello et al. 1989).

Table 3. Relative abundance of different life stages of brown shrimp in Sabine Lake within selected salinity zones (CCMA, no date).

Brown Shrimp | Sabine Lake

SALINITY ZONE	LIFESTAGE	Relative Abundance by Month											
		J	F	M	A	M	J	J	A	S	O	N	D
0-0.5 ppt.	ADULTS	2	2	2	2	2	2	2	2	2	2	2	2
	EGGS	0	0	0	0	0	0	0	0	0	0	0	0
	JUVENILES	0	0	0	3	3	3	3	3	3	3	3	0
	LARVAE	0	0	0	0	0	0	0	0	0	0	0	0
	SPAWNERS	0	0	0	0	0	0	0	0	0	0	0	0
0.5-5 ppt.	ADULTS	2	2	2	3	3	3	3	2	2	2	2	2
	EGGS	0	0	0	0	0	0	0	0	0	0	0	0
	JUVENILES	0	0	0	4	4	4	4	4	3	3	3	0
	LARVAE	0	0	0	0	0	0	0	0	0	0	0	0
	SPAWNERS	0	0	0	0	0	0	0	0	0	0	0	0
5-15 ppt.	ADULTS	2	2	2	3	3	3	3	2	2	2	2	2
	EGGS	0	0	0	0	0	0	0	0	0	0	0	0
	JUVENILES	0	0	0	4	4	4	4	4	3	3	3	0
	LARVAE	0	0	0	0	0	0	0	0	0	0	0	0
	SPAWNERS	0	0	0	0	0	0	0	0	0	0	0	0
15-25 ppt.	ADULTS	2	2	2	2	3	3	3	3	2	2	2	2
	EGGS	0	0	0	0	0	0	0	0	0	0	0	0
	JUVENILES	0	0	0	4	4	4	4	4	3	3	3	0
	LARVAE	0	0	0	4	4	0	0	0	0	0	0	0
	SPAWNERS	0	0	0	0	0	0	0	0	0	0	0	0
>25 ppt.	ADULTS	•	•	•	•	•	•	•	•	•	•	•	•
	EGGS	•	•	•	•	•	•	•	•	•	•	•	•
	JUVENILES	•	•	•	•	•	•	•	•	•	•	•	•
	LARVAE	•	•	•	•	•	•	•	•	•	•	•	•
	SPAWNERS	•	•	•	•	•	•	•	•	•	•	•	•

Legend: Relative Abundance

NI	No Information	2	Rare
•	Zone Not Present	3	Common
0	Not Present	4	Abundant
		5	Highly Abundant

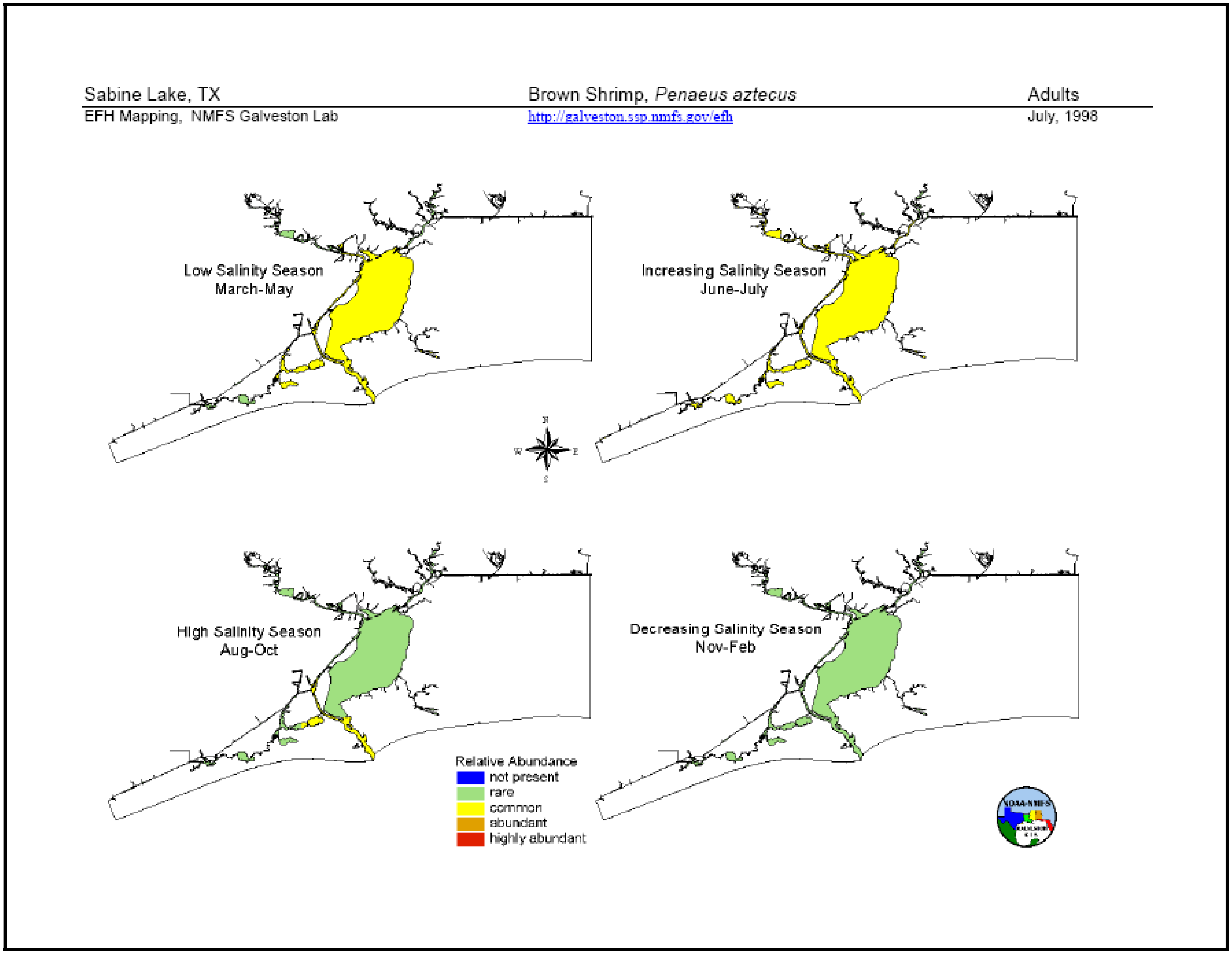


Figure 7. The seasonal relative abundance of brown shrimp adults in Sabine Lake (NOAA 1998a).

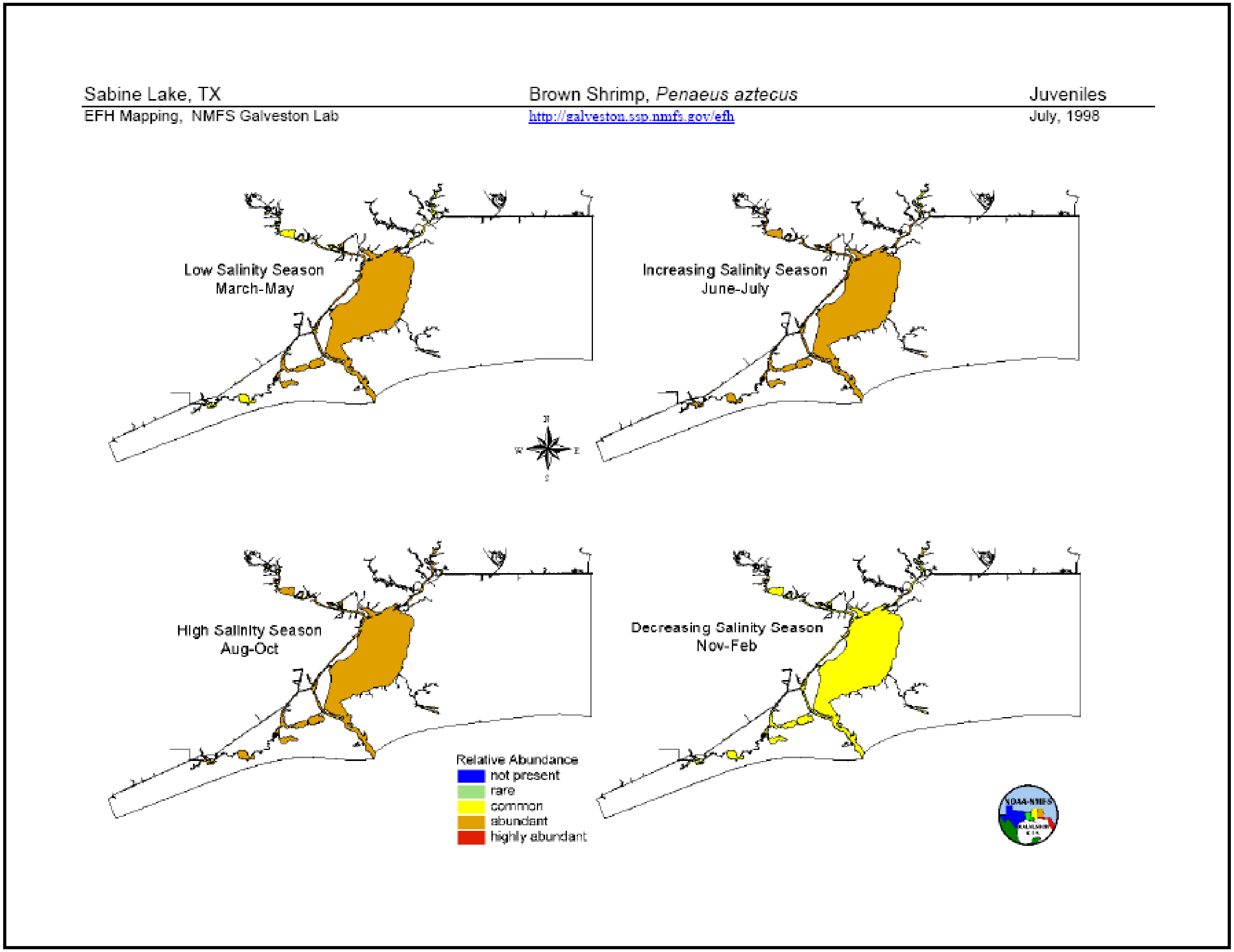


Figure 8. The seasonal relative abundance of brown shrimp juveniles in Sabine Lake (NOAA 1998b).

3.3.3 Blue crab (*Callinectes sapidus*)

General Description

Blue crab, *Callinectes sapidus* (Rathbun), is a member of the decapod family Portunidae, the swimming crabs. The blue crab performs a variety of functions in the estuarine ecosystem, and occupies a variety of habitats in fresh, brackish, and shallow oceanic waters. Blue crabs historically supported one of the largest commercial and recreational fisheries in the GOM. They have a large geographic distribution and are abundant throughout the nearshore and estuarine areas of the GOM and along the Atlantic coast from Nova Scotia to northern Argentina (Van Engel 1958). Blue crabs have also been introduced into coastal waters of Europe, the Mediterranean, and Japan (Van Engel 1958).

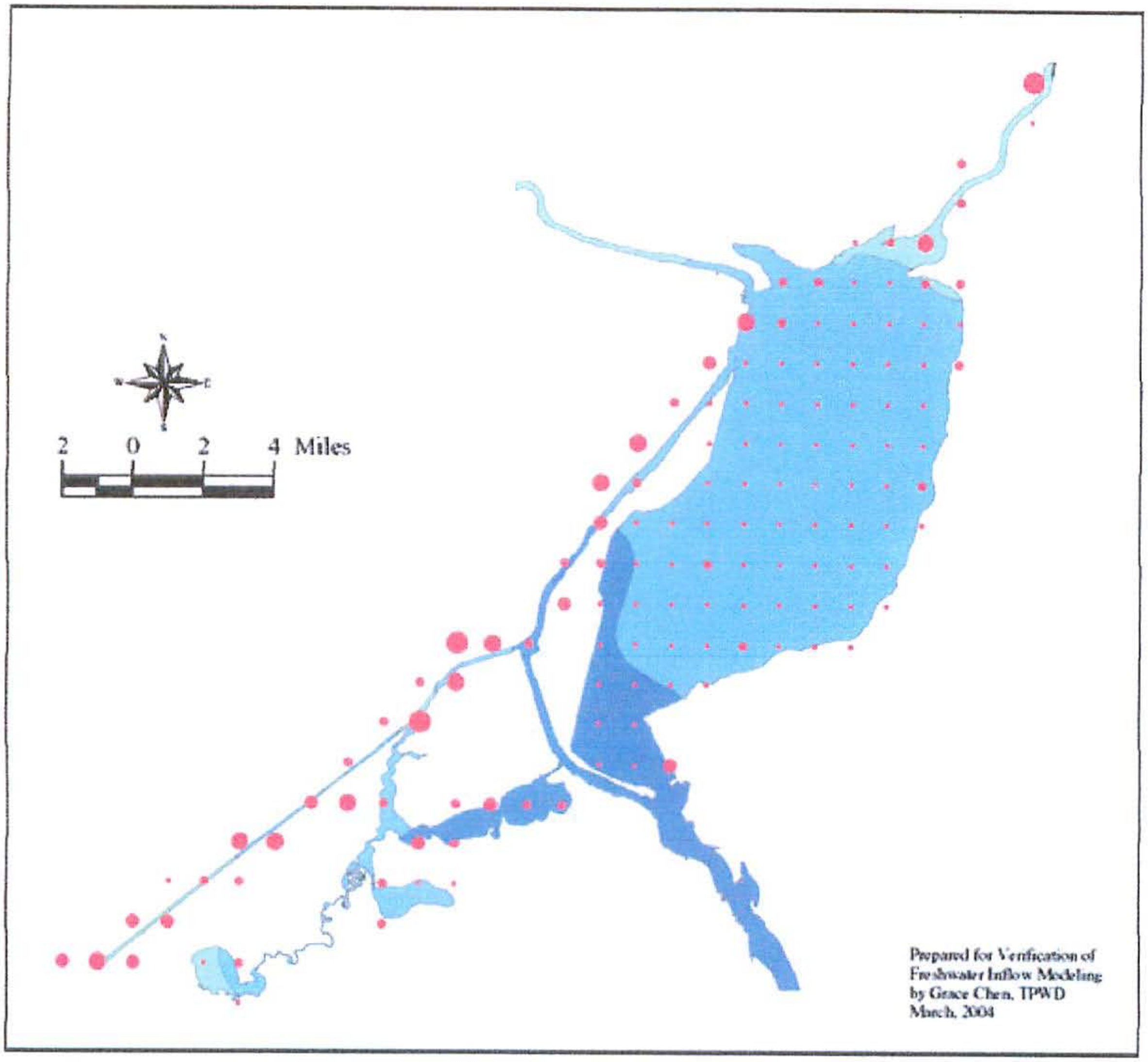
Blue crabs are highly abundant in Sabine Lake as both adults and juveniles (Pattillo et al. 1997). TPWD (2005) found blue crabs numerous throughout the year in Sabine Lake, with the highest abundances between February and July (**Figure 9**). Catch in the lowest salinity zone (0-3 ppt) was significantly higher than in any other salinity zone, and carapace width data indicated the majority were juvenile life stages (TPWD 2005).

Ecological Relationship with Freshwater Inflow and Salinity

Variations in salinity, temperature, pollutants, predation, disease, habitat loss, and food availability all affect blue crab survival. Overall populations are limited by post-settlement biotic processes that influence survival of small juveniles. Dissolved oxygen in the water column is also an important water quality parameter for blue crabs, with low levels of dissolved oxygen not only causing mortality of crabs but also impeding migration. The recruitment and dispersal of juvenile crabs into the estuary is influenced by factors such as freshwater inflow, causing flushing, salinity declines and low dissolved oxygen (Posey et al. 2005). Environmental conditions, such as temperature and salinity, can influence blue crab reproduction by the timing of molting and the spatial and temporal distribution of adult crabs in the estuary (Chazaro-Olvera and Peterson 2004). Adults show a differential distribution by sex and salinity, with males found in the lower salinity waters of the upper estuary, and females migrating along the salinity gradient between mating in the upper estuary and spawning in the high salinity waters of the lower estuary (Kennedy 2007).

Life History

Blue crabs spend most of their lives in estuaries and nearshore waters (Pattillo et al. 1997). Although there are few data about lifespan for GOM populations, typically the blue crab has an estimated life span of 3 to 4 years and can reach sexual maturity at 12 to 18 months (Kennedy 2007). Two spawning peaks typically occur in the GOM, one in late spring and the other during late summer or early fall. Blue crabs mate in low-salinity estuarine waters. Soon after mating, females travel to the saltier portions of the lower bays to prepare for spawning while the males remain dispersed in the upper estuary without migrating directionally along the salinity gradient (Pattillo et al. 1997, Kennedy 2007). Spawning occurs at the entrances to the estuary and lower bays between two and nine months after mating, which typically



Salinity Zones

Salinity (ppt)	% Bay Area	Mean CPUE	% Abundance
0.00 - 3	5.66	55.94	14.39
3.01 - 6	75.72	19.73	67.88
6.01 - 9	18.47	20.96	17.59
9.01 - 12	0.14	22.00	0.14
12.01 - 15	0.00	0.00	0.00
> 15.01	0.00	0.00	0.00

Species Abundance

CPUE (Catch per Hour)
0.00 - 12.67
12.68 - 34.80
34.81 - 72.00
72.01 - 162.00
162.01 - 301.50

Figure 9. Spatial distribution of blue crab collected in TPWD otter trawls in the Sabine Lake system between February – July (TPWD 2005).

takes place between August and September (Van Engel 1958; Williams 1965). Eggs hatch near the mouths of estuaries and the planktonic zoeal larvae are carried offshore (Pattillo et al. 1997) where they feed on phytoplankton and zooplankton while continuing to develop (Laughlin 1982).

Upon reaching the nektonic megalopal stage, blue crabs re-enter estuaries (Pattillo et al. 1997). Larvae and juveniles prefer submerged aquatic vegetation or flooded marshes as nursery habitat (Thomas et al. 1990). Juvenile crabs are widely distributed in estuaries and forage on diverse food sources and typically grow and molt for 0.5 to 1.5 years until they reach sexual maturity (Kennedy 2007). Larger juveniles and adults are demersal and prefer estuarine waters with soft sediments (Van Engel, 1958; Perry 1975). The adult crabs are omnivorous scavengers that feed on wide variety of plant and animal material.

Essential habitat for blue crab includes all habitats required during its life cycle, including offshore waters used for spawning and larval development and estuarine nursery grounds (Minello 1999, Guillory et al. 2001). Nursery habitats of critical concern include structured intertidal marshes, sub-tidal grass beds, and unvegetated soft sediment shoreline habitats where juveniles prefer to settle (Minello 1999, Jackson et al. 2001). Salt marshes in the northwest GOM are reticulated between stands of vegetation and interspersed tidal pools with tidal water level fluctuations generally less than one meter and relatively long inundation periods. As a result, marshes along the upper Texas and Louisiana coast are potentially more accessible for exploitation and may have greater value as nursery habitat for blue crabs that those of the Atlantic coast (Thomas et al. 1990).

Parasites and Predators

Infectious diseases of the blue crab have received less study than those of the American------ oyster and shrimp populations. While parasites may be common on crabs, most do not affect the life of the crab. Barnacles such as *Chelonibia patula*, worms and leeches attach themselves to the outer shell; gill parasites such as *Octolasmis muelleri* infect the gills (Overstreet et al. 2009); and small worms live in the muscles. Several pathogenic agents including viruses (two reported on the Gulf coast), *Vibrio* spp., *Hematodinium perezi* (dinoflagellate, only reported on the Atlantic coast), *Paramoeba perniciosa* (only reported on the Atlantic coast), *Loxothylacus texanus*, have the capacity to severely affect blue crab fisheries (Kennedy 2007).

Predators of the blue crab are numerous and vary throughout its life cycle. Juvenile and adult blue crab makes up part of the normal diet of red drum, Atlantic croaker, herons, sea turtles and humans.

3.4 Fish Focal Species

Life histories of many GOM fishes can be characterized as estuarine because these species are estuarine-dependent. These species typically spawn in the GOM, and their larvae are then carried inshore by currents. Juvenile fish generally remain in these estuarine nurseries for about a year, taking advantage of the greater availability of food and protection that that estuarine habitats afford. Upon reaching maturity, estuarine fishes may then remain in the estuary, migrate to sea to spawn (returning to the estuary between spawning periods), or migrate from the shallow estuaries to spend the rest of their lives in the deeper GOM.

Estuary-dependent species occurring within open water and intertidal brackish marsh habitats within Sabine Lake include, but are not limited to gizzard shad (*Dorosoma cepedianum*), Gulf menhaden, bay anchovy (*Anchoa mitchilli*), hardhead catfish (*Ariopsos felis*), sheepshead minnow (*Cyprinodon variegatus*), Gulf killifish (*Fundulus grandis*), silversides (*Menidia* spp.), bluefish (*Caranx crysos*), crevalle jack (*C. hippos*), pinfish (*Lagodon rhomboides*), silver perch (*Bairdiella chrysura*), spotted seatrout, sand seatrout (*C. arenarius*), spot, Atlantic croaker, red drum, black drum (*Pogonias cromis*), striped mullet (*Mugil cephalus*), southern flounder (*Paralichthys lethostigma*) (Nelson 1992), threadfin shad (*D. petenense*), least puffer (*Sphoeroides parvus*), blue catfish (*Ictalurus furcatus*), and alligator gar (*Atractosteus spatula*) (TPWD, *pers. comm.*, July 2009).

Estuarine species serve as "integrators of the environment" whereby both abiotic and biotic factors can influence or constrain the relative value of estuarine nursery zones. Variability in physicochemical parameters, such as temperature, salinity, and dissolved oxygen, affect the suitability and selection of habitat by estuarine fish and other organisms in their various life stages (Peterson et al. 2004). Therefore, for the purposes of this Summary Report and when available, life histories, physicochemical preferences of specific life stages, spatiotemporal abundance, and value are described below.

Based on the NOAA ELMR Program, relative abundance for fish species are also defined using the same categories presented in *Section 3.3* (Nelson 1992; Patillo et al. 1997).

3.4.1 Atlantic croaker (*Micropogonias undulatus*)

General Description

The Atlantic croaker is an estuary-dependent (Lassuy 1983a; Pulich et al. 2002) sciaenid species found in coastal waters off the western Atlantic Ocean and in the GOM (Patillo et al. 1997). Within the GOM, Atlantic croaker are found from southern Florida to Mexico, most abundant off Louisiana and Mississippi (Lassuy 1983a), and considered one of the most common bottom-dwelling estuarine fish in the region (Patillo et al. 1997). The high abundance of Atlantic croaker within the GOM has made it one of the most important bottom-fish fisheries, as well as a recreationally important species (Patillo et al. 1997). Other common names include golden croaker, croaker, and hardhead.

Morphology

Atlantic croaker is characterized by a conical snout, subterminal mouth, and a row of barbels on either side of the mandible. The preopercular margin is serrated and the dorsal fin is deeply notched (McEachran and Fechhelm 2005). Young fish are silvery and older fish are a brassy yellow with short, irregular, oblique bars or streaks formed by spots on the scales above the lateral line (Hoese and Moore 1998; TPWD 1999).

Ecological Relationship with Freshwater Inflow and Salinity

Atlantic croaker salinity preferences are similar to that of blue crab; in Texas and Louisiana bays, juveniles and adults have been documented as most abundant in salinities less than 15 ppt (Pulich et al. 2002). In Sabine Lake, Nelson (1992) reported that Atlantic croaker adults are abundant in a wide range of salinity zones (0.0 to 25.0 ppt) and abundant from September to November. Juveniles are also reported as abundant in Sabine Lake within salinities ranging from 0.5 to 25.0 ppt, and are present throughout the whole year. Higher abundance of juveniles is typically associated with salinities ranging from oligohaline to mesohaline (0.5 to 12.0 ppt) (Weinstein et al. 1980).

Turbidity does not negatively affect Atlantic croaker, which is adapted for tactile feeding. High turbidity is associated with high organic loads and food availability as well as protection from predators (Diaz 1982). Weinstein et al. (1980) and Lassuy (1983a) described low salinity (0.5 to 5.0 ppt) and maximum turbidity zones of estuaries common habitat for juvenile Atlantic croaker.

Life History

Atlantic croaker spawns in marine waters from September to May with peak activity from October to November (Patillo et al. 1997; Petrik et al. 1999). Spawning occurs over the continental shelf at depths of at least 54 meters or near tidal passes and the mouths of bays and estuaries (Diaz 1982; Lassuy 1983a; Petrik et al. 1999). Early larvae are pelagic and planktonic, but become increasingly demersal as they age (Patillo et al. 1997). Larval croaker, 8 to 15 millimeters standard length (SL), appear to then actively move and/or are passively transported towards estuarine nursery grounds, primarily to marshes in the GOM (Diaz 1982).

Through spring and early summer, postlarvae and juveniles utilize estuaries and concentrate in shallow waters less than 1.2 meters deep near sources of fresh to brackish waters that have flowed through *Spartina* marshes and tidal flats (Lassuy 1983a). Diaz (1982) reported that the best combination of habitats for juveniles appear to be low salinity marshes interspersed with tidal creeks, where food items are particularly abundant and protection from predators is provided.

Prior to leaving estuaries, juveniles move to higher salinity areas within estuaries. As juveniles grow, ranging in size from 11 to 140 millimeters, they migrate to Gulf waters, around September to November (Lassuy 1983a). Lassuy (1983a) suggests that seaward migration is closely related to decreasing temperatures in estuarine waters. Adults move between estuarine and marine environments and are often associated with oyster reefs (Lassuy 1983a).

Atlantic croaker is associated with sandy and muddy bottoms along the coast and in estuaries (Lassuy 1983a; McEachran and Fechhelm 2005). As previously mentioned, juveniles are the dominant croaker life stage found in estuarine habitats and typically reside in marshes and tidal riverine habitats which provide an abundance of food and shelter. Within these habitats, Atlantic croaker is typically found in less than 1.8 meters in water depth. Additional habitat utilized as good nursery areas include subtidal channels and areas with soft bottoms and high detrital content (Weinstein et al. 1980; Diaz 1982).

Feeding Preferences and Predators

Atlantic croaker preys on a wide variety of organisms, the bulk of which include benthic invertebrates, such as mysids, decapods, amphipods, copepods, and polychaetes. Other prey includes mollusks, finfish, and detritus. Larvae and early juvenile fish (15 to 30 millimeters) are carnivores and feed on zooplankton in the water column, such as calanoid and harpacticoid copepods. Older juveniles and adults are opportunists, forcefully digging in the substrate in order to feed on benthic invertebrates. Adults also prey on some fishes in addition to bottom feeding. Detritus in the diet of Atlantic croaker appears to be a byproduct of feeding along the bottom, rather than for nutritive purposes (Diaz 1982; Lassuy 1983a; Patillo et al. 1997). A number of larger piscivorous fish species, such as bass (*Morone spp.*), red drum, and seatrout (*Cynoscion spp.*), are predators of Atlantic croaker (Patillo et al. 1997).

3.4.2 Spot (*Leiostomus xanthurus*)

General Description

Spot is a demersal sciaenid species found in estuarine and coastal waters of the western Atlantic Ocean and GOM, from the Gulf of Maine to the Bay of Campeche, Mexico. Spot are commercially harvested, primarily from Chesapeake Bay and the Atlantic coast; however, spot does contribute to the bottom-fish industry of Louisiana and Mississippi (Patillo et al. 1997). Spot is not a particularly important recreational species. Spot are associated with sandy or muddy bottoms and use estuaries as nursery grounds (McEachran and Fechhelm 2005). Massman (1954) reported that in Virginia, spot occurred in freshwater 35 kilometers upstream of brackish waters. Other common names include flat croaker, yellowtail, golden croaker, and spot croaker.

Morphology

Spot is a deep bodied fish characterized by a small, nearly horizontal mouth; deeply notched dorsal fin; and a single, large spot located behind the operculum. Spot have 12 to 15 oblique, dark streaks that may be indistinct in larger specimens and are silvery gray color, darker dorsally than ventrally (McEachran and Fechhelm 2005; Maier, no date). Spot are one of the smaller members of the Sciaenidae (Patillo et al. 1997).

Ecological Relationship with Freshwater Inflow and Salinity

Nelson (1992) reports adult spot as abundant in Sabine Lake at salinities up to 25 ppt from September to October; while juveniles are reported as common in similar salinities throughout the year. TPWD (2005) showed that spot selected salinities between 6 to 12 ppt in Sabine Lake.

Life History

Spot spawn offshore in moderately deep water over the continental shelf during from November through March in Louisiana (Cowan and Shaw 1988) and from November to April, with peaks from December to February (Patillo et al. 1997). Larvae are then transported inshore towards estuarine nursery grounds where transformation to juveniles occurs around 15 millimeters. Larvae exhibit a diurnal vertical migration, where they are dense in mid-water and at the bottom during the day and at the surface during the night. Juveniles initially move into low salinity headwaters in the estuary during the spring and summer. As juveniles mature towards the end of their second year, they move from shallower, less saline, headwaters of tidal creeks, to seagrass beds or deeper, more saline areas within estuaries. Like many of these estuarine-dependent fish species, spot adults and juvenile commonly make inshore-offshore migrations (Patillo et al. 1997).

Feeding Preferences and Predators

Spot are selective planktivores in the early stages of their life eating organisms such as pteropods, larval pelecypods, and cyclopoid copepods. Juveniles and adults are nocturnal, opportunistic bottom feeders with prey items including benthic infauna. Feeding by juveniles in estuaries appears to be tidally influenced, taking advantage of prey available in marsh habitats during high tides, consisting of insect larvae, bivalves, and detritus (Patillo et al 1997).

Predators include a number of piscivorous fish, including silky sharks (*Carcharhinus falciformis*), longnose gar (*Lepisosteus osseus*), bass (*Morone* spp.), seatrout, flounders, and to seabirds such as cormorants (*Phalacrocorax* spp.) (Phillips et al. 1989; Patillo et al. 1997).

3.4.3 Gulf menhaden (*Brevoortia patronus*)

General Description

The Gulf menhaden is an estuarine-dependent (Christmas et al. 1982; Patillo et al. 1997; VanderKooy and Smith 2002) marine species found from freshwater to hypersaline environments. Other common names include shad, pogy, largescale menhaden, sardine, fatback, and bunker. Gulf menhaden range from Florida to Mexico and supports one of the most important clupeid and largest single-species (by weight) fisheries in the GOM (Christmas and Gunter 1960; Christmas et al. 1982; Lassuy 1983c). Gulf menhaden are taken by purse seines from both estuarine and nearshore marine waters, with centers of abundance in Mississippi (Christmas et al. 1982; Lassuy 1983c), Louisiana (Christmas and Gunter 1960; Christmas et al. 1982; Lassuy 1983c; Hoese and Moore 1998), and Texas (Christmas et al. 1982), including Sabine Estuary (Nelson 1992).

Morphology

Gulf menhaden are distinguished from other clupeids, particularly menhaden species, by being considerably smaller, having a large head, large scales, and a dark humeral spot usually followed by a series of smaller spots (Christmas and Gunter 1960; Hoese and Moore 1998; TPWD 1999; VanderKooy and Smith 2002).

Ecological Relationship with Freshwater Inflow and Salinity

As an inhabitant of both estuarine and marine waters, Gulf menhaden have adapted to a wide range of temperature and salinity tolerances. Nearshore bays and estuaries inhabited by adults range from 5 to 15 ppt, whereas offshore marine waters are characterized by higher salinities, greater than or equal to 30 ppt

(Christmas et al. 1982). Non-gravid and developing adults occupy mid-range salinities with high abundances at 20 to 25 ppt, though they are capable of ranges from 0 to 67 ppt (Patillo et al. 1997). Gulf menhaden adults have been documented as common in Sabine Estuary at a wide range of salinities from September through November (Nelson 1992). In general, postlarvae and juveniles also occupy a wide range of salinities from 5 to 30 ppt (Patillo et al. 1997). Nelson (1992) reports juveniles as highly abundant in Sabine Estuary during the summer months, abundant during the fall months, and common through the winter and spring months. TPWD (2005) showed that Gulf menhaden in the Sabine Estuary selected salinity ranges of 3 to 6 ppt.

Life History

Gulf menhaden life history is typical of most estuarine-dependent species in the GOM, spawning offshore in Gulf waters with recruitment and maturation in nearshore rivers, bays, and bayous (VanderKooy and Smith 2002), sometimes in waters of very low salinities considered to be in the freshwater range (Christmas and Gunter 1960).

Beginning around October, Gulf menhaden move from shallow inshore areas offshore, wintering on the inner and middle continental shelf, from 2 to 128 meters deep (Roithmayr and Waller 1963). Spawning occurs in these offshore waters over the continental shelf from October through March (Fore and Baxter 1972a) at temperatures between 15 and 18 °C and salinities greater than 25 ppt (VanderKooy and Smith 2002); though spawning is suspected to occur in some years from September to May (Christmas et al. 1982). The spawning season, which may be composed of as many as four to five spawning peaks, appears to coincide with relatively cool Gulf waters from approximately 25 °C in October to 18 °C in March (Christmas et al. 1982). Based on the distribution of eggs, Gulf menhaden spawning occurs mainly over the continental shelf between Sabine Pass, Texas and Alabama (VanderKooy and Smith 2002).

After a period of approximately 3 to 5 weeks, larvae are transported by currents into low salinity estuarine nursery areas (Fore and Baxter 1972b; Christmas and Gunter 1982). Peak influxes of larvae into estuaries along Texas and Louisiana occur in November-December to February-April, where they are carried into tidal creeks and ponds of marshes and estuaries (Patillo et al. 1997). While in estuaries, larvae metamorphose to juveniles as they reach 30 to 33 millimeters (Lassuy 1983c). After transformation, juveniles remain in the low salinity, nearshore marshes (Fore and Baxter 1972b; Lassuy 1983c; Hoese and Moore 1998) though they may move to deeper, open, higher salinity (Fore and Baxter 1972b) estuarine waters as reach lengths greater than 50 millimeters (Patillo et al. 1997). Juveniles were reported to have been collected in the lower Neches River, approximately 30 nautical miles upstream from Texas Point, at the Sabine Pass entrance, in salinities ranging from 0.16 to 20.4 ppt (Gunter and Christmas 1960).

Peak Gulf ward migrations of maturing juveniles and adults occur from October through January (Lassuy 1983c). Migration back into inshore estuarine waters by individuals of all age groups, including adults, occur early the following spring, March to April, following an overwintering or spawning season (Christmas et al. 1982; Lassuy 1983c) at depths of 1.8 to 14.6 meters (Patillo et al. 1997), where fish are sexually inactive (Christmas et al. 1982) and returning primarily to feed in the food rich waters of estuaries. Inshore-offshore migrations are common for juveniles and adults, though both have been documented in estuaries and inshore areas year-round (Lassuy 1983c), including Sabine Lake (TPWD 2005).

Though the dependence of Gulf menhaden to lower salinity estuarine habitats is not well understood, metamorphosing larvae have rarely been collected in higher salinity marine waters, indicating a relationship between development and food availability. The shelter provided in estuarine habitats is also important for Gulf menhaden. Small (less than 20 hectares) marsh areas generally do not support large concentrations of menhaden unless they are part of a larger estuarine complex. Additionally, despite a lack of data related to physiological requirements for estuarine dependence, gonadogenesis of young Gulf menhaden is completed only in brackish, estuarine waters (Christmas et al. 1982).

Feeding Preferences and Predators

Gulf menhaden have two distinct feeding stages through their life cycle. Larval Gulf menhaden (30 to 33 millimeters) are selective carnivores (Patillo et al. 1997) in estuarine and marine waters, feeding primarily on zooplankton. The loss of teeth and elongation of gill rakers occurs during metamorphoses and juveniles and adults become omnivorous filter-feeders, consuming phytoplankton, zooplankton, detritus, and bacteria (Christmas et al. 1982; Lassuy 1983c).

Gulf menhaden are not only an economically important commercial fishery, but are also ecologically important. Because of their great abundance and schooling behavior, Gulf menhaden support a number of piscivorous fish and bird species including: mackerel (Scombridae), spotted seatrout, alligator gar, red drum, brown pelican (*Pelecanus occidentalis*), and osprey (*Pandion haliaetus*) (VanderKooy and Smith 2002). Additionally, larval Gulf menhaden are one of the dominant species of ichthyoplankton in the GOM during the winter, spawning months (Raynie and Shaw 1994).

4.0 SUMMARY

It is widely accepted that the Sabine-Neches estuary (Sabine Lake), like other Gulf Coast estuaries, is a highly dynamic environment that reacts to many drivers, one of which is freshwater inflow. Freshwater inflow studies are complex, usually involving an assessment of processes occurring across multiple spatial and temporal scales regarding the hydrology, water quality, geomorphology, and biology of the estuary. Several studies documenting the importance of freshwater inflows to the Sabine Lake system have been conducted over the last few decades. The Texas Department of Water Resources (1981) used indicators including freshwater inflows, circulation and salinity patterns, nutrients, and aquatic indicator species in their analyses. Methods for their analyses included statistical analysis of relationships among freshwater inflow, commercial fishery harvest and estuarine salinity, estimates of marsh freshwater inundation needs, estimates of nutrient exchange, records of historical freshwater inflow, and seasonal pulses (TDWR 1981). More recently, the Texas Parks and Wildlife Department (2005) also stressed the importance of the timing of inflow, in addition to volume, in maintaining an ecologically sound environment. The purpose of this biological summary document is to provide the Sabine-Neches BBEST with the background biological information on the selected focal species in Sabine Lake to allow for the examination of potential environmental flow regimes required for the Senate Bill 3 process.

Freshwater inflow influences the spatial distribution, abundance, and productivity of aquatic organisms in estuaries in several ways. In addition to creating the salinity gradient across the estuary, freshwater inflows also transport sediment and nutrients into the open bay and surrounding marshes. Seasonal flood pulses allow for high waters to inundate the floodplain and fringing marshes. During flood conditions, marsh habitats are inundated and nutrients and sediment are deposited in the marsh, helping to flush stagnant water, increase plant productivity, and maintain marsh elevation in the landscape. Phytoplankton also use these nutrients in the water column for primary production, forming the base of the estuarine food web.

The spatial distribution of wetland plants and bivalve mollusks are particularly related to the longer-term trends of freshwater inflow to the Sabine Lake system since they are sessile organisms, not capable of moving in response to changing environmental conditions. The spatial distributions of the crustacean and fish focal species are related to freshwater inflow on a seasonal basis due to their life cycles and their ability to move in response to changes in environmental gradients (salinity, temperature, etc.). However, the juvenile life stages of these species are typically less able to tolerate large changes in salinity and do not have the mobility of adults. Juvenile life stages require nursery habitats for shelter and food for successful development before they are able to survive in the open estuary and GOM. A map outlining the general trends in spatial distribution of the ten focal species is shown in **Figure 10**.

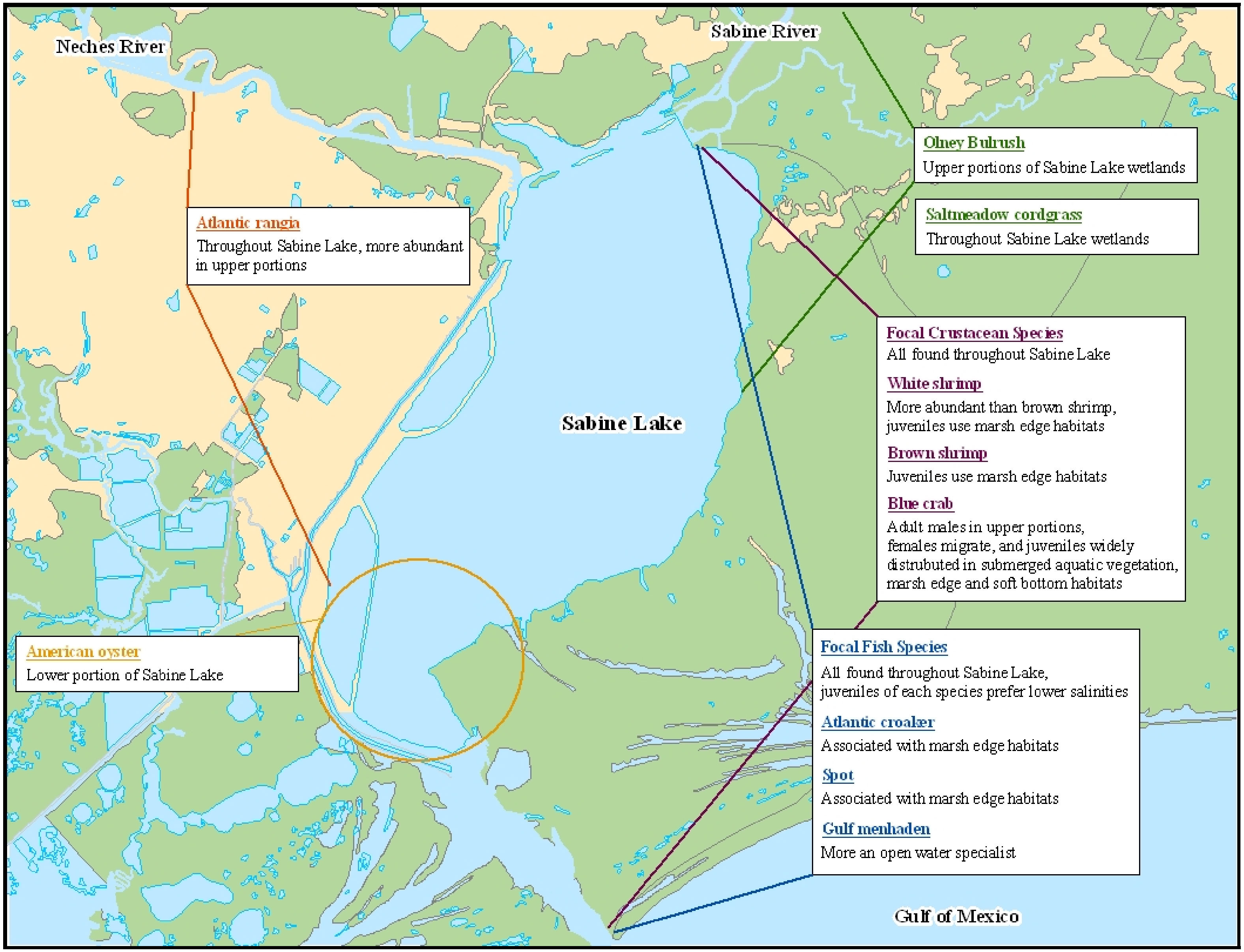


Figure 10. General spatial distribution patterns of focal species in the Sabine Lake system.

The timing of freshwater inflow to a bay has long been acknowledged as being extremely important in maintaining the ecological productivity of the system. Aquatic organisms respond to pulses of nutrients, alterations in salinity, and habitat conditions (e.g. temperature, dissolved oxygen, food availability), which may vary seasonally and with variations in freshwater inflow to the estuary. Historically, the discharge rates of Texas rivers have fluctuated on a seasonal basis. Monthly freshwater inflows usually peak in the spring and early fall, following patterns of increased rainfall and runoff that normally occur during these months (http://waterdata.usgs.gov).

As estuarine-dependent organisms, these species have developed a unique relationship with freshwater inflow that is related to all or a part of its life cycle. Freshwater inflow regimes directly influence the salinity regimes observed within estuaries. In Sabine Lake, NOAA (1998e) developed salinity seasons for Sabine Lake (prepared for Gulf of Mexico Fishery Management Council): decreasing salinity season (November to February), low salinity season (March to May), increasing salinity season (June to July), and high salinity season (August to October). These salinity seasons along with a general pattern of freshwater inflow from the Sabine and Neches Rivers to Sabine Lake is provided in **Figure 11**. Also shown in **Figure 11** are key temporal and ecological relationships of each of the ten estuarine focal species in Sabine Lake as they relate to the seasonal pattern of freshwater inflow. Key points outlined in Figure 11 regarding the freshwater inflow-ecology relationships for each of the focal species include:

- Atlantic rangia – spawning may be continuous during the year, but peak spawning periods have been documented from March to May and from late summer to November (Louisiana; LaSalle and de la Cruz 1985). Spawning may be triggered by an increase in salinity and temperature, and the larvae require some salinity for development, tolerating a range of approximately 2 to 10 ppt.
- American oyster – in southern waters, spawning occurs in all but the coldest months (Berrigan et al. 1991) with oyster growth optimal in salinities from 10 to 28 ppt.
- White shrimp – in Texas, postlarvae enter and utilize nursery areas from April to November (Kilma et al. 1982).
- Brown shrimp – juveniles are abundant in Sabine lake in summer and fall, decreasing in late fall as they migrate to the GOM (Nelson 1992, NOAA 1998b, CCMA).
- Blue crab – mate in low salinity waters of the upper estuary, where the males remain. Females migrate to the lower bays to spawn between two and nine months after mating, typically between August and September (Van Engel 1958, Williams 1965).
- Atlantic croaker – postlarvae and juveniles utilize estuaries and concentrate in shallow waters near sources of fresh to brackish waters during spring and early summer (Lassuy 1983a).
- Spot – enter estuaries as larvae in the spring and head to low salinity headwaters of the estuary and tidal creeks throughout the summer (Patillo et al. 1997).
- Gulf menhaden – generally spawn from October to March (Christmas et al. 1982), from Sabine Pass to Alabama with peak influxes to the estuaries in February – April (VanderKooy and Smith 2002, Patillo et al. 1997).

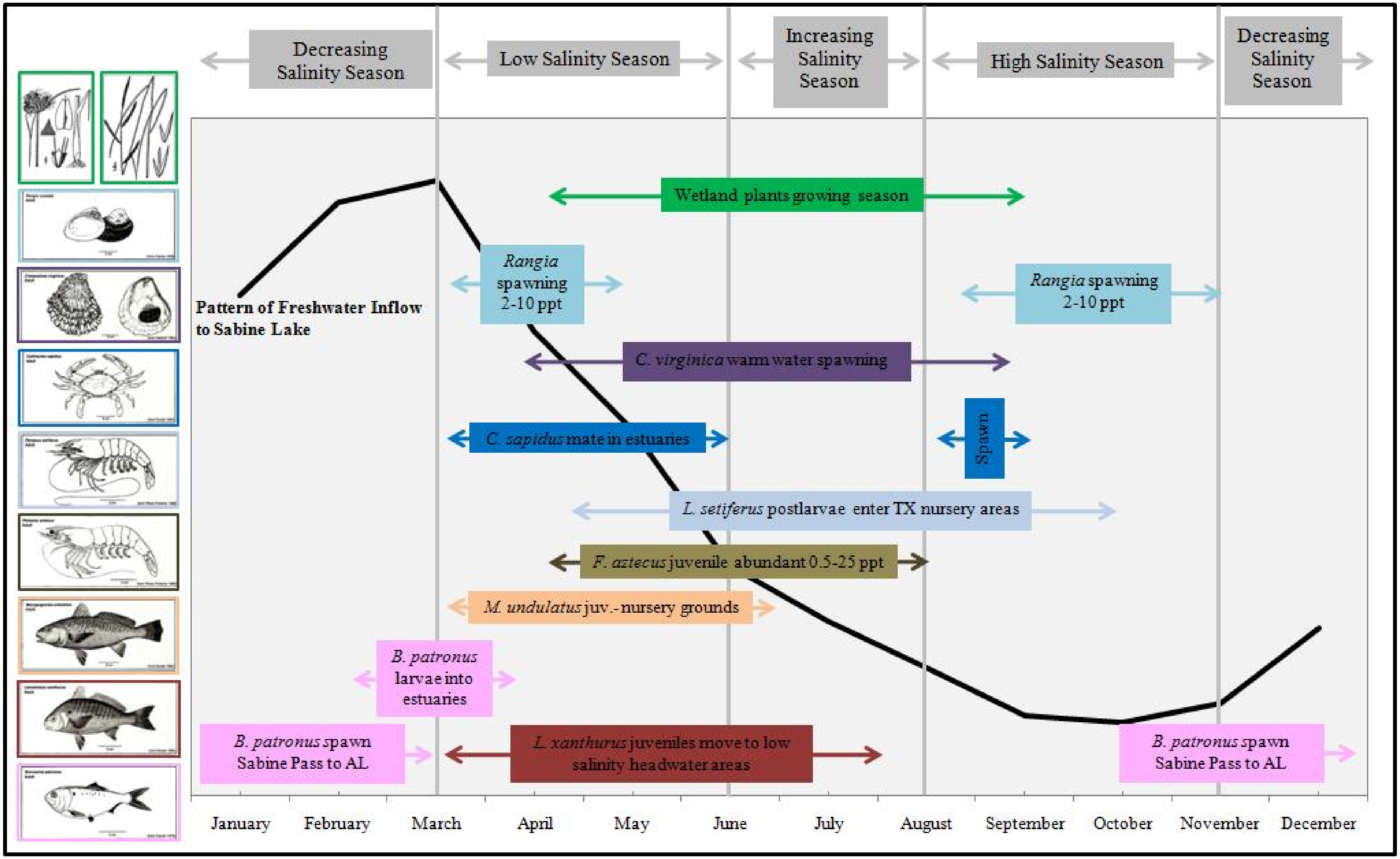


Figure 11. General ecological relationships of each focal species with the seasonal pattern of freshwater inflow to the Sabine Lake system.

Of primary importance to many of these species is the availability of estuarine habitats for nursery and foraging areas, where postlarval and juvenile life stages typically select for vegetative cover and lower salinity conditions. Crustacean and fish species also depend on the nutrients and shelter provided by freshwater inflows through adjacent marsh habitats and from tidal creeks. Economically, the bulk of commercial fisheries depend on the survival and recruitment success of these species established during their time in estuaries.

It is evident that maintaining the variability in freshwater inflows to estuaries is important. One aspect that is also clear is that the inflows to Sabine Lake tend not to be steady, but rather occur in high flow pulses or longer-term seasonal freshets. As examined in a freshwater inflow analysis for Matagorda Bay, Texas, simply meeting an average or median inflow at all times would not maintain the long-term average primary productivity in the estuary because the bulk of the essential nutrients that support the long-term average chlorophyll-a levels are supplied by the relatively infrequent high flow events that are a critical part of the system variability (MBHE 2008). The seasonal timing of inflows are also important, since pulses of flow and nutrients that occur in the spring and early summer would translate into chlorophyll-a more rapidly than they would if the same pulse occurred in the winter. However, these high-flow pulse or freshet events are largely due to natural storm events (including hurricanes) unrelated to managed river flows. An example of an inflow regime study that addresses these important pulse events was recently developed for the Matagorda Bay system, which typically receives less freshwater inflow than Sabine Lake, and the report provides an overview of the topics discussed in this document as related to Matagorda Bay (MBHE 2008).

Shifts in the overall magnitude and duration of freshwater inflow to Sabine Lake will also influence the spatial distribution, abundance and productivity of the focal species, although some species will be affected differently than others. **Table 4** provides potential general trends in the freshwater inflow-ecology relationships of the focal species in Sabine Lake in relation to hypothetical overall changes in the magnitude of freshwater inflow to the estuary. Generally, because many of these focal species are euryhaline, slight or moderate shifts in overall freshwater inflow between years will not greatly affect or impact many of these organisms. However, more dramatic responses in the species' distribution and abundance can be reasoned from individual salinity and habitat requirements, based on dramatic changes in inflows to the estuary, whether it be a large shift to less inflow or a large shift to more inflow (**Table 4**). The more tolerant species, such as spot, Gulf menhaden, and brown shrimp, primarily in their adult life stage, would likely not be significantly affected in either scenario. In a more saline environment, wetland plants and Atlantic rangia would be under higher salinity stress and would likely decrease in overall abundance and productivity. Atlantic rangia distribution in particular would likely be considerably reduced by increased salinity conditions, since even adults do not tolerate salinities above 18 ppt. Since white shrimp are highly abundant in Sabine Lake under current conditions and juveniles are found in nursery areas with relatively low salinities, it is likely than a dramatic decrease in freshwater inflow to the system would lead to a decrease in the abundance of white shrimp.

Table 4. Potential general trends in the freshwater inflow-ecology relationships of focal species in Sabine Lake; (~) – similar spatial distribution, abundance, and productivity; (↓), (↑) – implies decrease or increase in potential abundance and productivity, respectively, where size of arrow depicts the potential degree of change.

Estuarine Focal Species		**Life Stage**	**Shift in Annual Inflow (maintaining seasonal variability)**		
Common Name	**Scientific Name**		**Slight shift, more or less**	**Large shift to less inflow**	**Large shift to more inflow**
Olney bulrush	*Schoenoplectus americanus*	n/a	~	↓	↑
Saltmeadow cordgrass	*Spartina patens*	n/a	~	↓	↑
Atlantic rangia	*Rangia cuneata*	n/a	~	↓	↑
Eastern oyster	*Crassostrea virginica*	n/a	~	↑	↓
Blue crab	*Callinectes sapidus*	n/a	~	~	~
White shrimp	*Litopenaeus setiferus*	n/a	~	↓	~
Brown shrimp	*Farfantepenaeus aztecus*	n/a	~	↑	↓
Atlantic croaker	*Micropogonias undulatus*	Juvenile	~	↓	~
		Adult	~	~	↓
Spot	*Leiostomus xanthurus*	Juvenile	~	↓	~
		Adult	~	~	↓
Gulf menhaden	*Brevoortia patronus*	Juvenile	~	~	~
		Adult	~	~	↓

Brown shrimp, however, are generally found in higher salinities than white shrimp and might benefit from an increase in salinity in Sabine Lake. Oysters are also currently limited in distribution in Sabine Lake, occurring only in the lower portion since the upper estuary is too fresh for oysters to survive. A decrease in freshwater to Sabine Lake might allow for the extension of the oyster range to more northern portions of Sabine Lake, provided there were adequate substrate for spat settlement and sufficient freshwater inflows to regulate oyster parasites and predators.

Under the scenario of higher freshwater inflows to Sabine Lake, with a less saline environment, the same wetland plant species and Atlantic rangia would likely be more productive and more abundant. *S. americanus* thrives with inundation of the soil and less salt stress and *S. patens* would be similarly more productive under lower salinities. However, if inundation of the high marsh were to occur more frequently and for longer duration, *S. alterniflora* may outcompete *S. patens* in the brackish marsh and cattail or common reed may outcompete *S. patens* in the fresh and intermediate marsh areas. The Atlantic rangia population could extend further down in Sabine Lake under fresher conditions, since the necessary salinity conditions required for spawning may exist over larger spatial areas. In contrast to Atlantic rangia, oyster productivity and distribution would likely decrease under this higher inflow scenario.

The distribution of the more euryhaline species, fishes and crustaceans, though they may prefer low salinities during their juvenile life stages, would likely not be highly influenced by a more saline or less saline environment, though in both cases, a decrease in survivability, recruitment, and abundance is possible.

Shifts in the seasonal variability of freshwater inflow may also have an effect on the distribution, abundance and productivity of the focal species in Sabine Lake. A slight to moderate shift in variability, such as slightly increasing the magnitude of the spring freshet or having the fall freshet occur a few weeks later than average, will not likely cause such a change. However, a large shift in the inflow variability, such as inverting the seasonal inflow pattern or maintaining a constant flow to the estuary, will likely cause a decrease in the abundance and productivity of many or all the focal species in the estuary since their life cycles have developed around variations in inflow patterns.

Other factors influencing bay conditions are near-shore gulf salinity, meteorology, physiographic modifications, harvest pressures, adjacent land-use change, habitat alterations or losses, and large-scale GOM conditions. All of these factors can affect habitat and species distributions and productivity in the bay, as well as chemical constituents, the availability of food, fishing pressure, and for migratory species, the status of the larger population in the Gulf.

In conclusion, although ecological responses to freshwater inflow are complex, we feel that the focal species approach taken by the Sabine/Neches BBEST is appropriate for the SB3 objectives. To support the mission of guiding the establishment of freshwater inflow recommendations to Sabine Lake, we feel that a detailed evaluation of 1) the HEFR output from the most downstream gages or combination thereof and/or 2) any alternative inflow-regime hydrology prescription can be accomplished by overlaying the freshwater inflow to ecology relationships for the selected focal species as presented.

5.0 LITERATURE CITED

Allen, D. M., J. H. Hudson, and T. J. Costello. 1980. Postlarval shrimp (*Penaeus*) in the Florida Keys: species, size, and seasonal abundance. Bulletin of Marine Science 30:21-33.

Anastasiou, C.J. and J.R. Brooks. 2003. Effects of soil pH, redox potential and elevation on survival of Spartina patens planted at a west central Florida salt marsh restoration site. Wetlands 23(4):845-859.

Anderson, W. W. 1956. Observations upon the biology, ecology, and life history of the common shrimp, *Penaeus setiferus* (Linnaeus) along the south Atlantic and Gulf coasts of the United States. Proceedings of the Indo-Pacific Fisheries Council 6:399-403.

Bhattacharjee, J., D. A. Haukos, and J. Neaville. 2009. Influence of biotic and abiotic factors on annual aboveground biomass of an intermediate coastal marsh. Wetlands 29(2):690-696.

Baxter, K. N. and W. C. Renfro. 1967. Season occurrence and size distribution of postlarval brown and white shrimp near Galveston, Texas, with notes on species identification. Fishery Bulletin 66(1):149-158.

Bedford, W. B. and J. W. Anderson. 1972. The physiological response of the estuarine clam *Rangia cuneata* (Grey) to salinity. I. Osmoregulation. Physiological Zoology 45(3):255-260.

Berrigan, M., T. Candies, J. Cirino, R. Dugas, C. Dyer, J. Gray, T. Herrington, W. Keithly, R. Leard, J. R. Nelson, and M. Van Hoose. 1991. The oyster fishery of the Gulf of Mexico, United States: a regional management plan, Number 24. Gulf States Marine Fisheries Commission, Ocean Springs, Missisippi.

Bertness, M. D. 1991. Zonation of *Spartina patens* and *Spartina alterniflora* in a New England salt marsh. Ecology 72:138-148.

Bertness, M. D. and A. M. Ellison. 1987. Determinants of pattern in a New England salt marsh community. Ecological Monographs 57:129-147.

Brammer, A. J., Z. Rodriguez del Rey, E. A. Spalding, and M. A. Poirrier. 2007. Effects of the 1997 Bonnet Carre spillway opening on infaunal macroinvertebrates in Lake Pontchartrain, Louisiana. Journal of Coastal Research 23(5):1292-1303.

Buroker, N. E. 1983. Population genetics of the American oyster *Crassostrea viginica* along the Atlantic coast and Gulf of Mexico. Marine Biology 75:99-112.

Buzan, D., W. Lee, J. Culbertson, N. Kuhn, and L. Robinson. 2009. Positive relationship between freshwater inflow and oyster abundance in Galveston Bay, Texas. Estuaries and Coasts 32:206-212.

Cake, E. W., Jr., 1983. Habitat suitability index models: Gulf of Mexico American oyster. U.S. Department of the Interior Fish and Wildlife Service, FWS/OBS-82/10.57.

Cain, T. D. 1973. The combined effects of temperature and salinity on embryos and larvae of the clam *Rangia cuneata*. Marine Biology 21:1-6.

Cain, T. D. 1974. Combined effects of changes in temperature and salinity on early stages of *Rangia cuneata*. Virginia Journal of Science 25:30-31.

Cain, T. D. 1975. Reproduction and recruitment of the brackish water clam *Rangia cuneata* in the James River, Virginia. Fisheries Bulletin 78:412-430.

Cain, T. D. 1976. Reproduction and recruitment of the brackish water clam *Rangia cuneata* in the James River, Virginia. Fishery Bulletin 73(2):412-430.

CCMA (Center for Coastal Monitoring and Assessment). No date. Gulf of Mexico essential fish habitat: NOAA's estuarine living marine resources (ELMR) relative abundance and distribution data. Available: http://ccma.nos.noaa.gov/products/biogeography/efh/gom-efh/ELMR.pdf. (July 2009).

Chanley, P. 1965. Larval development of the brackish water mactrid clam, *Rangia cuneata*. Chesapeake Science 6:209-213.

Chazaro-Olvera, S. and M. S. Peterson. 2004. Effects of salinity on growth and molting of sympatric *Callinectes* spp. from Camaronera Lagoon, Veracruz, Mexico. Bulletin of Marine Science 74(1):115-127.

Christmas, J. Y. and G. Gunter. 1960. Distribution of menhaden, genus *Brevoortia*, in the Gulf of Mexico. Transactions of the American Fisheries Society 89(4):338-343.

Christmas, J. Y., J. T. McBee, R. S. Waller, and F. C. Sutter III. 1982. Habitat suitability index models: Gulf menhaden. U.S. Department of the Interior Fish and Wildlife Service, FWS/OBS-82/10.23.

Cook, H. L. and M. A. Murphy. 1971. Early developmental stages of the brown shrimp, *Penaeus aztecus* Ives, reared in the laboratory. Fishery Bulletin 69(1):223-238.

Cowan, J. H., Jr., and R. F. Shaw. 1988. The distribution, abundance, and transport of larval sciaenids collected during winter and early spring from the continental shelf waters off west Louisiana. Fisheries Bulletin 86:129-142.

Darnell, R. M. 1958. Food habits of fishes and larger invertebrates of Lake Pontchartrain, Louisiana, an estuarine community. Publications of the Institute of Marine Science, University of Texas 5:353-416.

Darnell, R. M. 1961. Trophic spectrum of an estuarine community based on studies of Lake Pontchartrain, Louisiana. Ecology 42:553-568.

Dekshenieks, M. M., E. E. Hofmann, and E. N. Powell. 2000. Quantifying the effects of environmental change on the oyster population: a modeling study. Estuaries 23(5):593-610.

Denno, R. F. 1980. Ecotope differentiation in a guild of sap-feeding insects on the salt marsh grass, *Spartina patens*. Ecology 61(3):702-714.

Diaz, R. J. 1982. Habitat suitability index models: juvenile Atlantic croaker. U.S. Department of the Interior Fish and Wildlife Service, FWS/OBS-82/10.21.

Fairbanks, L. D. 1963. Biodemographic studies of the clam *Rangia cuneata* Gray. Tulane Studies in Zoology 10:3-47.

Flynn, K. M., K. L. McKee, I. A. Mendelssohn. 1995. Recovery of freshwater marsh vegetation after a saltwater intrusion event. Oecologia 103:63-72.

Fore, P. L. and K. N. Baxter. 1972a. Collections of larval Gulf menhaden, *Brevoortia patronus*, from Galveston entrance (1959-1969) and Sabine Pass (1963-1967), Texas. National Marine Fisheries Service Data Report 74.

Fore, P. L. and K. N. Baxter. 1972b. Diel fluctuations in the catch of larval Gulf menhaden, *Brevoortia patronus*, at Galveston entrance, Texas. Transactions of the American Fisheries Society 101(4):729-732.

Galtsoff, P. S. 1964. The American oyster *Crassostrea virginica* (Gmelin). U.S. Fish and Wildlife Service Fisheries Bulletin 64:1-480.

Gleason, M. L. and J. C. Zieman. 1981. Influence of tidal inundation on internal oxygen supply of *Spartina alterniflora* and *Spartina patens*. Estuarine, Coastal and Shelf Science 13:47-57.

Guillory, V., H. Perry, S. Vanderkooy (eds.). 2001. The blue crab fishery of the Gulf of Mexico, United States: a regional management plan. Gulf States Marine Fisheries Commission.

Gunter, G. and J. Y. Christmas. 1960. A review of literature on menhaden with special reference to the Gulf of Mexico menhaden, *Brevoortia patronus* Goode. U.S. Fish and Wildlife Service, Special Scientific Report 363.

Hargis, W. J., Jr. and D. S. Haven. 1999. Chesapeake oyster reefs, their importance, destruction, and guidelines for restoring them. Pages 329-358 *in* M. W. Luckenback, R. Mann, and J. A. Wesson, editors. Oyster reef habitat restoration: a synopsis, and a synthesis of approaches. Virginia Institute of Marine Science Press, Gloucester Point, Virginia.

Hass, H. L., K. A. Rose, B. Fry, T. J. Minello, and L. P. Rozas. 2004. Brown shrimp on the edge: linking habitat to survival using an individual-based simulation model. Ecological Applications 14(4):1232-1247.

Harrel, R. C. 1993. Origin and decline of the estuarine clam *Rangia cuneata* in the Neches River, Texas. American Malacological Bulletin 10(2):153-159.

Hoese, H. D. 1973. Abundance of the low salinity clam, *Rangia cuneata* in southwestern Louisiana. Proceedings of the National Shellfisheries Association 63:99-106.

Hoese, H. D. and R. H. Moore. 1998. Fishes of the Gulf of Mexico, second edition. Texas A&M University Press, College Station, Texas.

Hofmann, E. E., E. N. Powell, J. M. Klick, and E.A. Wilson. 1992. Modeling oyster populations III. Critical feeding periods, growth and reproduction. Journal of Shellfish Research 11(2):399-416.

Hofmann, E. E., E. N. Powell, J. M. Klinck, and G. Saunders, 1995. Modelling diseased oyster populations I. Modelling *Perkinsus Marinus* infections in oysters. Journal of Shellfish Research 14(1):121-151.

Hofstetter, R. P. 1977. Trends in population levels of the American oyster *Crassostrea virginica* Gmelin on public reefs in Galveston Bay, Texas. Texas Parks and Wildlife Technical Series 24, PWD-Bull-3000-29.

Hopkins, S. H. and J. D. Andrews. 1970. *Rangia cuneata* on the East Coast: thousand mile range extension, or resurgence? Science 167(3919):868-869.

Hopkins, S. H., J. W. Anderson, K. Horvath. 1973. The brackish water clam *Rangia cuneata* as indicator for ecological effects of salinity changes in coastal waters. U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, Contract Report H-73-1.

Howard, R.J. and I.A. Mendelssohn. 1999. Salinity as a constraint on growth of oligohaline marsh macrophytes. I. Species variation is stress tolerance. American Journal of Botany 86:785-794.

Howard, R. J. and I. A. Mendelssohn. 2000. Structure and composition of oligohaline marsh plant communities exposed to salinity pulses. Aquatic Botany 68:143-164.

Ikegami, M., D. F. Whigham, M. J. A. Werger. 2007. Responses of rhizome length and ramet production to resource availability in the clonal sedge Scirpus olneyi A. Gray. Plant Ecology 189:247-259.

Jackson, E.L., A.A. Rowden, M.S. Attrill, S.J. Bossey, and M.B. Jones. 2001. The importance of seagrass beds as a habitat for fishery species. Oceanography and Marine Biology: An Annual Review 39:269-303.

Jenkins, J. B., A. Morrison, and C. L. MacKenzie, Jr. 1997. The molluscan fisheries of the Canadian Maritimes. Pages 15-44 *in* C. L. MacKenzie, Jr., V. G. Burrell, Jr., A. Rosenfield, and W. L. Hobart, editors. The history, present condition, and future of the molluscan fisheries of the North and Central America and Europe, volume 1. Atlantic and Gulf Coasts. U.S. Department of Commerce, NOAA Technical Report, National Marine Fisheries Service.

Jovanovich, M. C. and K. R. Marion. 1989. Gemetogenic cycle of *Rangia cuneata* (Mactridae, Mollusca) in Mobile Bay, Alabama, with comments on geographic variation. Bulletin of Marine Science 45(1):130-138.

Kane, H. E. 1961. Occurrence of *Rangia cuneata* Gray and *Crassostrea viginica* (Gmelin) in Sabine Lake, Texas-Louisiana. Journal of Sedimentary Petrology 31(4):627.

Kennedy, V. S. and L. E. Cronin, editors. 2007. The blue crab: *Callinectes sapidus*. University of Maryland Sea Grant College, College Park, Maryland.

Kennedy, V. S., R. I. E. Newell, and A. F. Eble, 1996. The eastern oyster (*Crassostrea virginica*). University of Maryland Sea Grant Publications, College Park, Maryland.

Kilma, E.F., K.N. Baxter, and F.J. Patella Jr. 1982. A review of the offshore shrimp fishery and the 1981 Texas closure. Marine Fisheries Review 44(2-10):16-30.

La Peyre, M.K., A.D. Nickens, A.K. Volety, G.S. Tolley, J. F. La Peyre. 2003. Environmental significance of freshets in reducing *Perkinsus marinus* infection in eastern oysters *Crassostrea virginica*: potential management applications. Marine Ecology Progress Series 248:165-176.

Langdon, C. J. and R. I. E. Newell. 1996 Digestion and nutrition in larvae and adults. Pages 231-269 *in* V. S. Kennedy, R. I. E. Newell and A. F. Eble, editors. The Eastern Oyster *Crassostrea virginica*. Maryland Sea Grant College, University of Maryland, College Park, Maryland.

LaSalle, M. W. and A. A. de la Cruz. 1985. Species profiles: life histories and environmental requirements of coastal fisheries and invertebrates (Gulf of Mexico) – common rangia. U.S. Fish and Wildlife Service Report 82(11.31). U.S. Army Corps of Engineers, TR EL-82-4.

Lassuy, D. R. 1983a. Species profiles: life histories and environmental requirements (Gulf of Mexico): Atlantic croaker. U.S. Fish and Wildlife Service, Division of Biological Services, FWS/OBS-82/11.3. U.S. Army Corps of Engineers, TR EL-82-4.

Lassuy, D. R. 1983b. Species profiles: life histories and environmental requirements (Gulf of Mexico): Gulf menhaden. U.S. Fish and Wildlife Service, Division of Biological Services, FWS/OBS-82/11.2. U.S. Army Corps of Engineers, TR EL-82-4.

Lassuy, D. R. 1983c. Species profiles: life histories and environmental requirements (Gulf of Mexico): brown shrimp. U.S. Fish and Wildlife Service, Division of Biological Services, FWS/OBS-82/11.1. U.S. Army Corps of Engineers, TR EL-82-4.

Laughlin, R. A. 1982. Feeding habits of the blue crab, *Callinectes sapidus* Rathburn, in the Apalachicola estuary, Florida. Bulletin of Marine Science 32:807-822.

Lefor, M. W., W. C. Kennard, and D. L. Civco. 1987. Relationships of salt-marsh plant distributions to tidal levels in Connecticut, USA. Environmental Management 11:61-68.

Maier, P. no date. Spot (*Leiostomus xanthurus*). South Carolina Department of Natural Resources, Comprehensive Wildlife Conservation Strategy, Species Descriptions. Available: http://www.dnr.sc.gov/cwcs/pdf/Spot.pdf. (July 2009).

Massman, W. H. 1954 Marine fishes in fresh and brackish waters of Virginia rivers. Ecology 35:75-78.

(MBHE) Matagorda Bay Health Evaluation Project Team. 2005. Progress Report, Matagorda Bay health evaluation, habitat assessment. Prepared for Lower Colorado River Authority and San Antonio Water System.

(MBHE) Matagorda Bay Health Evaluation Project Team. 2008. Final Report, Matagorda Bay inflow criteria, Matagorda Bay health evaluation. Prepared for Lower Colorado River Authority and San Antonio Water System.

McEachran, J. D., and J. D. Fechhelm. 2005. Fishes of the Gulf of Mexico, volume 2: Scorpaeniformes to Tetraodontiformes. University of Texas Press, Austin, Texas.

Minello, T. J. 1999. Nekton densities in shallow estuarine habitats of Texas and Louisiana and the identification of essential fish habitat. American Fisheries Society Symposium 22:43-75.

Minello, T. J., R. J. Zimmerman, and E. X. Martinez. 1989. Mortality of young brown shrimp *Penaeus aztecus* in estuarine nurseries. Transactions of the American Fisheries Society 118:693-708.

Mitsch, W.J. and J.G. Gosselink. 2000. Wetlands, third edition. John Wiley & Sons, New York, NY, USA. 920 pp.

Muncy, R. J. 1984. Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (Gulf of Mexico) – white shrimp. U.S. Fish and Wildlife Service, FWS/OBS-82/11.20. U.S. Army Corps of Engineers, TR EL-82-4.

Nelson, D. M. (ed.). 1992. Distribution and abundance of fishes and invertebrates in Gulf of Mexico estuaries, volume I: data summaries. Estuarine Living Marine Resources Report 10, NOAA/NOS Strategic Environmental Assessments Division, Rockville, Maryland.

(NOAA) National Oceanic and Atmospheric Administration - Fisheries Service Galveston Laboratory. 1998a. Brown shrimp, *Penaeus aztecus* Adults. Available: http://galveston.ssp.nmfs.gov/research/fisheryecology/EFH/Relative/maps/Texas/SabineLk/sblkbsa.PDF. (July 2009).

(NOAA) National Oceanic and Atmospheric Administration - Fisheries Service Galveston Laboratory. 1998b. Brown shrimp, *Penaeus aztecus* Juveniles. Available: http://galveston.ssp.nmfs.gov/research/fisheryecology/EFH/Relative/maps/Texas/SabineLk/sblkbsj.PDF. (July 2009).

(NOAA) National Oceanic and Atmospheric Administration - Fisheries Service Galveston Laboratory. 1998c. White shrimp, *Litopenaeus setiferus* Adults. Available: http://galveston.ssp.nmfs.gov/research/fisheryecology/EFH/Relative/maps/Texas/SabineLk/sblkwsa.PDF. (July 2009).

(NOAA) National Oceanic and Atmospheric Administration - Fisheries Service Galveston Laboratory. 1998d. White shrimp, *Litopenaeus setiferus* Juveniles. Available:

http://galveston.ssp.nmfs.gov/research/fisheryecology/EFH/Relative/maps/Texas/SabineLk/sblkwsj.PDF. (July 2009).

(NOAA) National Oceanic and Atmospheric Administration – Center for Coastal Monitoring and Assessment. 1998e. Sabine Lake: estuary-specific isohaline distribution map. Available: http://ccma.nos.noaa.gov/products/biogeography/efh/gom-efh/sabine.gif

Nelson, D. M., E. A. Irlandi, L. R. Settle, M. E. Monaco, and L. Coston-Clements. 1991. Distribution and abundance of fishes and invertebrates in southeast estuaries. NOAA/NOS Strategic Environmental Assessments Division, Rockville, Maryland.

O'Neil, S. P. and M. P. Weinstein. 1987. Feeding habitats of spot, *Leiostomus xanthurus*, in polyhaline versus meso-oligohaline tidal creeks and shoals. Fishery Bulleting 85(4):785-796.

Overstreet, R. M., J. Jovonovich, and H. Ma. 2009. Parasitic crustaceans as vectors of viruses, with emphasis on three penaeid viruses. Integrative & Comparative Biology 49(2):127-141.

Palmisano, A. W., Jr. and J. D. Newsom. 1968. Ecological factors affecting occurrence of *Scirpus olneyi* and *Scirpus robustus* in the Louisiana coastal marshes. Proceedings of the Association of Game and Fish Commissioners 21:161-172.

Partridge, T. R. 1987. *Spartina* in New Zealand. New Zealand Journal of Botany 25:567-575.

Patillo, M. E., T. E. Czapla, D. M. Nelson, and M. E. Monaco. 1997. Distribution and abundance of fishes and invertebrates in Gulf of Mexico estuaries, volume II: species life history summaries. Estuarine Living Marine Resources Report 11, NOAA/NOS Strategic Environmental Assessments Division, Silver Spring, Maryland.

Perez-Farfante, I. 1969. Western Atlantic shrimps of the genus *Penaeus*. Fishery Bulletin 67(3):461-591.

Perry, H. M. 1975. The blue crab fishery of Mississippi. Gulf Research Reports 5:39-57.

Peterson, M. S., B. H. Comyns, C. F. Rakocinski, and G. L. Fulling. 2004. Defining the fundamental physiological niche of young estuarine fishes and its relationship to understanding distribution, vital metrics, and optimal nursery conditions. Environmental Biology of Fishes 71:143-149.

Petrik, R., P. S. Levin, G. W. Stunz, and J. Malone. 1999. Recruitment of Atlantic croaker, *Micropogonias undulatus*: do postsettlement processes disrupt or reinforce initial patters of settlement? Fisheries Bulletin 97:954-961.

Pfauth, M. and M. Sytsma. 1998. Key to West Coast *Spartina* species based on vegetative characters. Portland State University Lakes and Reservoirs Program Publication 98-1.

Phillips, J. M., M. T. Huish, J. H. Kerby, and D. P. Morgan. 1989. Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (mid-Atlantic) – spot. U.S. Fish and Wildlife Service, Biological Report 82(11.98). U.S. Army Corps of Engineers, TR EL-82-4.

Posey, M. H., T. D. Alphin, H. Harwell, B. Allen. 2005 Importance of low salinity areas for juvenile blue crabs, *Callinectes sapidus* Rathbun, in river-dominated estuaries of southeastern United States. Journal of Experimental Marine Biology and Ecology 319:57-68.

Powell, E. N., J. M. Klinck, E. E Hofmann, and S. Ford. 1997. Varying the timing of oyster transplant: implications for management from simulation studies. Fisheries Oceanography 6(4):213-237.

Powell, E. N., J. M. Klinck, E. E. Hofmann, E. A. Wilson-Ormond, and M.S. Ellis. 1995. Modeling oyster populations. V. Declining phytoplankton stocks and the population dynamics of American oyster (*Crassostrea virginica*) populations. Fisheries Research 24:199-222.

Pulich, W. Jr., J. D. Tolan, W. Y. Lee, and W. P. Alvis. 2002. Freshwater inflow recommendation for the Nueces Estuary. Coastal Studies Technical Report, Resource Protection Division, Texas Parks and Wildlife Department, Austin, Texas.

Raupp, M. J. and R. F. Denno. 1979. The influence of patch size on a guild of sap-feeding insects that inhabit the salt marsh grass *Spartina patens*. Environmental Entomology 8:412-417.

Raynie, R. C. and R. F. Shaw. 1994. Ichthyoplankton abundance along a recruitment corridor from offshore spawning to estuarine nursery ground. Estuarine, Coastal, and Shelf Science 39:421-450.

Roithmayr, C. M. and R. S. Waller. 1963. Seasonal occurrence of *Breoortia patronus* in the northern Gulf of Mexico. Transactions of the American Fisheries Society 92(3):301-302.

(SAC) Science Advisory Committee. 2009. Methodologies for establishing a freshwater inflow regime for Texas estuaries within the context of the Senate Bill 3 environmental flows process. Working Draft Report, Report Number SAC-2009-03.

Seneca, E. D. 1974. Seedling response to photoperiod and thermoperiod by saltmeadow cordgrass, *Spartina patens*, from Ocracoke Island, North Carolina. Chesapeake Science 15:230-246.

Shackelford, J. 2008. Water bottom assessment of selected portions of public oyster seed ground within Cameron Parish, Louisiana and Calcasieu & Sabine lakes. Final Report to the Louisiana Department of Wildlife and Fisheries, LDWF Contract Number 669712.

Shumway, S. E. 1996. Natural environmental factors. Pages 467-513 *in* V. S. Kennedy, R. I. E. Newell and A. F. Eble, editors. The Eastern Oyster *Crassostrea virginica*. Maryland Sea Grant College, University of Maryland, College Park, Maryland.

Silander, J. A. 1984. The genetic basis of the ecological amplitude of *Spartina patens*. III. Allozyme variation. Botanical Gazette 145:569-577.

Soniat, T. M., and E. V. Kortright, 1998. Estimating time to critical levels of *Perkinsus marinus* in eastern oysters, *Crassostrea virginica*. Journal of Shellfish Research 17(4):1071-1080.

Soniat, T. M. Nicholls State University, Thibodaux, LA. Personal communication with QEA and BIO-WEST personnel. July 25, 2005.

Stanley, J. G. and M. A. Sellers. 1986. Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (Gulf of Mexico) – American oyster. U.S. Fish and Wildlife Service Report 82(11.64). U.S. Army Corps of Engineers, TR EL-82-4. 25 pp.

Stutzenbaker, C. D. 1999. Aquatic and wetland plants of the western Gulf Coast. Texas Parks and Wildlife Press, Austin, Texas.

Tarver, J. W. 1972. Occurrence, distribution and density of *Rangia cuneata* in Lakes Pontchartrain and Maurepas, Louisiana. Louisiana Department of Wildlife and Fisheries Technical Bulletin 1.

(TDWR) Texas Department of Water Resources. 1981. Sabine-Neches Estuary: A study of the influence of freshwater inflows. Texas Department of Water Resources Report LP-116.

Tiner, R. W., Jr. 1987. A field guide to coastal wetland plants of the northeast United States. The University of Massachusetts Press, Amherst, Massachusetts.

(TPWD) Texas Parks and Wildlife Department. 1999. Texas saltwater fish identification pocket guide. Outdoor Empire Publishing, Inc., Seattle.

(TPWD) Texas Parks and Wildlife Department. 2005. Freshwater inflow recommendation for the Sabine Lake Estuary of Texas and Louisiana. Texas Parks and Wildlife Department, Coastal Studies Program, Austin, Texas.

(TPWD) Texas Parks and Wildlife Department. August 2009. Personal communication with TPWD staff regarding wetland plant species around Sabine Lake.

(TPWD) Texas Parks and Wildlife Department. No date. TPWD coastal fisheries data viewer. Available: http://midgewater.twdb.state.tx.us/TPWD/tpwd.html. (August 2009)

Thomas, J. L., R. J. Zimmerman, and T. J. Minello. 1990. Abundance patterns of juvenile blue crabs (*Callinectes sapidus*) in nursery habitats of two Texas bays. Bulletin of Marine Science 46:115-125.

Turner, R. E. and M. S. Brody. 1983. Habitat suitability index models: northern Gulf of Mexico brown shrimp and white shrimp. U.S. Department of the Interior, Fish and Wildlife Service, FWS/OBS-82/10.54.

(USDA) United States Department of Agriculture. 2009. Natural Resources Conservation Service: online plants database. Available: http://plants.usda.gov. (August 2009).

VanderKooy, S. J., and J. W. Smith. 2002. The menhaden fishery of the Gulf of Mexico, United States: a regional management plan. Gulf States Marine Fisheries Commission, Ocean Springs, Mississippi.

Van Engel, W. A. 1958. The blue crab fishery in Chesapeake Bay: part 1 - reproduction, early development, growth, and migration. Commercial Fisheries Review 20(6):6-17.

Voss, E. G. 1972. Michigan flora. Cranbrok Institute of Science, Bloomfield Hills, Michigan & University of Michigan Herbarium, Ann Arbor, Michigan.

Weinstein, M. P., S. L. Weiss, and M. F. Watters. 1980. Multiple determinants of community structure in shallow marsh habitats, Cape Fear River Estuary, North Carolina, USA. Marine Biology 58:227-243.

Williams, A. B. 1965. Marine decapod crabs of the genus *Callinectes* (Decapoda: Portunidae). Fishery Bulletin 72(3):685-798.

Wilson, C., L. Scotto, J. Scarpa, A. Volety, S. Laramore, D. Haunert. 2005. Survey of water quality, oyster reproduction and oyster health status in the St. Lucie Estuary. Journal of Shellfish Research 24:157-165.

Zein-Eldin, Z. P. and G. W. Griffith. 1969. An appraisal of the effects of salinity and temperature on growth and survival of post larval penaeids. Pages 1015-1026 *in* M. N. Mistakidis, editor. Proceedings of the World Scientific Conference on the Biology and Culture of Shrimps and Prawns, FAO Fisheries Report 57.

Zein-Eldin, Z. P. and M. L. Renaud. 1986. Inshore environmental effects on brown shrimp, *Penaeus aztecus*, and white shrimp, *P. setiferus* populations in coastal waters, particularly of Texas. Marine Fisheries Review 48:9-19.

Zimmerman, R., T. Minello, T. Baumer, and M. Castiglione. 1989. Oyster reef as habitat for estuarine macrofauna. NOAA Technical Memorandum, NMFS-SEFC-249.