THE ABUNDANCE AND SPATIAL DISTRIBUTION OF BLUE CRABS (*CALLINECTES SAPIDUS*) IN THE GUADALUPE ESTUARY RELATED TO LOW FRESHWATER INFLOW CONDITIONS

THESIS

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CHAPTER 1

INTRODUCTION AND PURPOSE OF THE STUDY

As growth continues in coastal areas, and as inland urban areas seek out alternative sources of fresh water, there is growing competition for the water resources that supply bay and estuary environments. Water resource managers must know and understand the factors that impact estuarine ecosystems that depend upon the unique hydrology of the coastal region. Management decisions that significantly reduce freshwater inflows during critical growth seasons may produce detrimental effects on sensitive wetlands, coastal fishery harvests, or indirectly affect the survival of protected species by disrupting the food web. The blue crab is a major food source for the federally endangered whooping crane (*Grus americana*), many of which winter in and around the Aransas National Wildlife Refuge just south of the Guadalupe estuary, (Figure 1) (Stehn 2001). In Texas, the blue crab (*Callinectes sapidus*) has been identified as both an ecologically and commercially important species, and it is dependent on the estuarine environment (Longley ed. 1994).

Geography draws upon and integrates the physical sciences with the social sciences and the humanities from a spatial perspective. With its integrative, location-oriented perspective, geography provides a way to study the estuary environment as a combination of physical and biological processes. This approach toward understanding environmental problems was introduced into geography more than a century ago by

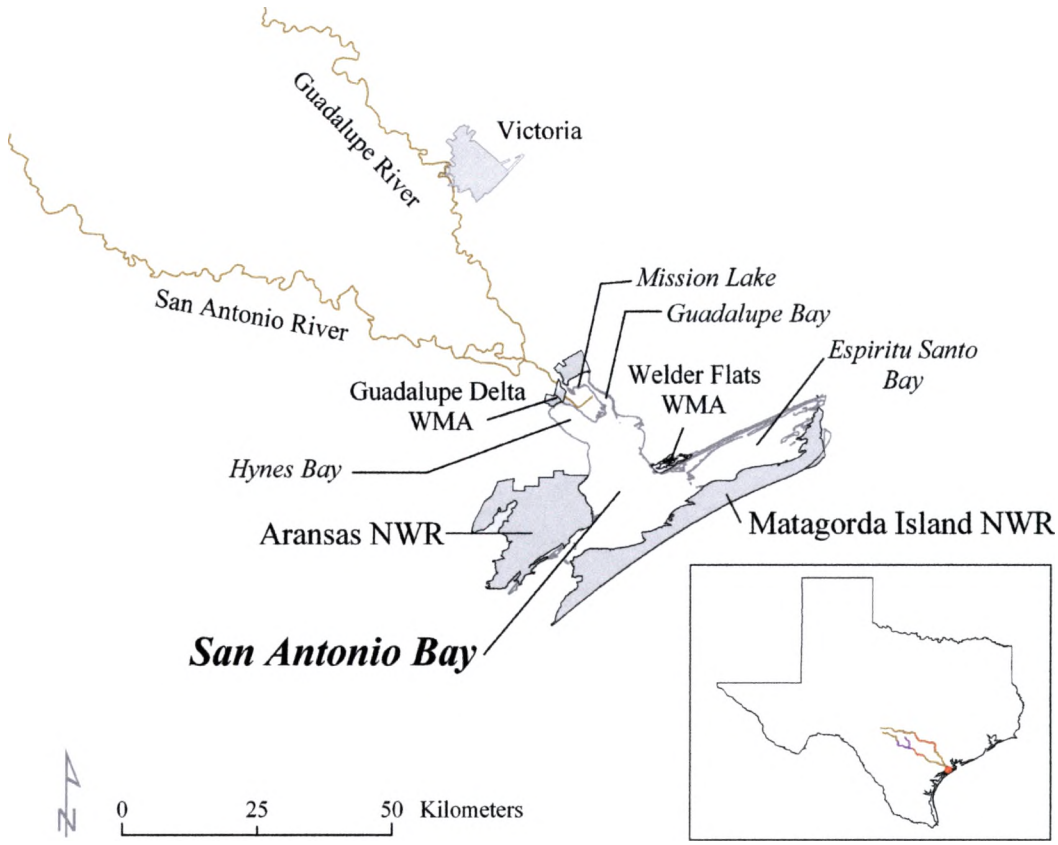


Figure 1. Guadalupe Estuary Region

George Perkins Marsh in *Man and Nature; or, Physical Geography as Modified by Human Action* (1864) and continues to be an active subfield in the discipline (Trombulak 2001). This approach, with its emphasis on spatial relationships, leads to a better understanding of environmental factors related to blue crab behavior, and some level of prediction about blue crab activity. Studies of the connections between estuary inflows and ecologically important species such as the blue crab assist in providing answers about where blue crabs are located, why they are there, and how changes in the abundance of blue crabs affect the populations of endangered whooping cranes. In this study, the

spatial abundance of blue crabs are evaluated in relation to changes in estuary salinity concentrations that result from changes in freshwater inflows from the Guadalupe River.

Freshwater inflow into coastal estuaries creates a unique transitional environment between land and seawaters, the preferred habitat for blue crabs. With an interest in protecting these sensitive and valuable estuarine environments, the Texas Legislature mandated development of state programs to collect hydrologic data and samples of fishery populations, and also to develop technical methods for modeling Texas' estuarine environments. After several years of data collection and model development, individual minimum freshwater inflow volumes, or MinQs, were established for several estuaries including the Guadalupe. The purpose of MinQ inflow volumes, defined on a monthly and annual basis, are to maintain an estuary's historical mean annual harvest potential for seven commercially important species which were defined by the Legislature. A nationally recognized component of the technical analysis that advanced the field of estuarine studies was development of statistical relationships linking freshwater inflows with salinity levels and species abundance (Longley ed 1994).

The MinQ annual inflow recommendation for the Guadalupe estuary is 1.27 billion cubic meters (1.03 million acre-feet) (TPWD 1998). A study of blue crab populations when historical fresh water inflows fell below this minimum target inflow have not been conducted, and it is the subject of this research.

This research compares the abundance and distribution of adult- and juvenile-sized blue crabs in the Guadalupe estuary under lower- and higher-inflow conditions during the period 1982 through 1999. In this research a critical growth season for blue crabs is identified which corresponds to the time of year, in months, with the highest

catch rate. The critical growth season is related to overall population and not to the size of the crab. Following the identification of the growth season, freshwater inflow-based salinity profiles for the two inflow cases were developed using statistical analyses and a geographical information system (GIS). Results of this research describe and compare the abundances and spatial patterns exhibited by adult and juvenile blue crabs in relation to seven salinity zones and two inflow cases. Juvenile-sized blue crab catch rates were compared in relation to four different estuarine habitat types: open bay waters, seagrasses and submerged vegetation, estuarine marshes, and a combined beach and bare-shoreline habitat.

This research addresses several questions:

1. How do the abundance and spatial distribution patterns of adult and juvenile blue crabs during their critical growth seasons differ when freshwater inflows from the Guadalupe River are greater than or less than MinQ target inflows?
2. And, what are the spatial and temporal differences between adult and juvenile blue crab populations within the estuary?

And, how do adult and juvenile blue crab populations vary spatially according to salinity levels and habitat features?

CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

Water Resources Planning for Texas Bays and Estuaries

Freshwater inflows from rivers into coastal estuaries create a transitional low-salinity habitat necessary for many commercially important species such as the blue crab. During the 1980s and 1990s, strong political desire to protect their ecological environments led to legislative action and the implementation of two significant programs for the collection of field data and analytical study for coastal bays and estuaries. It was these programs that contributed to the development of individual MinQ targets for several Texas estuaries by providing the supporting data that enabled computer modeling of the estuary. TxEMP is the optimization model used by the government for estuary modeling and the modeling analyses are based, in part, on relationships between historical inflows, measurements of salinity, and sampled fishery data (Longley ed. 1994). MinQ targets are used by water planners to evaluate the impacts of surface water management projects on estuaries in long-term regional water plans, and for the purpose of this study, the most relevant.

However, in the course of applying the TxEMP optimization model to develop monthly MinQ target inflows for an estuary, another inflow volume was generated by the model that corresponded to the volume of freshwater inflow needed to maximize

commercial fishery harvests in the estuary, called MaxH. Similar to the MinQ, freshwater inflows associated with MaxH were derived using harvest data for several commercially important species and not just the blue crab. The difference between the MaxH and MinQ inflows is that MaxH intends to maximize harvest potential, while MinQ simply achieves historically moderate harvests for particular species while maintaining certain salinity constraints. For comparison of the different inflow volumes, table 1 summarizes the modeled freshwater inflows by month required to achieve MinQ and MaxH harvest levels in the Guadalupe estuary, and also the 1941-1999 median monthly inflows. Although MinQ and MaxH inflow volumes are similar on an annual basis, their differences occur only during the summer months of May through August.

The previous study of adult blue crabs in the Guadalupe estuary identified January through June as the season of highest abundance (TPWD 1998). During the January to June period, inflows under the MinQ and MaxH simulations are the same except for the last two months of the blue crab season, May and June. Results from the previous study showed an increase in adult blue crab harvests under MaxH inflows, which indicates that the timing of freshwater inflows in addition to volume could be an important factor in the peak seasonal abundance of adult blue crabs. When the recommended inflows of MinQ are compared with the estuary's historical monthly median inflows, MinQ is much lower than the historical median during the months of March and April, as well as the four-month period September through December.

Since MinQ was identified as the recommended minimum inflow to maintain a sound estuary environment, it was used in this study to categorize abundance and salinity data into two inflow cases that represent lower- and higher-inflow conditions. In this

Table 1. Modeled Guadalupe Estuary Inflows for Attainment of MinQ and MaxH Fishery Harvests, and the 1941-1999 Period of Record Median Estuary Inflow (Cubic Meters (m^3) and Acre-Feet (AF))

Month	Modeled MinQ		Modeled Max H		Historical Median	
	10^6 m^3	(10^3 AF)	10^6 m^3	(10^3 AF)	10^6 m^3	(10^3 AF)
January	137.2	(111.2)	137.2	(111.2)	137.2	(111.2)
February	153.2	(124.2)	153.2	(124.2)	149.4	(121.1)
March	64.6	(52.4)	64.6	(52.4)	157.8	(127.9)
April	64.6	(52.4)	64.6	(52.4)	144.8	(117.4)
May	229.4	(186.0)	274.6	(222.6)	249.5	(202.2)
June	167.8	(136.0)	200.7	(162.7)	202.8	(164.4)
July	75.0	(60.8)	109.3	(88.6)	120.7	(97.9)
August	75.0	(60.8)	108.9	(88.3)	96.7	(78.4)
September	64.6	(52.4)	64.6	(52.4)	142.6	(115.6)
October	64.6	(52.4)	64.6	(52.4)	141.3	(114.6)
November	91.0	(73.8)	91.0	(73.8)	123.4	(100.1)
December	81.7	(66.2)	81.7	(66.2)	126.8	(102.8)
Total	1,269.0	(1,028.8)	1,415.3	(1,147.4)	2,550.0	(2,067.3)

Sources: MinQ and MaxH TPWD 1998, historical medians based on TWDB calculated surface inflows 1941-1999 with all conversion into metric units by author.

study, the recommended MinQ is also referred to as the target MinQ, and in most cases it refers to an inflow volume that has been summed over several months corresponding to the particular season of interest.

Legislative History

The legislative background of the bay and estuary programs which led to development of the target MinQ, its relationship to state water resources planning efforts, and the obstacles encountered when attempting to integrate MinQ into the water resources planning process are discussed in the following paragraphs.

Texas House Bill 2 was enacted in 1985 with clarifying amendments added two years later in Senate Bill 683 (Longley ed. 1994, TWDB 2004). Among other things, the amended legislation provided for data collection and analytical study programs for Texas bays and estuaries that would be administered jointly by the Texas Water Development Board (TWDB) and the Texas Parks and Wildlife Department (TPWD). The TWDB performs hydrologic sampling and salinity analyses, modeling, and methods development. The TPWD performs monthly field sampling of certain fishery species and water quality parameters, database management, and modeling validation studies. The legislation originally required completion of seven bay and estuary analytical studies by 1990; however this was ultimately extended into the late 1990s. As the bay and estuary monitoring and analytical study programs continued into the 1990s, a statewide drought emerged and lingered over several years prompting legislative changes in statewide and regional water planning requirements. Because of these changes, establishing MinQ targets for individual estuaries took on greater importance.

In 1997, the Texas Legislature passed Senate Bill 1 (SB1) that established a new approach to water management and planning in Texas. SB1 created a long-range water planning process where regions became responsible for assessing the various needs for water in their regions during a drought, and for developing management plans to meet those needs (TWDB 2001). This planning approach included providing for sufficient water supplies in order to protect natural resources such as bays and estuaries. SB1 did not provide guidance, however, on issues related to the prioritization of surface water use among different consumer groups, or whether the state could grant water rights for leaving waters in-stream for the purpose of meeting the needs of bays and estuaries.

These unanswered questions, among others, created difficulty integrating the freshwater needs of bays and estuaries into an overall water resources planning and development process.

As water planners worked to fulfill the requirements of SB1, the studies produced by the TPWD's Coastal Studies Program were employed to establish the quantity of freshwater inflows in acre-feet per year, by month, necessary for maintenance of bay and estuary ecosystems. It was anticipated that proposed water management strategies would be evaluated in terms of their impacts on freshwater inflows into the bays and estuaries as required by current Texas law (TWDB 2002). However, planners encountered several obstacles while addressing freshwater inflows, and environmental flows in general that include inflows for streams, as well as bays and estuaries, and their ecosystems. These obstacles are summarized in the most recent state water plan, *Water for Texas – 2002* (TWDB 2002). The essence of the environmental flow debate, according to this plan, asks how planners can provide for current environmental needs while recognizing past practices and current laws. Existing rights to surface water were established without a requirement for environmental protection. Therefore, assuming there are available water supplies, the burden of environmental inflow protection may fall on just a small group of the most recent water permit applicants.

The plan also identifies problems with defining environmental flows in terms of which species to protect, and how to balance protection with effects on public welfare. Although the plan asserts that these problems are exacerbated due to the lack of data about the water needs of healthy ecosystems, MinQ targets for five of the seven major Texas estuaries have in fact been determined (TWDB 2002).

In order to address issues relating to environmental flows, the 2003 Texas legislature established the Study Commission on Environmental Flows with the passage of Senate Bill 1374. The commission will recommend whether future legislatures should authorize environmental flow permits, and address the ways ecosystems can be protected in the surface water allocation process (Texas Senate 2003). Their recommendations are expected in December 2004.

The agencies working together on the bay and estuary data collection and analytical study programs pressed forward during the 1990s, producing a nationally recognized report (Longley ed. 1994). This work documents the importance and functions of estuarine freshwater inflows and presents a resource-based methodology for determining freshwater inflow needs for estuaries. It was followed in 1998 by the first estuary recommendation report, *Freshwater Inflow Recommendation for the Guadalupe Estuary of Texas* (TPWD 1998). The resource-based methodology links beneficial freshwater inflows to fishery harvest resources, which are defined by their commercial importance (Alber and Florey 2002). The ecological connection between beneficial inflows and fishery harvests is provided in the following legislative definition:

> "Beneficial inflows" means a salinity, nutrient, and sediment loading regime adequate to maintain an ecologically sound environment in the receiving bay and estuary system that is necessary for the maintenance of productivity of economically important . . . estuarine life upon which such fish and shellfish are dependent (TWC 2004).

Based on this definition, seven economically important estuarine-dependent fish and shellfish species have been identified. As a group, the seven are referred to as the 'target species'. One of these target species is the blue crab (*C. sapidus*) (Longley ed 1994). Because blue crab populations are known to respond directly to changes in

estuarine salinity which is controlled by freshwater inflow, examination of freshwater inflow hydrology is important in understanding blue crab population changes.

Relationships between Freshwater Inflows, Salinity and Species Harvests

Freshwater inflow effects on estuarine ecology are often manifested through direct and indirect changes in salinity. As a result, estuarine scientists have established salinity as a critical determinant of the habitat characteristics of estuaries (Longley ed. 1994, Alber and Florey 2002). The state of Texas freshwater inflow modeling approach relates salinity levels and harvests of estuarine species with freshwater inflows through a series of regression-based equations that are based on historical data. The details of such modeling are beyond the scope of this research, however more information is available in the report *Freshwater Inflows to Texas Bays and Estuaries: Ecological Relationships and Methods for Determination of Needs* (Longley ed. 1994). Generally, the TWDB's estuarine computer modeling program, TxEMP, employs salinity-inflow and harvest–inflow equations to quantify, among other things, a MinQ target for the estuary such that harvest levels for target species would be maintained within 80% of their mean historic levels. MinQ will be used in this research for the purpose of separating years with lower- and higher-inflows. As previously stated, it was selected because of its importance as the product of a legislatively directed process.

In addition to MinQ, the TxEMP model also computes a maximum harvest inflow volume for the estuary, MaxH, which was discussed in an earlier section. MinQ-salinity, or MinQ-Sal, is another model-derived inflow volume that is generally based on

maintaining estuary salinity within a particular percentile range according to records of estuary salinity. MinQ-Sal is not related to achieving any particular fishery harvest level, and only salinity constraints are maintained by the salinity-inflow equations in the model (Pulich 2004). The annual MinQ-Sal inflow, 941.6 million m^3 (763.4 thousand acre-feet), is significantly lower than both MaxH and MinQ (See Table 1). The significance of MaxH and MinQ-Sal are such that they represent alternative goals for maintaining the estuarine environment. Maximizing commercially important fishery harvests with MaxH inflows would economically benefit those in the fishing and related tourism industries, while a lower- inflow target such as MinQ-Sal, that focuses on maintenance of a salinity pattern rather than fishery harvests, would lead to availability of additional surface water that could be allocated to consumers upstream from the estuary.

Although it has been recognized that regression-based methods such as those used in the TxEMP model will introduce statistical error into the estuarine modeling process, researchers believe this captures the essential element of the salinity and inflow mixing process (Matsumoto 1994). Other factors that may impact estuarine salinity levels are direct rainfalls onto the estuary and tidal influences (Longley ed. 1994, TPWD 1998). Salinity effects on sensitive estuarine habitats, which species such as the blue crab depend are also important, but beyond the scope of this study.

Freshwater Inflows into the Guadalupe Estuary

Freshwater inflows from the Guadalupe River generate a salinity gradient in the estuary according to the quantity of inflow from the river and tidal circulation in the bay. Salinities are lowest in the upper estuary and gradually increase to oceanic saline

conditions approaching 35 grams of salt ions per thousand grams of seawater, or 35 ppt, near the Gulf of Mexico. Salinity is commonly referred to in units of "parts per thousand", or ppt, replacing the word 'gram' with 'part'. In this study, salinity levels within the estuary are grouped into seven zones using increments of 5 ppt.

Freshwater inflows into the Guadalupe estuary are estimated by the TWDB's Bay and Estuary Program using a procedure that adjusts inflow volumes for surface water additions and diversions that occur between the estuary and the gage location where flow rates are recorded. Total freshwater inflow data tabulated by month and year were obtained from the TWDB through their website with original units in acre-feet.

Total freshwater inflows are the sum of gaged and ungaged flows into the estuary. Gaged flows are those recorded at monitoring stations located on the Guadalupe River. Ungaged flows include permitted surface water diversions, return flows from municipal treatment plants or agricultural sources, and modeled estimates of inflows due to rainfall. Approximately 93% of the Guadalupe estuary's contributing drainage area is measured through gaged sources, while 7% is ungaged and calculated using alternative methods (Longley ed. 1994).

Freshwater inflows into the Guadalupe estuary for the period of record, 1941-1999, were obtained from the TWDB. The Estuary's freshwater inflows are in units of acre-feet which is a *volume* of inflow as opposed to many hydrologic studies which use a *rate* of flow, typically cubic meters (or feet) per second. The TWDB calculated inflow volumes used daily streamflows recorded by gages upstream from the Estuary and converted them into a volume of acre-feet per month. Relatively small adjustments were then made by TWDB to account for precipitation, surface water diversions, and return

flows from point sources that occurred between the instream gages and the upper Estuary. Precipitation adjustments are referred to as modeled inflows presumably because surface runoff from precipitation was modeled using 1972 Soil Conservation Service techniques (Longley 1994). Figure 2a shows the contributions of gaged, modeled, diverted and returned inflows for the Guadalupe estuary between 1981 and 1999. Note that the diverted and returned flows are shown using a much smaller scale on the right side of the graph. This was done so that annual trends could be seen. Figure 2b shows relatively little difference between inflow volumes calculated based using instream gage data and the total volume, which includes the adjustments for precipitation, diverted and returned flows. It is recognized, however, that surface runoff and flows returned to the Guadalupe River from agriculture, municipal and other point sources could affect the quality of surface water that reaches the estuary and produce effects on blue crab populations and habitats, in addition to salinity changes. With regard to inflow volume, the instream gage data accounts for most of the Guadalupe River inflow into the Guadalupe estuary (monthly inflows for the year 1981 are shown in the figures below since evaluation of critical inflow months for 1982 required using inflows from the year before).

Comparison of MinQ and Historical Inflows

MinQ was also compared with historical inflows from 1981 to 1999 to illustrate differences between MinQ, a controlled inflow volume, and a portion of the historic record that shows the existing variation of inflows for the estuary (Figure 3). From the graph it can be seen that MinQ inflow volumes correspond with hydrologically drier

periods, such as the late 1980s and mid 1990s. Also, MinQ is the primary factor used to categorize the lower- and higher-inflow years in this study and therefore the general location of this separation with respect to the inflow record can be appreciated.

Inflow Frequency

In order to compare inflow volumes for the critical inflow period with the long-term historical record, an inflow frequency histogram was created (Figure 4). Cumulative December to May inflow frequencies were grouped into inflow ranges and compared with the 1982 to 1999 study period shown in the lower histogram (Figure 5). The study period is generally similar to the longer-term frequency distribution with inflows falling below MinQ about 30% of the time. The 59-year record shows 18 December to May inflow periods below MinQ (apx. 31%), and the 18-year study period shows five inflow periods fell below MinQ (apx. 28%). For reference, the location of MinQ is shown on the x-axis as the third inflow bin from the left.

Blue Crab Biology and Life History Summary

The blue crab is the most common large crab within Texas and Gulf of Mexico estuaries, as well as other estuaries in eastern North America (Britton and Morton 1989). The scientific name of the blue crab *Callinectes sapidus* translates from Latin and Greek to mean "beautiful swimmer" (Callinectes), and "savory" (sapidus) (Guillory 2004). Though eight species of *Callinectes* have been documented in the Gulf region, this research is concerned with only *C. sapidus*. The blue crab *C. sapidus* belong to the

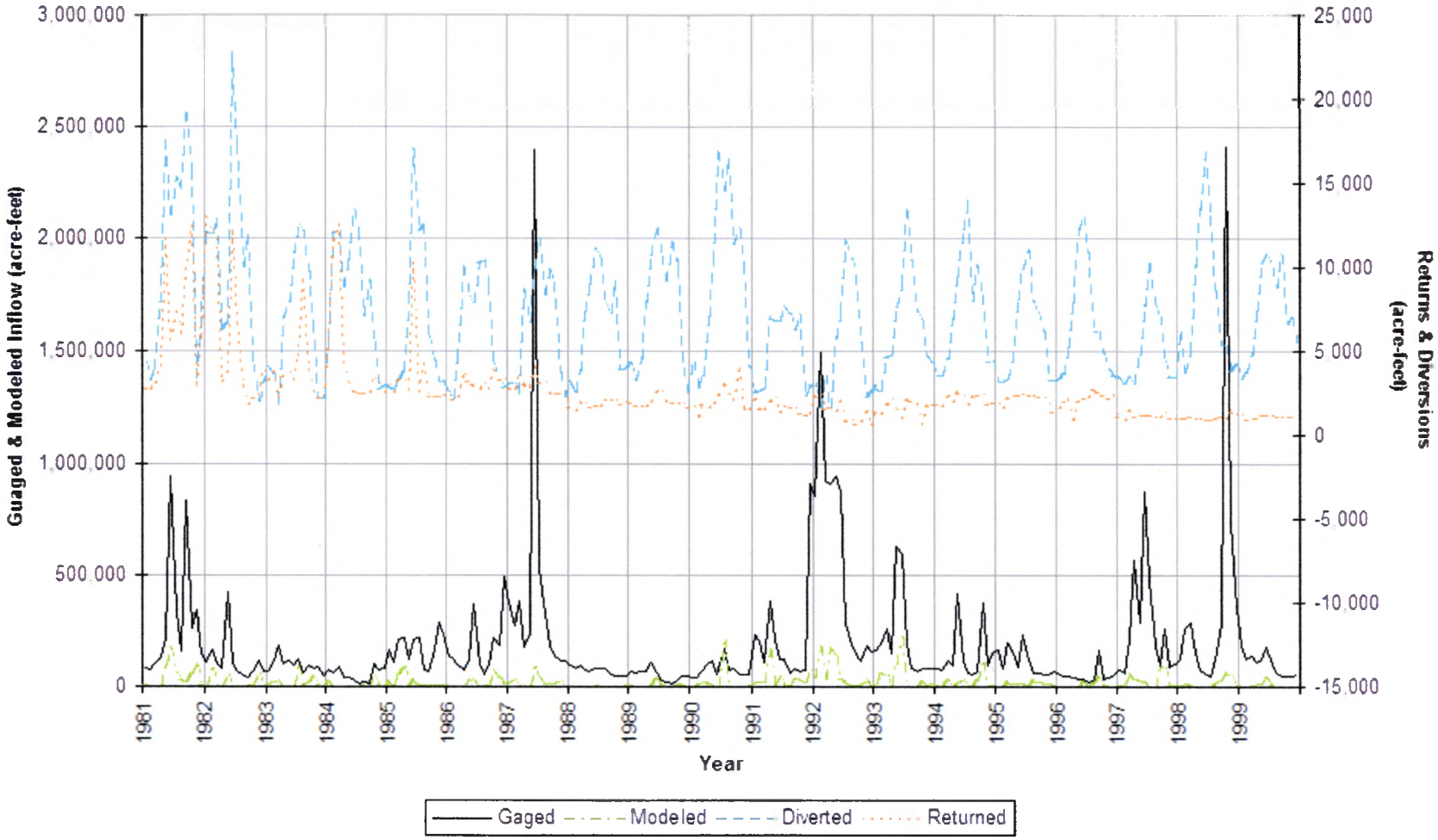


Figure 2a. Guadalupe Estuary Inflow Summary, 1981-1999

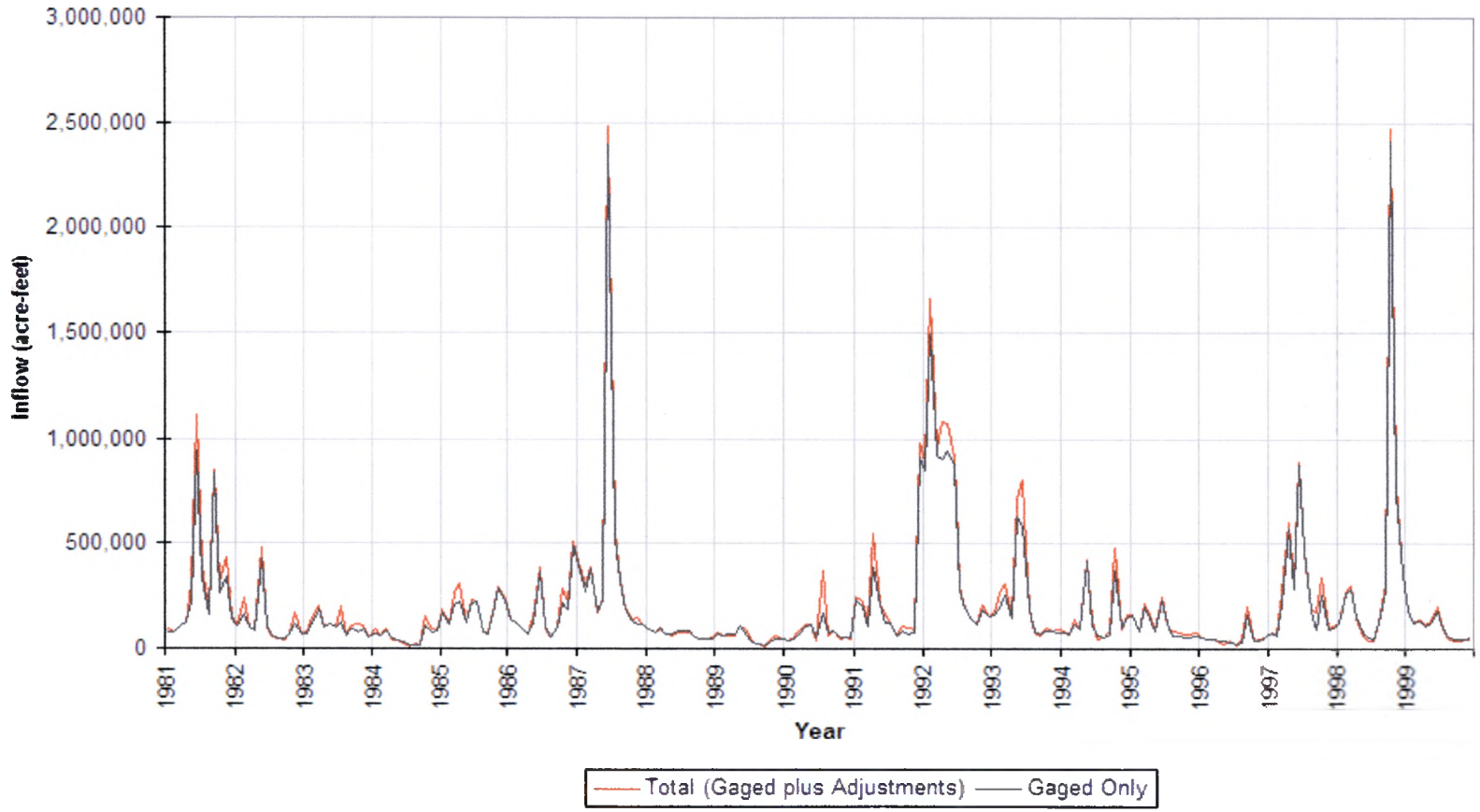


Figure 2b. Guadalupe Estuary Comparison of Total and Gaged Inflows, 1981-1999

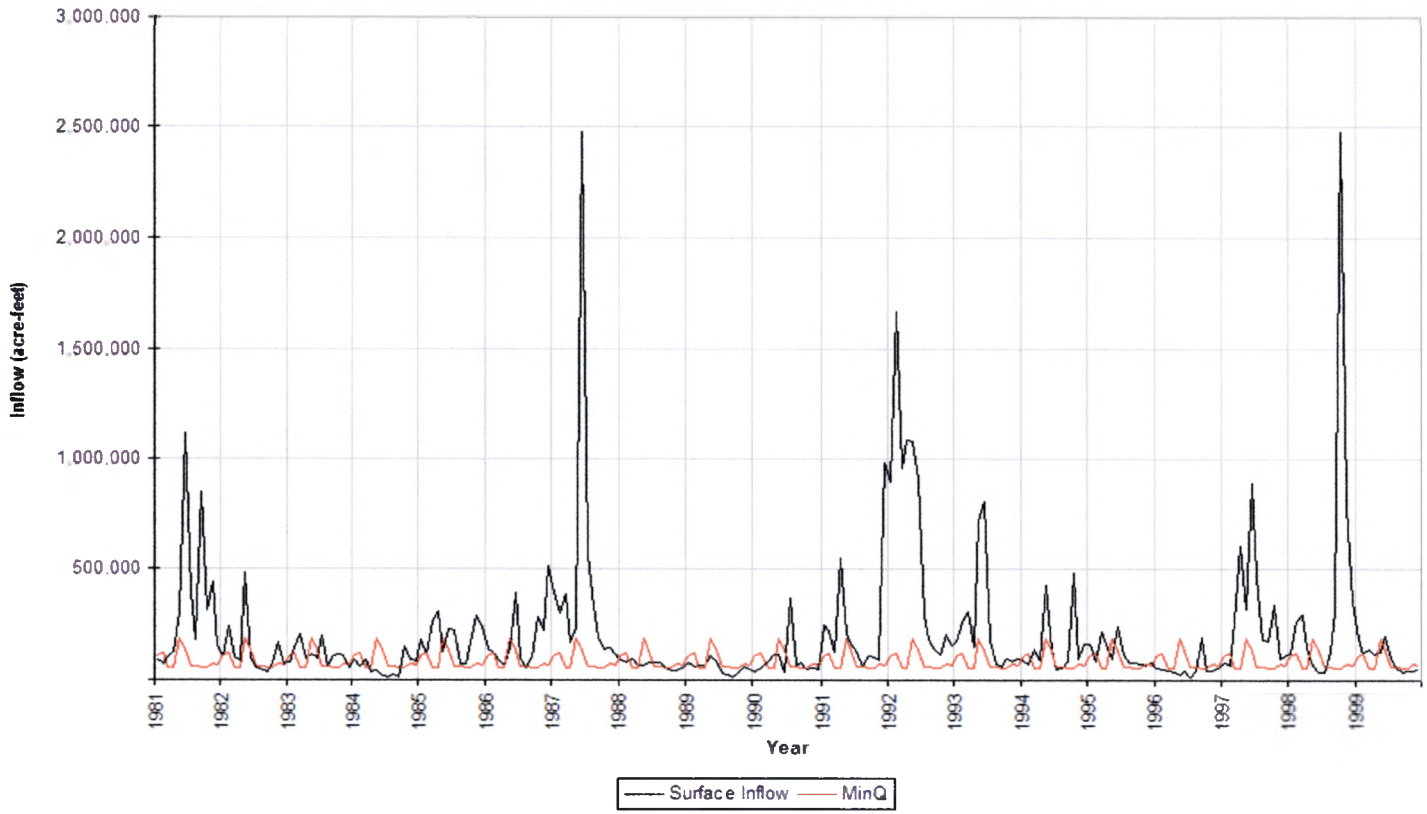


Figure 3. Guadalupe Estuary Inflows for 1981-1999 and Monthly MinQ

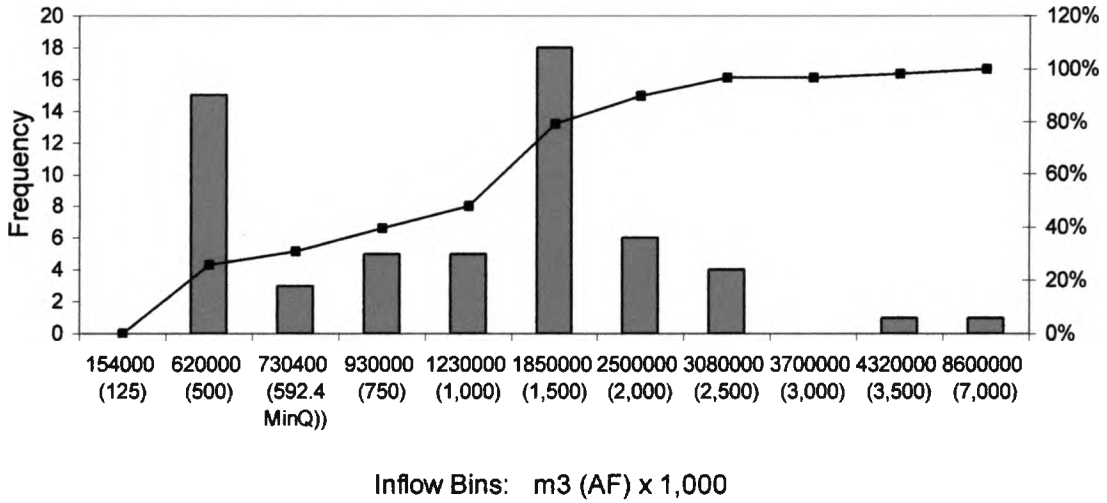


Figure 4. Inflow Frequencies for the Months Dec. to May, 1942-1999

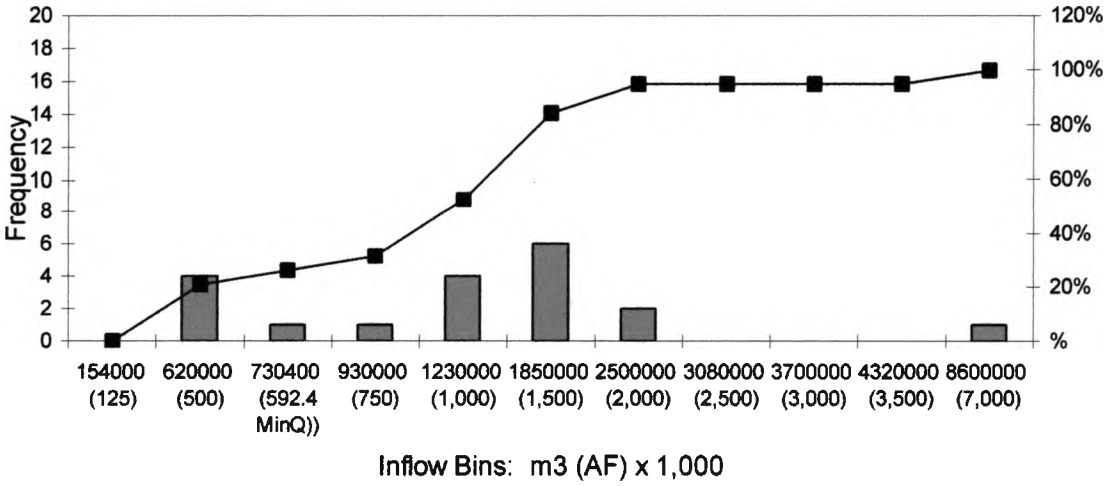


Figure 5. Inflow Frequencies for the Months Dec. to May over the Study Period, 1982 to 1999

Arthropoda Phylum, Malacostraca Class, Decapoda Order, Portunoidea Superfamily, Portunidae Family, Callinectes Genus, and Sapidus Species (NCBI 2004). Blue crabs are excellent swimmers, very mobile in water and on land, and will migrate away from areas where the water exceeds a salinity level of 40 parts per thousand (Britton and Morton 1989). Newly spawned crabs are tiny larvaes called zoeae about 1 mm in width, and grow through several stages into juvenile "first crabs" measuring about 2.5 mm in carapace width. Adults vary in size with a carapace width generally ranging between 51 and 177 mm (Van Den Avyle 1984).

The highest densities of adult blue crabs in the Guadalupe estuary have been recorded in areas where salinity is relatively low, ranging from 5 to 14.9 ppt, which are found in areas most influenced by the Guadalupe River inflows (Longley ed. 1994, TPWD 1998). Life history summaries of the juvenile blue crabs report that they are generally found in lower salinity waters ranging from 2 to 21 ppt. These values vary, however, and specific salinities are not critical for postlarval crabs (Patillo et al 1997). In addition to salinity, disease, and habitat conditions, there are other factors that affect blue crab populations such as predation from other wildlife species, and market demand from the human-based fishing industry.

Blue crab biology and their ecology have been relatively well studied due to their value as a commercial organism. In the estuarine environment, blue crabs are omnivores as they will consume just about every living or dead organism in an estuary. Because of their opportunistic feeding habits and their appeal as a food source for other species, blue crabs play an important role in the food web within the estuary (Van Den Avyle 1984, Guillory 2004).

The food consumed by the blue crab varies according to their developmental stage. In the earliest stages the blue crab larvae, or zoeal, consume phytoplankton and zooplankton. As they mature into the megalopae stage, they become benthic omnivores on the floor of the estuary where they consume fish larvae, small shellfish, and aquatic plants (Van Den Avyle 1984). When they are adults, blue crabs have the unusual ability to feed themselves through several methods that include capturing large moving prey, harvesting smaller organisms from stationary vegetation or structures, and ingesting decomposing material suspended in estuary waters. Mollusks (oysters, clams, mussels and snails) in particular are significant food items for larger adult crabs (Van Den Avyle 1984). The blue crab occupies all areas of the bay depending on the physiological requirements of each life stage. As such, the blue crab has a life stage geography in that its spatial patterns are related to its development. Salinity, among other environmental influences, is an important factor in the life stages of blue crabs.

Adult male blue crabs spend the majority of their lives in the less saline portions of the upper estuary. As they reach maturity, the females will join the males to mate, and then migrate to higher saline areas in the lower estuary where they lay their eggs and stay for the remainder of their lives. Laboratory experiments have shown that the spawning and early larval stages require certain temperature conditions and salinities greater than 20 ppt (Longley ed. 1994, Guillory 2004). The blue crab zoeae eventually move into higher saline open gulf waters. They progress through a total of seven stages of zoeal development lasting 31 to 49 days. At this point the young blue crabs mature into the megalopal larvae stage and reenter the estuary, migrating into low and intermediate salinity benthic environments. During the megalopal stage, lasting between 6 and 20

days, small fish, filter feeders, jellyfish and others feed upon the blue crabs. As they grow into maturity the post larval blue crabs will molt 18 to 23 times. During these molts, they are vulnerable and will seek sheltered areas of the estuary such as oyster beds, submerged vegetation beds or marsh-lined banks. They can also bury themselves in the soft sediments at the bottom of the estuary or shoreline. Important blue crab habitat areas identified by Britton and Morton (1998) are oyster and seagrass beds that are used for both shelter and food.

CHAPTER 3

STUDY AREA DESCRIPTION AND METHODS

Guadalupe Estuary Study Area

Several research fields come together in this study of the blue crab estuarine habitat. These include water resources, estuarine biology, and geography. The water resources field provides insight into surface water policy and management, and hydrologic conditions. Estuarine biology provides understanding of the blue crab's habitat requirements, life history, and ecological relationships with other estuarine species. Geography provides a framework to study their relationships from a location-oriented and environmental perspective. This perspective underlies the proposed research.

The Guadalupe estuary is located along the central Texas coast bordering the Gulf of Mexico and the estuary's hydrography, physical characteristics, and biological processes have been well documented (TDWR 1981, Longley ed. 1994). With more than 2,250 kilometers (1,400 miles) of shoreline, Texas has ten estuaries, seven major and three minor, between its northern border with Louisiana and its southern border with Mexico (TDWR 1981). The Guadalupe borders the counties of Aransas, Calhoun and Refugio. San Antonio Bay is the estuary's primary bay that is fed by the Guadalupe River to the north, and to the southeast it is protected from the Gulf of Mexico by

Matagorda Island. Espiritu Santo Bay is a large bay to the east that exchanges water through circular eddy currents with the San Antonio Bay. The largest contributors of fresh water into the estuary are the San Antonio and Guadalupe Rivers that merge several miles upstream from the delta. Together they have a combined contributing drainage area of about 26,730 square kilometers (10,320 square miles) (Longley ed. 1994). The Guadalupe estuary has a surface area of about 57,870 hectares (143,000 acres) with a relatively shallow mean depth of 0.8 meters (2.5 feet) (TDWR 1981).

There are a number of smaller secondary and tertiary bays in the estuary (Figure 6). Secondary and tertiary bays are typically found at the head of the estuary. Hynes and Guadalupe Bays are secondary bays that empty into San Antonio Bay. Mission Lake, an example of a tertiary bay, flows into Guadalupe Bay (TDWR 1981). As fresh water from the Guadalupe River enters through tertiary and secondary bays and flows down through San Antonio Bay, a salinity gradient is created as a result of fresh water mixing with higher saline waters from the Gulf of Mexico.

Relationship of the Study to Endangered Whooping Crane Habitat

The Guadalupe estuary provides coastal marsh habitat for many typical estuarine species, as well as several endangered and threatened species. The most famous of these is the whooping crane *(Grus americana)*, listed by the federal government as endangered in 1970, and which spends the winter in this part of the Texas coast. Blue crabs comprise a large percentage (as much as 90%) of the whooping crane's winter diet (TPWD 2004a).

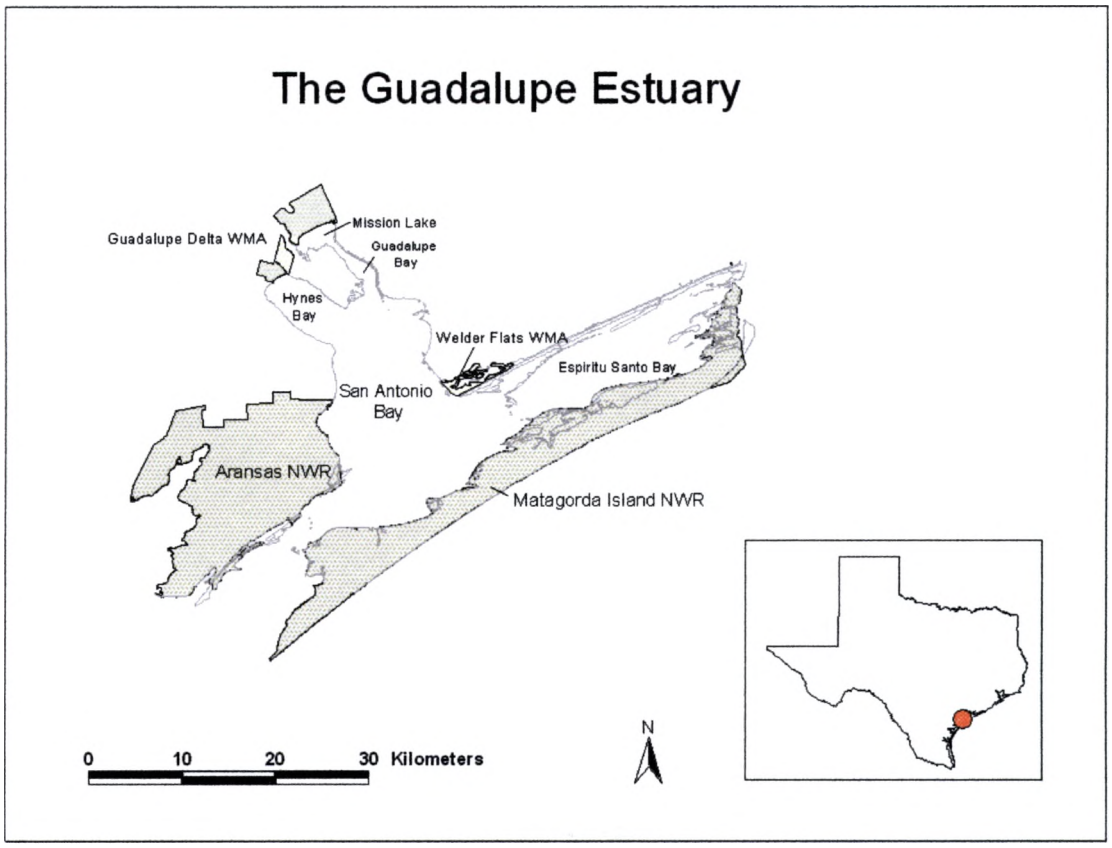


Figure 6. Research Study Area

Whooping cranes are also known to consume small amphibians and birds, rodents, shellfish, and berries (TPWD 2004a). Several wildlife sanctuary areas are located around the estuary and include those areas frequented by whooping cranes and which also provide a nursery habitat for the blue crab. Among these are the Guadalupe Delta Wildlife Management Area (WMA) in the upper estuary, Welder Flats WMA between San Antonio and Espiritu Santo Bays, Aransas National Wildlife Refuge (NWR) on the southwest side of the bay, and the Matagorda Island NWR bordering the Gulf of Mexico (Figure 6).

The Guadalupe Delta WMA in the upper estuary was established in the mid-1990s and consists of over 2,430 hectares (6,000 acres) of shallow, mostly freshwater and brackish marshes that are subject to flooding from the Guadalupe River (TPWD 2004b). A significant portion of the wild whooping crane population spends the winter months in and around the bay's southern end at the Aransas NWR. The cranes typically migrate into the region around the month of November and stay through March when they migrate to northern Canada (TPWD 2004a). Today's whooping crane population is approximately 400 wild and captive birds, and almost half wintered along the Texas central coast region during the winter of 2003-2004 winter season (Stehn 2004).

U.S. Fish and Wildlife Service Whooping Crane Coordinator Tom Stehn reported in 2001 that reductions in freshwater inflows are a major threat to whooping crane survival due to the blue crab's vulnerability to reduced freshwater inflows and the resulting loss of a significant portion of the crane's food supply. He observed that over eight winters there was an increase in crane mortality during the two years when crabs were scarce, with reported losses of six and seven birds. The mortality rates were zero or one bird for each of the other six winters when there were more abundant crab populations (Stehn 2001). A 1998 TPWD study, among others, support Stehn's observation of a relationship between blue crab populations and freshwater inflows. Inverse correlations were found to exist between population densities of blue crabs and salinity levels. The study used data from the Guadalupe estuary for the period 1982 to 1993 (TPWD 1998). Interestingly, the same study showed that blue crab populations were highest from January through June and also November, generally coincident with the time when whooping cranes were present in the area.

While it has been established that freshwater inflows affect estuarine salinity levels, researchers have recognized that other habitat factors affect blue crab populations. These factors include changes in geomorphology that result in the loss of habitat, changes in hydrology that result in a decrease in the ability to periodically flush out pollutants and pathogens, and changes in vegetative conditions that affect food production and predator populations (Alber and Florey 2002, TPWD 1998). Study of these factors is beyond the scope of this research.

Study Methods

The methodology for this research involves quantitative spatial analyses using geographic information system (GIS) and statistical tools to examine the population dynamics of blue crabs within the Guadalupe estuary in relation to 1982 through 1999 freshwater inflows from the Guadalupe River. Data sets that are used in this study are summarized in table 2.

The methodology for this research is based on procedures outlined in TPWD's 1998 report *Freshwater Inflow Recommendation for the Guadalupe Estuary in Texas*. This previous study was limited to analysis of open water trawl data for adult crabs for the years 1982 through 1993. The study did not include shoreline collected bag-seine samples that capture juvenile-sized blue crabs.

Table 2. Description of Study Data and Sources

Data	Source of Data
1. Freshwater inflow hydrology for 1982 – 1999	TWDB Bay and Estuary Program
2. Blue crab bay-collected bag seine and trawl samples with salinity measurements 1982 – 1999	TPWD Coastal Fisheries Resource Monitoring Program Database
3. Shapefile coverages of seagrasses, marshes, beach and bare shorelines	NWI* and TPWD Coastal Studies Program GIS maps obtained through the General Land Office

*NWI – 1992 National Wetlands Inventory, U.S. Fish and Wildlife Service/Texas General Land Office

Additional changes to the 1998 study methods which are conducted in this current research, include extending the period of study from 1993 to 1999, for a study period of 1982 through 1999, and:

- comparing two different inflow cases, one for lower inflows (below MinQ) and one for moderate to high inflows (above MinQ),
- performing a spatial comparison of the abundance of adult and juvenile blue crab populations under the two different flow cases,
- applying updated GIS-based geostatistical routines for spatially delineating salinity zones, and
- adding bag-seine collected samples of blue crabs to compare with trawl-collected samples,
- evaluating the significance of four habitat features that correspond to open bay waters, beach and bare shoreline, seagrass and submerged vegetation, and marsh areas, using multivariate statistical methods.

Therefore, this research was designed to add several new dimensions to the previous research, and to contribute to a clearer understanding of how freshwater inflows relate to the abundance of juvenile and adult blue crab populations in different salinity zones within the Guadalupe estuary.

Spatial Analyses of Blue Crab Abundance, Salinity Zones, and Habitat

The spatial analysis component of this research included the following steps:

1) identification of critical growth seasons for adult and juvenile blue crabs,
2) separation of abundance and salinity data into two inflow cases based on MinQ,
3) development and modeling of GIS shapefiles to generate salinity surface profiles for the two inflow cases,
4) development of overlay maps with blue crab abundance by salinity zone, and the
5) export of summary tables from the GIS to perform statistical analysis.

These steps are explained in more detail below.

1. The critical growth seasons were determined in two phases and were based on average monthly catch-per-unit-effort, CPUE. CPUE is a commonly used term that, for the purpose of this study, quantifies the number of blue crabs per unit of time, or area, that were collected while trawling, or using a bag seine along the shore. The units are "catch per hour" for trawl samples, and "catch per hectare" for bag seine samples. More detailed descriptions of these terms are shown below:

Trawl CPUE – standardized one-hour catch of adult crabs. It is standardized based on the collection method, and a simplified explanation is that a trawling vessel

tows a net at a speed of 3 miles per hour for 10 minutes in a circular pattern to collect the sample. The trawling nets are 5.7 meters wide at the mouth with a 35 mm mesh size.

Bag seine CPUE – standardized one-hectare catch of juvenile blue crabs. It is standardized based on the collection method, which consists of a two-person team dragging an 18.3 x 1.8 meter net parallel to the shore at a distance of approximately 15.2 meters. These are the definitions may help to better understand the term CPUE which is used throughout this study.

The first phase was to calculate the average CPUE of bag seine (juvenile) or trawl (adult) data by month for the 18-year study period. The second phase was to define the critical growth season by identifying the months with the highest average CPUE of blue crabs. These months identified the critical growth season used in the next step.

2. The second step separated the hydrologic inflow data into two inflow cases by comparing cumulative freshwater inflows during the critical growth season with the total MinQ target inflows over the same months. Thus two hydrologic inflow cases will be identified based on the 18 years of inflow data: years when inflows were lower than MinQ, and years when inflows were higher than MinQ. Using the dates associated with each inflow category, monthly fishery and salinity data were then extracted from the coastal fisheries dataset for the critical growth season. The next step involved transforming the salinity data for the two inflow cases into salinity gradients using the GIS.

3. Kriging tools contained in ArcView 8.3's geostatistical extension were used to interpolate salinity data, generate a contoured salinity surface, and then convert them into polygon coverages. Shapefile coverages for the habitat areas were prepared from the data

sources in table 2 and imported into the GIS project. For consistency, the seven salinity zones established in previous studies of the Guadalupe estuary were used (Table 3).

Table 3. Salinity Zones (parts per thousand)

Zone	Salinity (ppt)
0	0 to 4.99
1	5 to 9.99
2	10 to 14.99
3	15 to 19.99
4	20 to 24.99
5	25 to 29.99
6	> 30

4. GIS overlay methods were used to generate spatially related maps of blue crab CPUE by salinity zones and habitat types. The processing of trawl data employed the same approach described in the 1998 TPWD Guadalupe estuary report.

5. Once CPUE was related to salinity zone or habitat type, the attributes were summarized and exported for statistical analysis.

Statistical Analysis Methods

The statistical methods for this research were selected for the purpose of detecting correlations, patterns, and structure in the relationships between salinity zones, different habitat features, and the abundances of adult or juvenile blue crabs. The habitat features, or independent habitat variables, applied to juvenile blue crabs are open bay, submerged

vegetation including seagrasses, beach and bare shorelines, and estuarine marshes. The independent variables are salinity, stratified into seven zones, for adult blue crabs. The dependent variables are the populations of juvenile and adult blue crabs that were sampled randomly within the estuary on a monthly basis. Differences in sampling methodology, trawling versus bag seines, required that juvenile and adult blue crab data be evaluated separately.

Methods are based, in part, on those outlined in the TPWD's *Freshwater Inflow Recommendation for the Guadalupe Estuary of Texas* (TPWD 1998). In that study significant associations of blue crab spatial distributions with seven salinity zones were demonstrated using one-way ANOVA regression testing followed by a non-parametric Kruskal-Wallis ANOVA test when test assumptions were violated.

Initial testing of the data to determine the strength of associations between the variables consisted of developing univariate correlations, and simple linear regressions. Results from these analyses guided development of a multivariate model. Multivariate techniques revealed what, if any, combination of salinity and habitat variables explain most of the variation in blue crab populations during different inflow conditions. Multivariate methods for evaluating relationships between species abundance and habitat factors have been demonstrated through a range of multivariate techniques including, among others, canonical correspondence analysis, principal components analysis, and Spearman rank correlations (McBride and Able 1994, Marshall and Elliott 1998, Wilber and Bass 1998). Selection of the statistical analysis method depended upon the data meeting required assumptions of the test. In this study, it was determined that parametric testing was appropriate for adult abundance-salinity relationships, while nonparametric

tests were required for juvenile abundance-habitat relationships. These results were evaluated in conjunction with GIS-generated maps.

Visual inspection of the GIS-generated maps of abundance by salinity zone and habitat type, used in combination with statistical results helped identify differences in the spatial abundance of blue crabs and to make comparisons with earlier studies.

CHAPTER 4

CRITICAL GROWTH SEASONS AND THE CRITICAL INFLOW PERIOD

The numbers of trawl and by bag seine samples collected by year over the study period are shown in table 4. Over the 18-year study period, there were a total of 4,608 trawl samples, and 3,306 bag seine samples collected.

Table 4. Annual Total of Blue Crab Samples Collected in the Guadalupe Estuary, 1982-1999

Trawl					
Year	Samples	Year	Samples	Year	Samples
1982	240	1988	240	1994	312
1983	240	1989	240	1995	312
1984	240	1990	240	1996	240
1985	240	1991	240	1997	240
1986	240	1992	312	1998	240
1987	240	1993	312	1999	240
Total					4,608
Bag Seine					
1982	120	1988	138	1994	240
1983	120	1989	144	1995	240
1984	120	1990	192	1996	240
1985	120	1991	192	1997	240
1986	120	1992	240	1998	240
1987	120	1993	240	1999	240
Total					3,306

Adult and juvenile crab samples were treated separately due to differences in collection methods. Carapace width (c.w.), the length measured across the back of the crab, generally distinguishes between adults and juveniles. Trawling boats with larger net openings capture adult-sized crabs, averaging in size from 75 to 95 millimeters (mm) c.w. Smaller sized juvenile crabs captured by bag seines average in size from 30 to 45 mm c.w. Adult crabs are generally not captured in bag seines since they can swim fast enough to evade the slow moving net. The following sections detail how critical growth seasons for adult and juvenile blue crabs were determined.

Adult Blue Crab Critical Growth Season

Graphs of average trawl CPUE revealed a higher average catch rate during the first half of the year, January through May, followed by several months of lower catch rates (Figure 7).

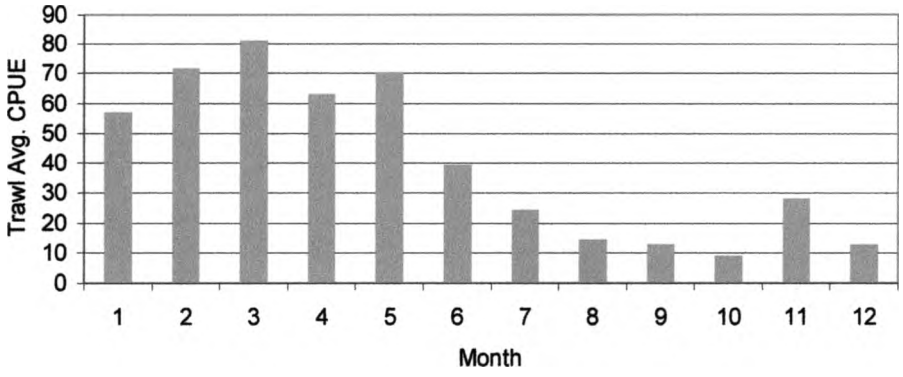


Figure 7. Monthly Distribution of Trawl CPUE in the Guadalupe Estuary from 1982-1999

Since it was unclear whether June, July, or November should be included in the adult critical growth period, statistical analysis using ANOVA was performed to test for significant differences between monthly means. The ANOVA significance level of 0.005 was selected based on the Anderson-Darling test for normally distributed residuals, and Levene's test for equal variances (MINITAB 2004).

Results from the ANOVA, significant at $p<0.005$ with $F(11, 4607) = 11.96$, showed January through May as the group of months whose confidence intervals about their means coincided the most. July and November were eliminated from consideration since their means and confidence intervals fell, for the most part, below the January through May group. It is interesting to note that the November catch rate is noticeably higher than surrounding months (Figure7). One possibility, beyond the scope of this study, might be that a weaker secondary abundance period exists that coincides with the time some of the juvenile blue crabs mature into adult sized crabs following their March to July critical growth season. The ANOVA and time series results were not straightforward for June, and therefore it was decided through consultation with Dr. Warren Pulich, Texas State University, and Dr. Wen Lee, with the TPWD in Austin, that June should also be included as the tail end of the critical growth period. Both Dr. Pulich and Dr. Lee have contributed to previous studies of the blue crab and estuarine freshwater inflows. January through June had also identified as the blue crab critical growth season in the 1998 Freshwater Inflow Recommendation (TPWD 1998). My study included seven additional years of sample data and confirmed this previous result. A summary of ANOVA results is shown in figure 8.

```
One-way ANOVA:

Source     DF        SS       MS      F      P
Factor     11   3310564   300960  11.96  0.000
Error    4596 115700814    25174
Total    4607 119011378

S = 158.7   R-Sq = 2.78%   R-Sq(adj) = 2.55%

                            Individual 99.5% CIs For Mean Based on
                            Pooled StDev
Level    N  Mean  StDev  ----+---------+---------+---------+-----
Jan    384  59.9  312.3                  (-------*-------)
Feb    384  75.3  336.2                        (------*-------)
Mar    384  84.0  169.8                          (-------*-------)
Apr    384  65.5  111.5                       (-------*------)
May    384  73.8  140.5                          (-------*------)
Jun    384  41.1   64.2             (-------*------)
Jul    384  25.2   40.0        (------*-------)
Aug    384  14.8   27.1   (-------*------)
Sept   384  13.5   24.3   (------*-------)
Oct    384   9.6   18.4  (------*-------)
Nov    384  29.7  141.6        (-------*------)
Dec    384  13.3   55.4   (------*-------)
                          ----+---------+---------+---------+-----
                              0        30        60        90
```

Figure 8. ANOVA for Guadalupe Estuary Blue Crab Trawl Samples, 1982-1999

Juvenile Blue Crab Critical Growth Season

Average monthly catch rate summaries for bag seine-collected juvenile blue crab samples revealed a strong two-month peak catch period, March and April, followed by three months of lower average catches (Figure 9). January and February differed the most from the adult blue crab peak abundance season with much lower catch rates during January and February than the following two months. Since it was unclear whether the months immediately before or after the March to April peak should be considered part of the critical growth period, further analysis was performed using ANOVA to compare monthly means.

The ANOVA confirmed March and April as a strong peak abundance season for juvenile blue crabs. These results were significant at $p<0.005$ with $F(11,3305) = 7.70$. In

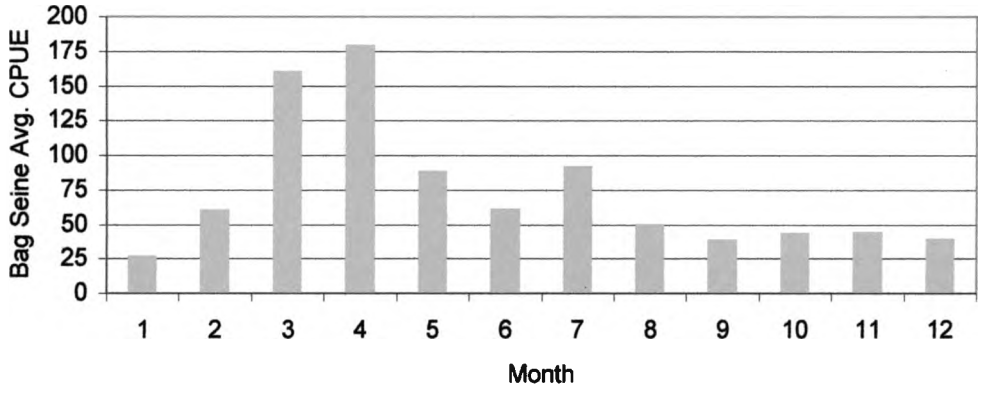


Figure 9. Monthly Distribution of Juvenile Blue Crab Catch Rates for the Guadalupe Estuary, 1982-1999

addition to the strong two-month peak abundance period, the chart of ANOVA-produced confidence intervals for the means showed May and July with slightly higher catch rates than most of the other months (Figure 10). At this point a judgement decision was needed whether to select March and April alone as the critical growth season, or whether the season should be expanded to include May through July.

The May through July critical growth season was selected after considering several factors: 1) the average monthly catch summary and ANOVA results with relatively higher May and July average catch rates, 2) consultation with Dr. Pulich and Dr. Lee, and 3) recognition that later phases of the study would benefit from the additional months of data, particularly the spatial mapping of crab populations. A

comparison with the 1998 Freshwater Inflow Recommendation could not be performed since that study did not include an analysis of bag seine-collected data.

```
One-way ANOVA:

Source     DF        SS      MS     F      P
Factor     11   7270258  660933  7.70  0.000
Error    3294 282646077   85806
Total    3305 289916336

S = 292.9   R-Sq = 2.51%   R-Sq(adj) = 2.18%

                          Individual 99.5% CIs For Mean Based on
                          Pooled StDev
Level    N   Mean  StDev  ---+---------+---------+---------+------
Jan    274   27.0   74.0  (------*------)
Feb    274   60.9  144.9      (------*------)
Mar    274  160.7  432.6                     (------*------)
Apr    276  179.5  795.5                        (------*------)
May    276   88.8  206.8          (------*------)
Jun    276   61.7  177.6      (------*------)
July   276   92.4  203.3          (------*------)
Aug    276   50.6  119.8    (------*------)
Sept   276   39.0  116.8   (------*------)
Oct    276   44.2  104.5   (------*------)
Nov    276   44.8  111.2   (------*------)
Dec    276   39.7  126.2   (------*------)
                          ---+---------+---------+---------+------
                             0        70       140       210
```

Figure 10. ANOVA Results for Guadalupe Estuary Blue Crab Bag Seine Samples, 1982-1999

The critical growth seasons for adult (January through June) and juvenile (March through July) blue crabs were then used to explore the relationship between abundances of blue crabs during their respective critical growth periods and freshwater inflows into the Guadalupe Estuary. Freshwater inflow during months determined to be most significant to the blue crab's critical growth seasons are referred to in this study as the critical inflow period.

Identification of the Critical Inflow Period

The approach used to identify critical inflow months consists of regressing groups of cumulative monthly inflows with average seasonal CPUE calculated from the critical growth season. The critical inflow period is important for this study since it establishes the inflow months that will be used in the next step to classify higher and lower inflow years. Rather than evaluating cumulative annual inflows to classify higher and lower inflow years, this smaller group of critical inflow months was used to narrow the hydrological record to the season of interest. Principal component factor analyses (PFA) were also performed for the purpose of detecting relationships between monthly inflows and catch rates, and also for comparison with the simple regression results. PFA produces a factor loading table for the monthly average inflows and catch rates in combinations that maximize the shared variance between variables. (MINITAB 2004).

Adult Blue Crab Critical Inflow Period

The critical growth season was matched to a group of critical monthly inflows through regression analysis. Since January through June was the adult blue crab critical growth season, regression analysis began with a simple correlation evaluation between the averaged January to June catch rate with cumulative January through June monthly inflows. The correlation coefficient (r) between the average catch rate and total inflow was 0.517 significant at the 0.03 level with 16 degrees of freedom (df), indicating a fairly strong strength of correlation or linear relationship. The r-square, a measure of the

proportion of variability shared by the two variables, was 0.267 indicating some shared variance but not a particularly strong result.

This was followed by correlations of average catch with lagged inflow volumes of 2- and 4-months, and several other combinations, and these are summarized in table 5. The strongest relationship defined by linear correlation, shared variances and test significance was determined to be the January through May inflow period with an r-value of 0.609, an r-square of 0.371, and significant at the 0.01 level. Slightly lower correlations were produced with the 6-month period December to May, and also the 2-month period January and February. Given their similarities, this analysis was followed by PFA,

MINITAB version 12, a statistical computer-based program, was used to perform the PFA for three principal factors with a VARIMAX rotation. The number of factors (three) needed for input into the PFA was determined using a scree plot of eigenvalues and the Kaiser selection method. First, the PFA computer routine was executed using all 13 variables to generate the scree plot. The Kaiser method advises dropping factors that are not at least as much equivalent to one variable, in other words, having an eigenvalue less than one. Use of the scree plot and counting the number of factors with an eigenvalue of one or more established that three factors would be used in the PFA.

Of the PFA results (Table 6) the first column in the table lists variable names: the seasonal catch rate (avg. seasonal tr_catch), followed by months numbered 1 (January) to P12 (December). The "P" identifies the month as inflow from the previous year. Interpretation of the factor 1 loads for each variable revealed that inflows from December through May were weighted, or correlated, with the average seasonal catch

variable with loadings ranging from a low of 0.592 for June to a high of 0.972 for January. Interpretation of the other factors were not necessary at this point since the objective of using PFA was to detect the principal group of inflow months which correlated the most with average catch rates. Review of the communality results showed a high level of explained shared variance, 83%, and therefore a lower undesirable unexplained error.

Table 5. Trawl Critical Growth Season Correlations

Lagged Inflow Period	Correlation Coefficient Avg. Trawl Critical Growth Season Jan to Jun Catch Rate, r	Coefficient of Determination, r-square	Significance *df=16*
Nov-April (2 month lag)	0.522	0.273	0.026
Sept-Feb (4 month lag)	0.150	0.022	0.554
Nov	-0.335	0.112	0.174
Nov-Dec	0.138	0.019	0.585
Nov-Jan	0.330	0.109	0.181
Nov-Feb	0.472	0.223	0.048
Nov-Mar	0.490	0.240	0.039
Nov-May	0.551	0.304	0.018
Dec	0.462	0.213	0.054
Dec-Jan	0.524	0.274	0.026
Dec-Feb	0.570	0.325	0.014
Dec-Mar	0.563	0.318	0.015
Dec-Apr	0.577	0.333	0.012
Dec-May**	0.597	0.356	0.009
Dec-Jun	0.517	0.267	0.028
Jan	0.579	0.335	0.012
Jan-Feb**	0.601	0.361	0.008
Jan-Mar	0.583	0.340	0.011
Jan-Apr**	0.589	0.347	0.010
Jan-May**	0.609	0.371	0.007
Jan-Jun	0.517	0.267	0.028

** Correlation is significant at the 0.01 level

Table 6. PFA 3-Factor Loading Table for Monthly Inflows and Adult Blue Crab Seasonal Catch

Rotated Factor Loadings and Communalities
Varimax Rotation

Variable	Factor1	Factor2	Factor3	Communality
Avg Seasonal TR_Catch	0.617	-0.333	0.529	0.772
1	0.972	0.042	-0.022	0.946
2	0.960	-0.050	0.070	0.928
3	0.958	-0.026	-0.030	0.920
4	0.845	-0.150	-0.057	0.739
5	0.872	-0.088	0.095	0.778
6	0.529	0.132	-0.227	0.348
P7	-0.070	-0.081	0.928	0.872
P8	-0.096	0.265	0.922	0.930
P9	0.093	0.811	0.393	0.820
P10	-0.038	0.951	-0.095	0.914
P11	-0.014	0.950	-0.057	0.907
P12	0.915	0.264	-0.054	0.911
Variance	5.7805	2.7735	2.2310	10.7850
% Var	0.445	0.213	0.172	0.830

The PFA results generally agreed with the simple correlation results however, there were several differences. A general decline in loading strength for inflows after March were identified with the PFA, contrary to correlation results where r and r-square values increased as inflows from April and May were added to the correlation. The disagreement was not seen as a problem since differences in both cases were relatively small, and the overall result identified March and April as important inflow months as indicated through higher correlations and PFA loadings. Additionally, the significance of December inflows became apparent with the PFA as seen in the higher loading factors for December (0.915) as compared with April (0.845) and May (0.872). Therefore, based upon the simple correlation and PFA results, December through May were identified as the critical inflow months for adult blue crabs.

The December through May critical inflow period established in this study differs from that used in the 1998 Freshwater Inflow Recommendation study, where the peak abundance season of January through June was used as the critical inflow period. The results presented in this report show that early season freshwater inflows, including one

month of antecedent inflow, are significantly related to the blue crab's critical growth season. Freshwater inflows during June, the last month of the critical growth season, were shown to be less significant.

Juvenile Blue Crab Critical Inflow Period

The critical inflow period for juvenile blue crabs was evaluated following the procedure outlined for the adult blue crabs. Significantly weaker correlations resulted between various combinations of inflow periods and the average March to July seasonal catch rate. The March to July inflows and March to July seasonal catch rate correlation produced a very low r-square coefficient of 0.03. Similar to the trend seen with the adult blue crabs, lagging the inflow 2-months (January to May) improved the r-squared result to 0.11, though still a low correlation. The 4-month lagged inflow (November to March) produced a lower r-square, 0.06.

The PFA result with four principal factors is shown in table 7. December through May produced the best combination of inflow months in relation to the critical growth season, similar to the adult blue crab season. The rotated factors explain 85% of the data variability, and the inflow variables are well represented by the four factors with communalities of 0.775 to 0.957.

Although statistical relationships for juvenile catch rates and inflow volumes were very weak, December through May was selected as the best inflow period based on the following two considerations. First, the December to May inflow period established for the adult critical inflow period includes the most abundant three of the five months that

define the juvenile critical growth season (March, April and May). Second, antecedent inflows produced a positive trend in the simple correlation analysis and PFA.

Table 7. PFA 4-Factor Loading Table for Monthly Inflows and Juvenile Blue Crab Seasonal Catch

Principal Component Factor Analysis of the Correlation Matrix
Rotated Factor Loadings and Communalities
Varimax Rotation

Variable	Factor1	Factor2	Factor3	Factor4	Communality
Avg Mar-Jul BS_Catch	0.446	-0.085	0.380	0.435	0.540
1	0.948	0.075	-0.181	0.087	0.944
2	0.977	-0.025	-0.040	0.008	0.957
3	0.925	-0.040	-0.276	-0.018	0.933
4	0.867	-0.097	-0.059	0.226	0.817
5	0.853	-0.097	-0.166	-0.105	0.775
6	0.339	0.051	-0.863	-0.005	0.862
7	0.265	-0.060	-0.812	0.284	0.813
P8	0.001	0.140	0.251	-0.877	0.852
P9	0.121	0.723	-0.012	-0.514	0.802
P10	-0.050	0.980	0.040	-0.013	0.964
P11	-0.039	0.963	-0.046	-0.050	0.933
P12	0.849	0.270	-0.309	-0.021	0.889
Variance	5.3113	2.5422	1.8516	1.3766	11.0817
% Var	0.409	0.196	0.142	0.106	0.852

Classification of Lower and Higher Inflow Years Into Two Inflow Cases

Thus far, two steps that contribute toward defining the lower and higher freshwater inflow years have been completed: 1) identification of critical growth seasons for adult and juvenile blue crabs, and 2) identification of corresponding critical inflow periods for adult or juvenile crabs. This information was then used for grouping each year into either a lower or higher inflow case.

Adult Blue Crab Inflow Cases

Each year is determined to be a lower or higher inflow year by comparing the annual, cumulative, December to May inflow with the cumulative, December to May

MinQ volume of 730.4 million cubic meters (592.4 thousand acre feet). Inflows from the previous December are labeled with the following year's January to May inflows for simplicity. For example, the critical inflow period for 1982 consists of inflows from December 1981 and January through May 1982.

Generally those years above the MinQ threshold are classified as higher inflow years and those below are classified as lower inflow years. Table 8 lists the cumulative monthly inflows for each study year, and the MinQ for the critical inflow period December through May. Comparing MinQ in the far right column with the cumulative total for each year identified five lower-inflow years. These were 1984, 1988, 1989, 1990, and 1996. Several years were close to the threshold and required further examination. As a result, three years were assigned to an inflow case based on two additional criteria: 1) how close the inflow volumes fell relative to the MinQ threshold, and 2) whether there were any significant inflow events that occurred at the beginning or end of the critical inflow period in what would otherwise be a low inflow year.

The three additional years added to the lower inflow case following the inspection of monthly inflows; these were 1983, 1986 and 1994. One of the years, 1994, was added due to a strong late season event that occurred May 14-16, during an otherwise low inflow season. Records from the USGS streamflow gage, station number 08177500 which is located upstream from the estuary near the city of Victoria (Figure 11) showed recorded flows in excess of 30 cubic meters per second (1,000 cubic feet per second) had occurred which likely contributed to the high May volume (USGS 2004). It was reasoned that inflows, such as this one, that occurred at the end of the season would not have a significant effect on the overall seasonal abundance. The two other years, 1983

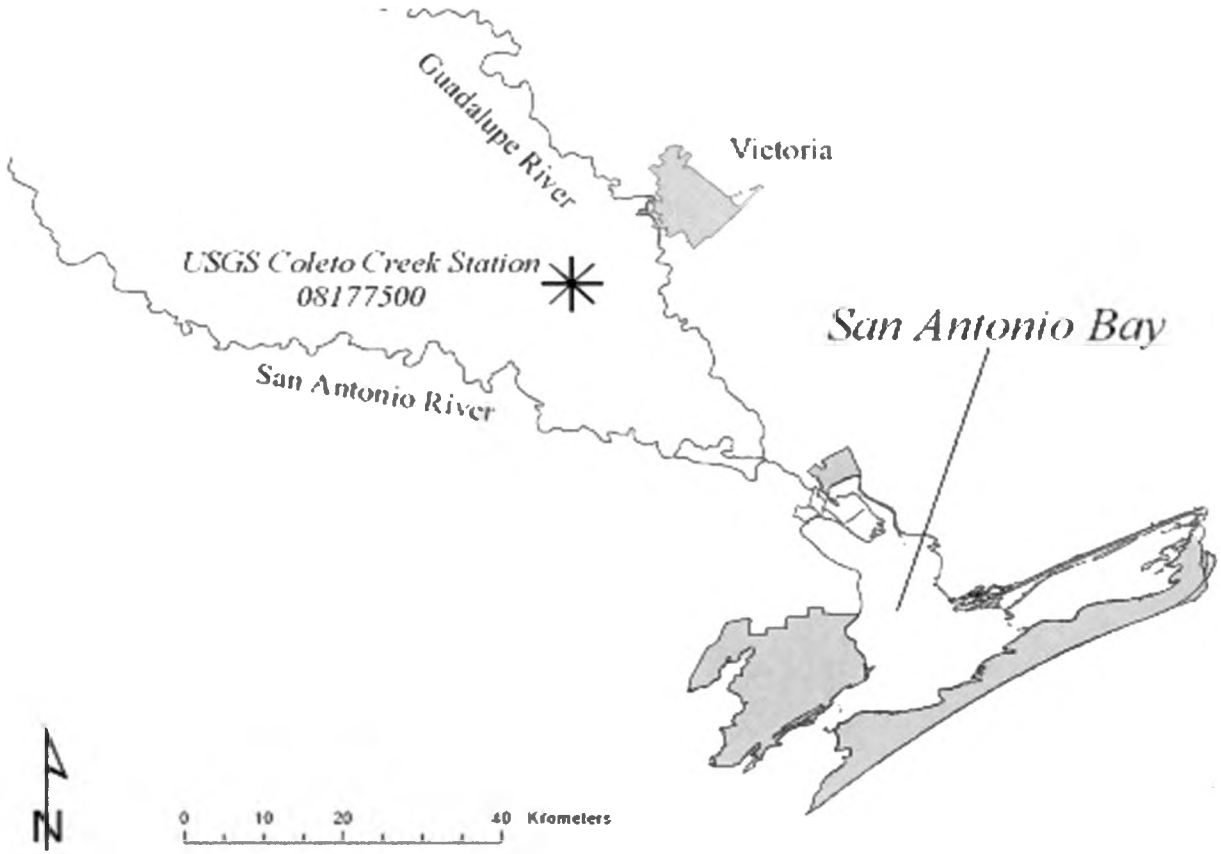


Figure 11. Location of USGS Station Number 08177500

and 1986, were added to the lower inflow case based on a month-to-month inspection of inflow and the MinQ threshold. For the 18-year study period, 1983 fell closest to MinQ and based on its proximity to the threshold it was included. Inflows during 1986 were slightly higher than 1983; however, that years' highest inflows occurred early in the season during December. As a result, 1986 was added as a lower inflow year after considering the relatively low total inflow for the season, and its high December inflows. The remaining years were grouped into the higher inflow case.

In summary, the lower inflow case consisted of the following eight years: 1983, 1984, 1986, 1988-1990, 1994 and 1996. The ten remaining years made up the higher inflow case: 1982, 1985, 1987, 1991-1993, 1995, 1997, 1998 and 1999.

Juvenile Blue Crab Inflow Cases

Due to the poor inflow and CPUE relationships, it was decided that juvenile blue crab abundance would not be evaluated by salinity zones. As a result, separate inflow cases for juvenile blue crabs were not required. However, in order to compare them with adult crab spatial distributions over the same time periods, juvenile CPUEs were mapped using the same inflow cases developed for the adult blue crabs.

Table 8. Adult Blue Crab Critical Inflow Period and MinQ Monthly Average Inflows

Year	Units	Previous Dec.	Jan.	Feb.	Mar.	Apr.	May	**Total Dec-May**
MinQ	1,000 m³	81,600	137,100	153,100	64,600	64,600	229,300	730,400
	AF	66,200	111,200	124,200	52,400	52,400	186,000	592,400
1982	1,000 m³	189,254	137,107	298,757	126,820	103,964	590,209	1,446,112
	AF	153,491	111,198	242,301	102,855	84,318	478,677	1,172,840
1983	1,000 m³	87,184	94,873	176,812	251,828	121,854	139,918	872,470
	AF	70,709	76,945	143,400	204,240	98,827	113,478	707,599
1984	1,000 m³	**64,504**	**112,922**	**73,043**	**112,212**	**47,124**	**49,752**	**459,556**
	AF	**52,315**	**91,583**	**59,240**	**91,007**	**38,219**	**40,350**	**372,714**
1985	1,000 m³	102,793	228,422	143,450	324,330	379,521	156,508	1,335,023
	AF	83,368	185,257	116,342	263,041	307,803	126,933	1,082,744
1986	1,000 m³	296,794	173,103	153,146	113,474	82,828	178,806	998,152
	AF	240,709	140,392	124,206	92,031	67,176	145,017	809,531
1987	1,000 m³	630,767	477,849	376,431	475,425	209,215	296,184	2,465,872
	AF	511,571	387,550	305,297	385,584	169,680	240,214	1,999,896
1988	1,000 m³	**143,614**	**114,800**	**97,790**	**117,776**	**84,401**	**79,718**	**638,100**
	AF	**116,475**	**93,106**	**79,311**	**95,520**	**68,452**	**64,654**	**517,518**
1989	1,000 m³	**65,719**	**99,169**	**77,452**	**80,247**	**80,313**	**131,686**	**534,586**
	AF	**53,300**	**80,429**	**62,816**	**65,083**	**65,136**	**106,801**	**433,565**
1990	1,000 m³	**58,533**	**48,268**	**64,201**	**107,785**	**145,721**	**141,749**	**566,258**
	AF	**47,472**	**39,147**	**52,069**	**87,417**	**118,184**	**114,963**	**459,252**
1991	1,000 m³	61,892	306,831	277,677	158,926	672,298	264,396	1,742,019
	AF	50,196	248,849	225,204	128,894	545,254	214,433	1,412,830
1992	1,000 m³	1,210,609	1,102,746	2,053,028	1,180,082	1,334,821	1,325,691	8,206,976
	AF	981,840	894,360	1,665,067	957,082	1,082,580	1,075,175	6,656,104
1993	1,000 m³	195,417	215,920	325,608	381,033	189,750	888,939	2,196,667
	AF	158,489	175,118	264,078	309,029	153,893	720,956	1,781,563
1994	1,000 m³	116,797	103,623	88,526	175,876	112,758	524,121	1,121,701
	AF	94,726	84,041	71,797	142,641	91,450	425,078	909,733
1995	1,000 m³	199,793	202,076	103,373	268,613	200,049	117,698	1,091,603
	AF	162,038	163,890	83,839	217,853	162,246	95,457	885,323
1996	1,000 m³	**99,032**	**69,090**	**58,014**	**55,716**	**42,717**	**30,654**	**355,222**
	AF	**80,318**	**56,034**	**47,051**	**45,187**	**34,645**	**24,861**	**288,096**
1997	1,000 m³	68,454	97,577	83,749	329,555	741,109	394,156	1,714,600
	AF	55,518	79,138	67,923	267,279	601,062	319,672	1,390,592
1998	1,000 m³	133,175	150,747	332,686	367,780	177,379	79,357	1,241,124
	AF	108,009	122,260	269,818	298,281	143,860	64,361	1,006,589
1999	1,000 m³	442,709	230,682	150,211	169,221	144,702	160,074	1,297,599
	AF	359,050	187,090	121,826	137,243	117,358	129,825	1,052,392

CHAPTER 5

SALINITY PROFILES FOR LOWER AND HIGHER INFLOW CASES

In order to relate the distribution of blue crab abundance to salinity for each inflow case, an interpolation method was used to develop continuous surface profiles for salinity. Kriging and surface contouring were accomplished using ArcView version 8.3 with the geostatistical extension. Kriging is a multiple step process that begins with an exploratory spatial analysis, followed by the testing of several models and spatial inputs to refine which combination produces the best result according to cross-validation statistics and a qualitative assessment of the new surface with original data.

Description of Salinity Data

Salinity levels, measured when coastal fishery samples were collected, provided the data that were used to develop salinity profiles for the two inflow categories. Station locations where samples and salinity data were collected were selected randomly on a monthly basis according to a 1.6-kilometer (1-mile) grid (Figure 12). Salinity data for the critical inflow period were extracted from annual records, and then classified into lower- or higher-inflow years. The selection option accessible through ArcView's toolbar was used to query the attribute table containing all the salinity by month and year; the selected records were then saved as two new shapefiles, one for each inflow year case.

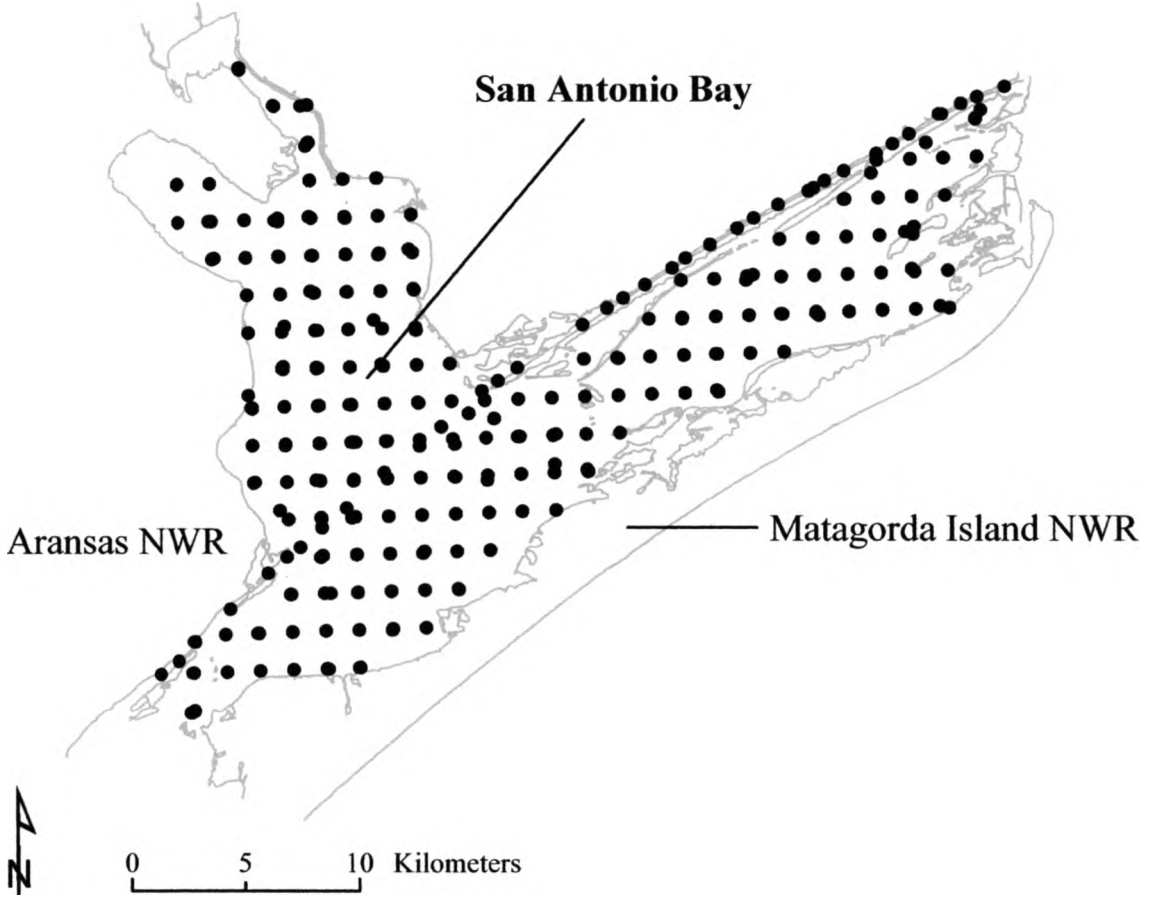


Figure 12. Locations of Trawl Sampling Stations in the Guadalupe Estuary

Median salinity values and interquartile ranges (IQR) by location and inflow case were used in the selection of a kriging model. The median and IQR values were calculated using an external computer program, SPSS, and then added to the shapefile attribute tables.

The seven salinity ranges generated through kriging were seen in table 3. Note that the spatial extent of each salinity range generated through kriging is an important output of this process since the CPUE is then matched by location with each salinity zone.

GIS Data and Spatial Definition

An outline of the San Antonio bay shoreline was extracted from the 1:24,000 scale coastal hydrography (GLO 2004). A Lambert Conformal Conic coordinate system with Texas State Mapping System (TSMS) parameters was the projection used in this study (Appendix A).

Modeling of Salinity Profiles

Exploratory Analysis

Technical guidance published by the kriging model's developer recommended several exploratory steps to be accomplished in order to better understand the dataset and to provide input for future modeling decisions (ESRI 2001). These steps included producing frequency histograms, normal quantile-quantile or QQ plots, and a trend analysis in which points were projected onto vertical planes and a best-fit line or

polynomial was fit to the scatter plot. Although not required for kriging prediction models, both data sets were determined to be normally distributed through examination of the QQ plot, a plot of quantiles from the data versus quantiles of a standard normal distribution (Figure 13).

Information from the other plots generally did not reveal useful information for this study probably because of the high density of sample points available for use during interpolation, which resulted in fewer internal assumptions required by the model. For example, similar salinity profiles were obtained in a comparison between the inverse distance weighting (IDW) method, which calculates an autocorrelation function based solely on distance, and the ordinary kriging method, which calculates autocorrelation functions based on distance and direction (Figure 14). Seven salinity classes are shown in the figures, ranging from zero to greater than thirty parts per thousand salinity, in five part increments. It is important in these cases to note the similar pattern rather than the number scale.

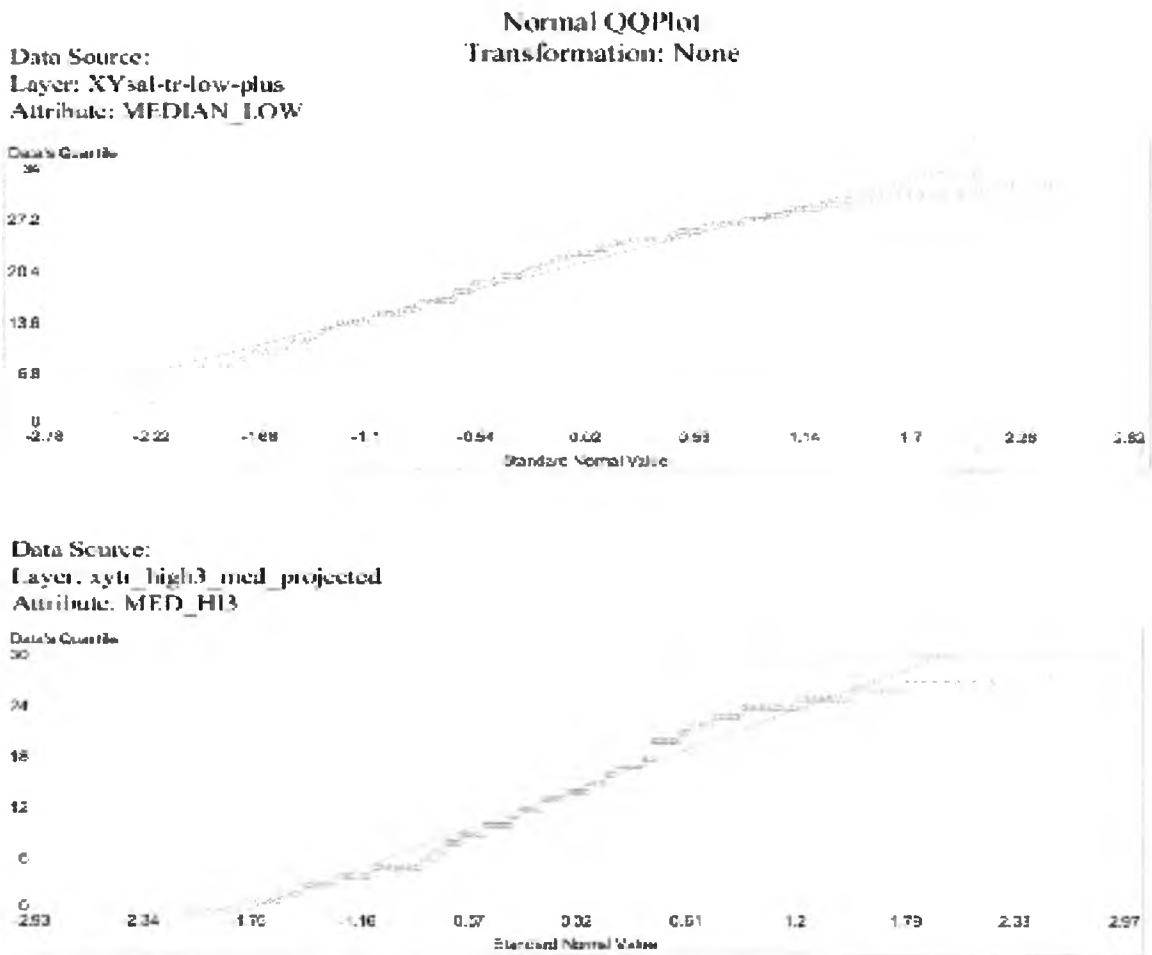
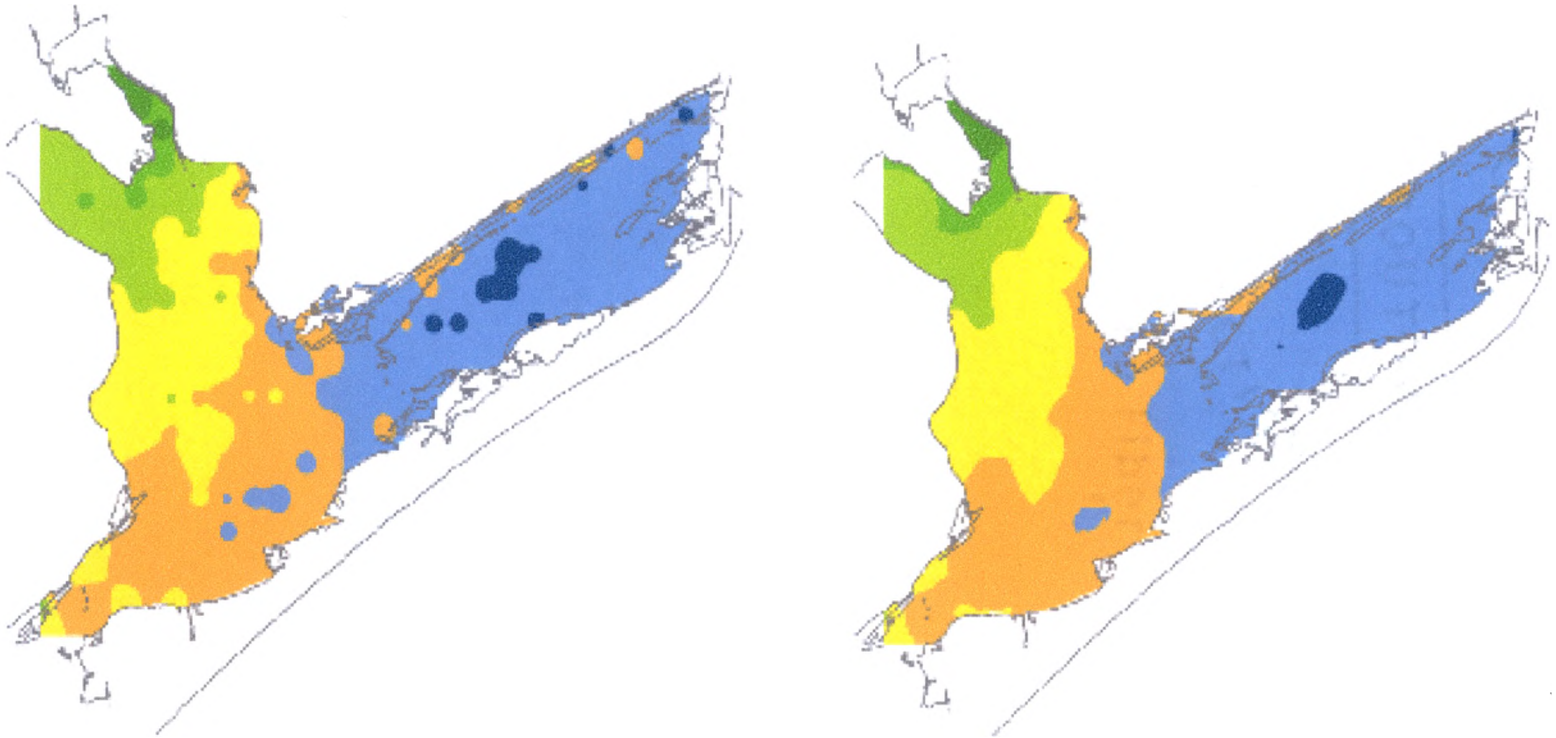


Figure 13. Salinity QQ Plots for Lower (top) and Higher (bottom) Inflow Cases



(A) (B)

Figure 14. Comparison of (A) IDW and (B) Ordinary Kriging Salinity Profiles for the Lower-Inflow Case

Kriging Method

The final spherical model semivariogram used for kriging was selected by review of two criteria: (1) semivariogram parameter values estimated from the data, and (2) cross-validation error statistics. It was preferable to use the same modeling method for both lower- and higher-inflow years for consistency, and therefore the selection criteria were evaluated against both salinity data sets. Both inflow cases were similar in terms of semivariogram parameters and the error statistics they produced, and therefore, for simplicity, only the lower-inflow results are presented.

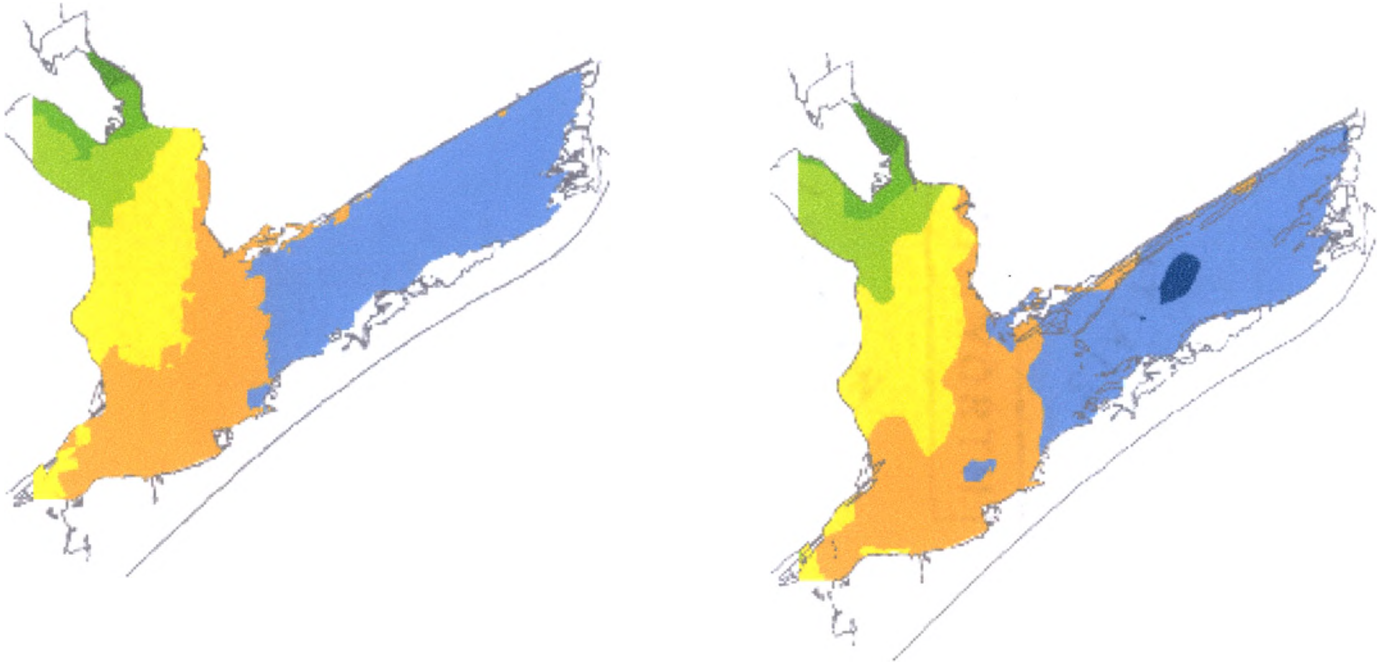
The semivariogram parameters included: (1) the nugget, a measure of the variance random error in the model, (2) the partial sill which represents the non-random variance for the spatially autocorrelated portion of the semivariogram, and (3) the range, a distance beyond which no autocorrelation between points could be assessed by the model.

Cross-validation error statistics guided the selection of a model for the purpose of providing unbiased and valid estimates of uncertainty, or prediction standard errors. For unbiased prediction errors, the mean prediction error and its standardized version should be near zero. For valid prediction standard error estimates, the average standard errors should be similar to the total root-mean-squared prediction error (RMSE) (ESRI 2001). In addition to minimizing the model's total RMSE, the standardized RMSE value should be close to one which would mean the standard error estimate is being neither over- nor under-estimated.

Kriging Analysis

A review of several semivariograms and trend analysis scatterplots revealed a spatially autocorrelated range of approximately 19 kilometers (12 miles) along a northwest to southeast axis where freshwater enters the bay and flows toward the Gulf of Mexico. Another minor autocorrelation trend of about 16 kilometers (10 miles) along a minor axis was also identified, which is generally orientated from the southwest to the northeast, parallel to the coastline. Important information obtained from the semivariogram parameters were (1) that the decline in spatial autocorrelation for salinity occurs well beyond the 1.6-kilometer (1-mile) sampling distance, and (2) the final model selected minimizes the amount of the variance random error (the nugget value) in terms of magnitude when considered in relation to the partial sill.

Spherical and Gaussian models produced very similar error statistics and salinity profiles as seen in figure 15 and table 9. Since only one model was needed, the spherical model's lower random error nugget value (5.3 versus 10.1), and its lower proportion in relation to the partial sill (20% versus 45%), led to the final selection of the spherical model for this study. Once the model was selected, the searching neighborhood needed to be refined. The searching neighborhood for interpolation consisted of twelve data points divided into four sectors along the major and minor axes determined by the semivariogram. There were two considerations when selecting the search neighborhood criteria. The first consideration was to minimize the number of less significant outlying points drawn into the interpolation process, which were identified by analysis as contributing 1% to the interpolation.



(A) (B)

Figure 15. Comparison of Salinity Profiles for the Lower Inflow Case using (A) Gaussian and (B) Spherical Models

Table 9. Lower-Inflow Semivariogram Parameter Results for Several Similar Models

Statistic	Ordinary Krig Spherical Model No Anisotropy	Ordinary Krig Spherical Model W/Anisotropy	Ordinary Krig Gaussian Model W/Anisotropy	Ordinary Krig Spherical Model Constant Trend W/Anisotropy
Mean Prediction Error	0.039	0.012	0.019	0.009
RMSE	3.427	3.394	3.328	3.394
Avg Standardized Error	2.656	3.138	3.403	3.138
Mean Standardized Error	0.004	-0.002	0.003	-0.003
RMSE Standardized	1.269	1.066	0.966	1.066
Nugget	2.694	5.343	10.082	5.343
Partial Sill	71.618	27.3	22.3	27.3
Anisotropy (minor axis/direction)	--	10/43.2	10/22.3	10/43.2

Note: Anisotropy minor axis is in miles, and direction is degrees clockwise from north.

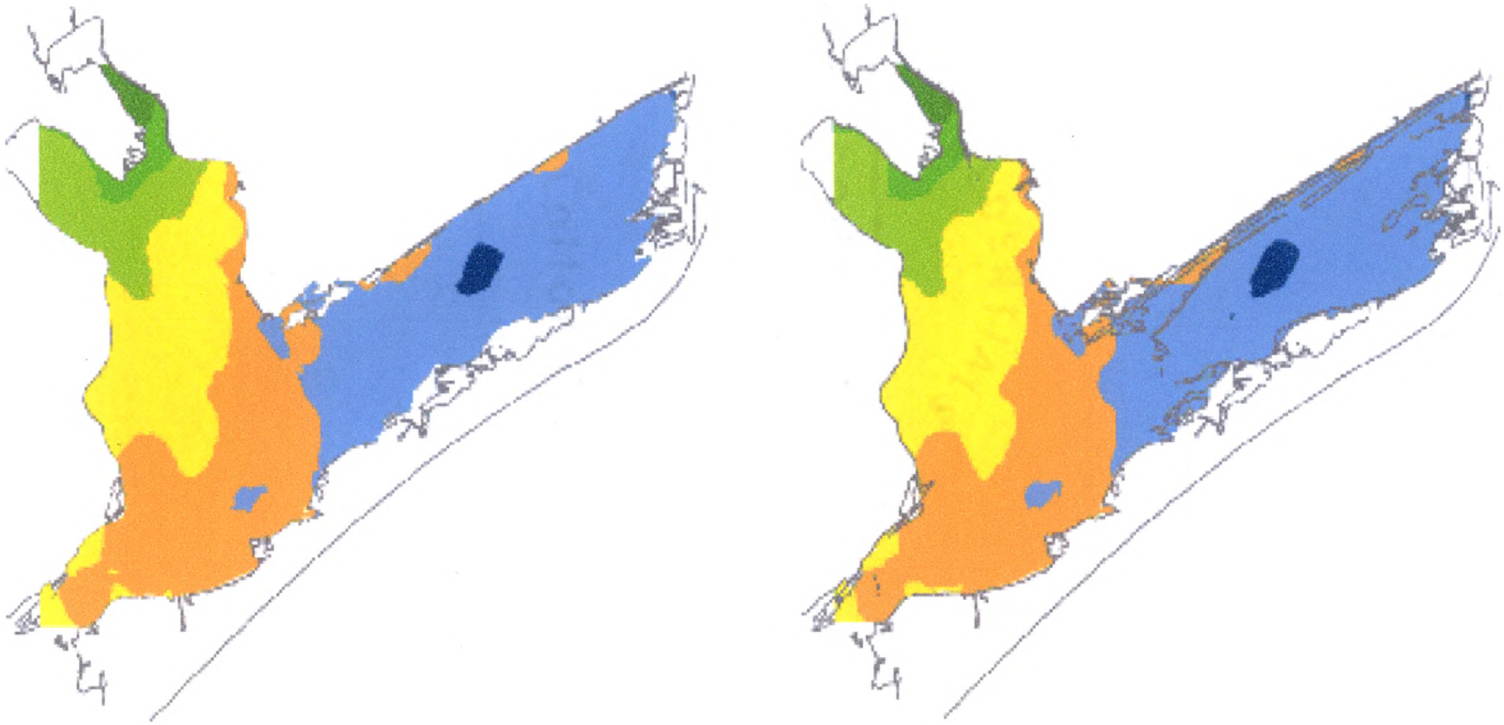
The second consideration was spatial in nature. Along the lower arms of the estuary it was undesirable for points in the upper bay to be captured for interpolation in those places where the lower arms were separated by land from the upper bay. Twelve points appeared to best optimize these considerations as determined through an interactive evaluation of the searching neighborhood where points used for interpolation were displayed on the computer screen when a point on the map was selected.

Anisotropy is a directional influence, and in this study it is a directional salinity trend, which can be accounted for in the kriging model, and it was determined to be applicable in this study by inspection of the semivariogram surface produced by

Geostatistical Analyst. The presence of anisotropy means that "in certain directions closer things are more alike than in other directions" and, therefore, the kriging model could be adjusted to account for this (ESRI 2001). Anisotropy was shown by the semivariogram surface to occur along a southwest to northeast axis. The reason for this trend is unclear, and more study on the hydrodynamic nature of the bay may help to explain this phenomenon. ESRI's guidelines for cross-validating semivariograms, as outlined earlier, were applied to the new modeling results that included anisotropy. The following positive changes are explained using the statistics in table 9. These included an improved prediction error statistic, a slightly reduced RMSE, and an improvement in the model's ability to correctly assess the variability in predictions by producing an average standard error closer in magnitude to the RMSE. Note that the benefit of including anisotropy, however, appears to be primarily for slightly improving the estimate of error versus any significant change in the salinity surface profile. As seen in figure 16, the salinity surface on the left produced without anisotropy is nearly the same as the surface with anisotropy, right. This effect is attributed to the spatially intensive network of available data.

Adding a global trend into the model did not produce a significant change in semivariogram parameters or cross-validation results as seen in the last column of table 9. Global trends differ from anisotropy in that a global trend affects all measurements in some way and is usually explainable, whereas anisotropy applies to only some measurements in a particular direction and the cause is usually unknown. Differences between the spherical model with and without a global trend were subtle, and occurred for the most part beyond the third decimal point cutoff applied to the table. This is

attributed again to the close network of sample points, which allowed the model access to a robust amount of data for interpolation. A comparison of their salinity surfaces also showed no significant differences. Since there was relatively little change, the general guidance from ESRI that it is better to keep the model simple and not to detrend a surface unless there was a good reason to do so was followed. Therefore, the spherical model was selected for kriging.



(A) (B)

Figure 16. Comparison of Salinity Profiles without Anisotropy (A) and with Anisotropy (B)

Final Salinity Surface Profiles

The final salinity profiles developed for and used in this study are shown in the following figures along with the corresponding trawl and bag seine CPUE for the critical growth season (Figures 17 - 20). Area calculations for each zone are shown in table 10. When the profiles were overlayed with catch rates, they showed that during lower-inflow years the adult blue crabs are most abundant in the upper and middle parts of the estuary which correspond to a salinity range of about 5 to 20 ppt. The percent of estuary area with 5 to 15 ppt salinity is approximately 12%, and about 20% of the estuary has salinity levels ranging from 15 to 20 ppt. During higher-inflow years, the most abundant zones seem to be the 5 to 15 ppt salinity range, which covers about 50% of the estuary. Higher adult catch rates can also be seen in lower regions of the bay during higher-inflow years. These observations were tested using statistical methods outlined in the next section.

Table 10. Area by Salinity Zone for Lower- and Higher-inflow Cases

Lower-inflow Salinity Zone	Area km^2 (mi^2)	Percent of Total	Higher-inflow Salinity Zone	Area km^2 (mi^2)	Percent of Total
0	5.0 (1.91)	1	0	56.2 (21.7)	11
1	10.6 (4.1)	2	1	90.3 (34.9)	18
2	44.1 (17.0)	9	2	104.2 (40.2)	20
3	106.0 (41.0)	21	3	105.9 (40.9)	21
4	150.0 (57.8)	29	4	109.7 (42.3)	22
5	186.1 (71.9)	37	5	41.6 (16.1)	8
6	7.1 (2.7)	1	6	0	0
Total	508.9 (196.4)	100	Total	507.9 (196.1)	100

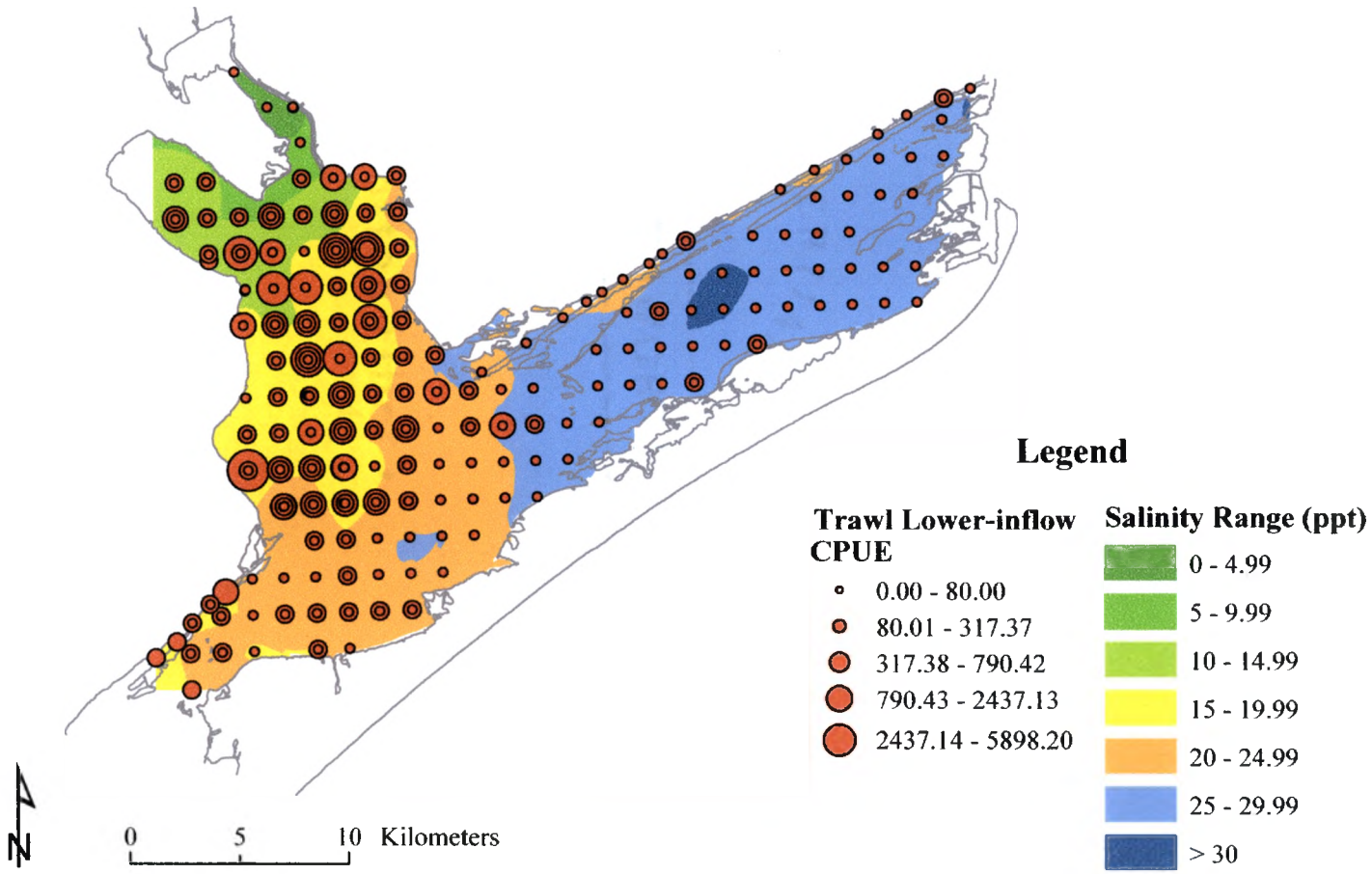


Figure 17. Lower-inflow Salinity Profile with Trawl Blue Crab CPUE

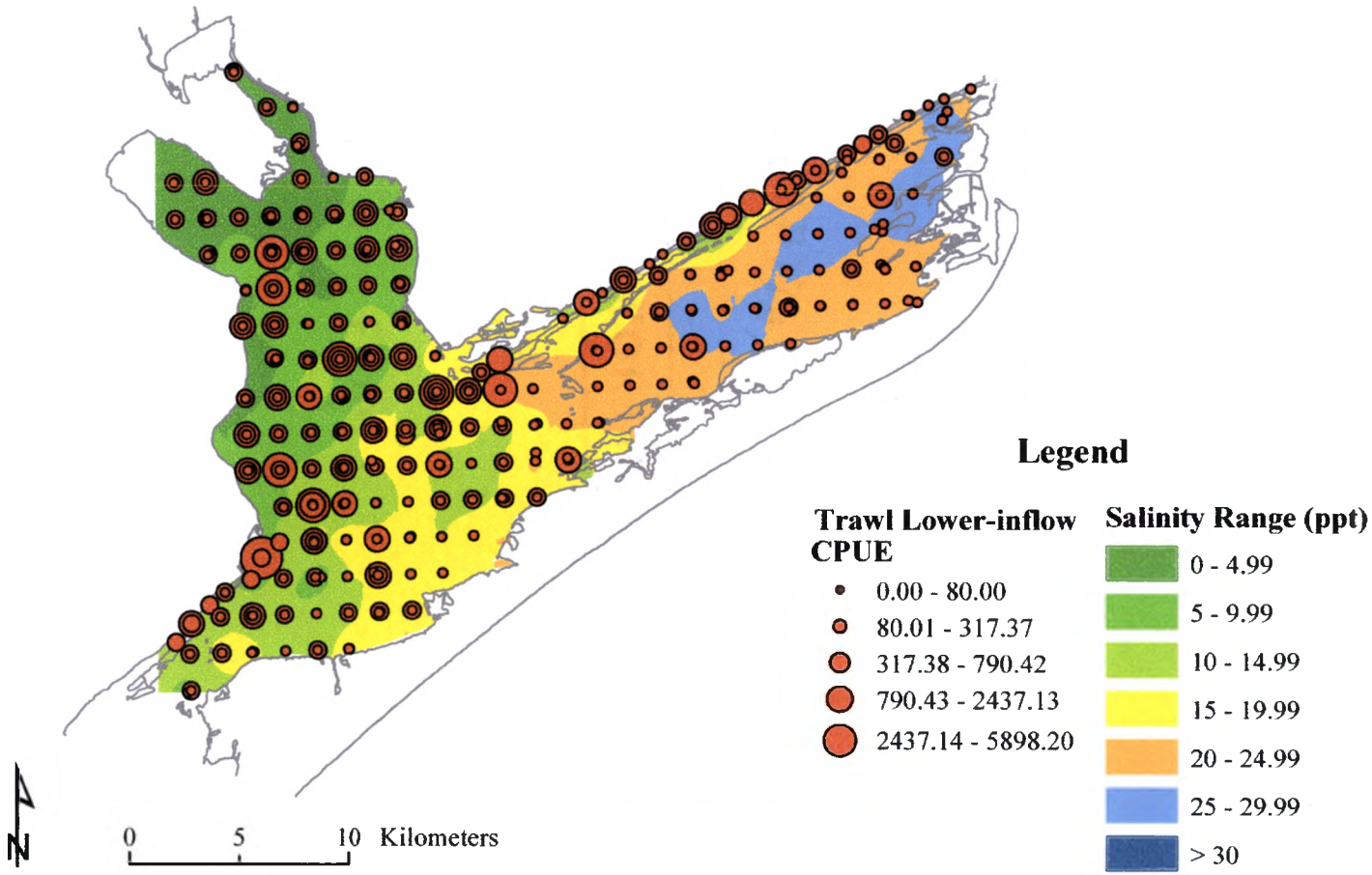


Figure 18. Higher-inflow Salinity Profile with Trawl Blue Crab CPUE

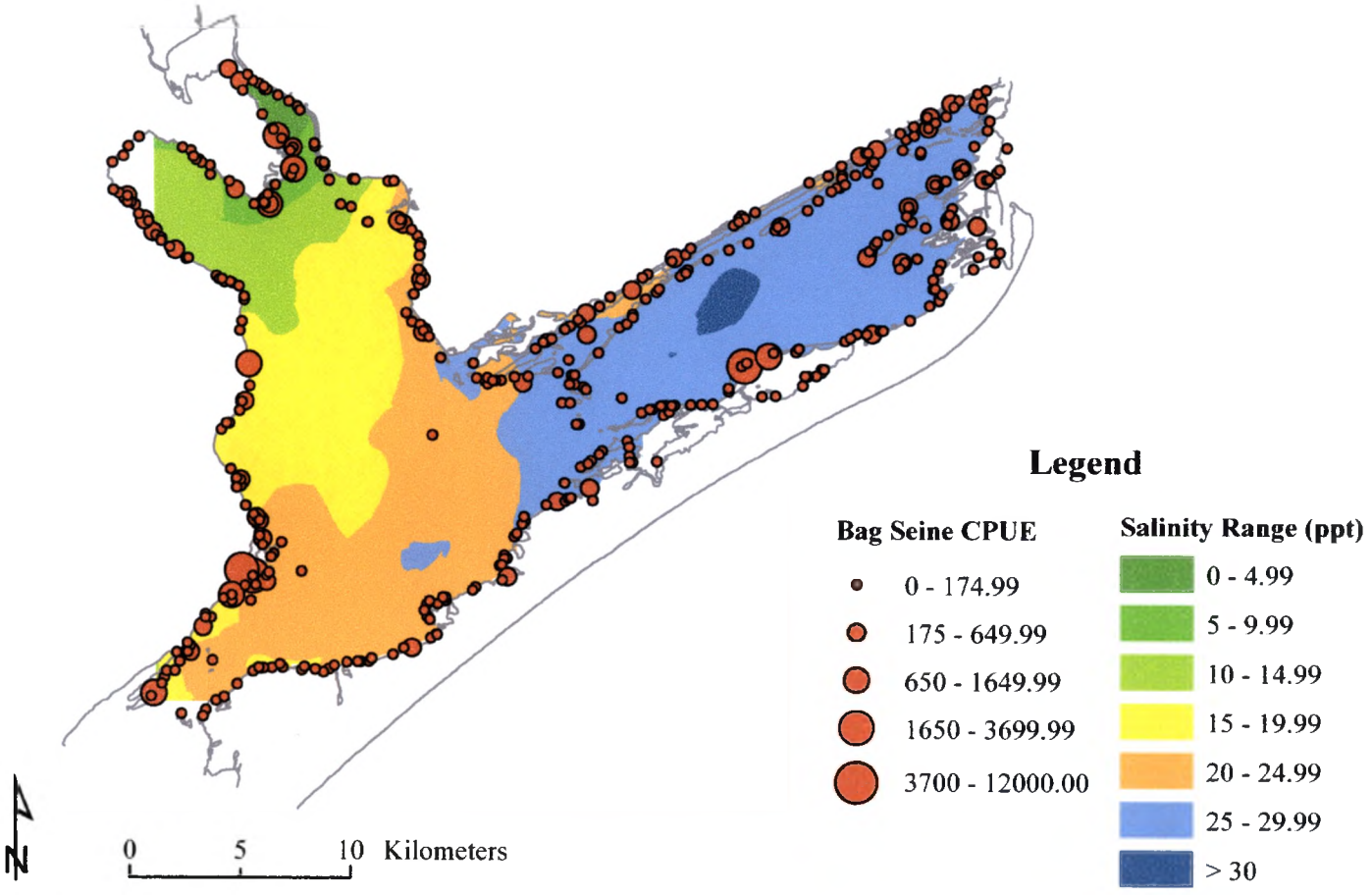


Figure 19. Lower-inflow Salinity Profile with Bag Seine (Juvenile) Blue Crab CPUE

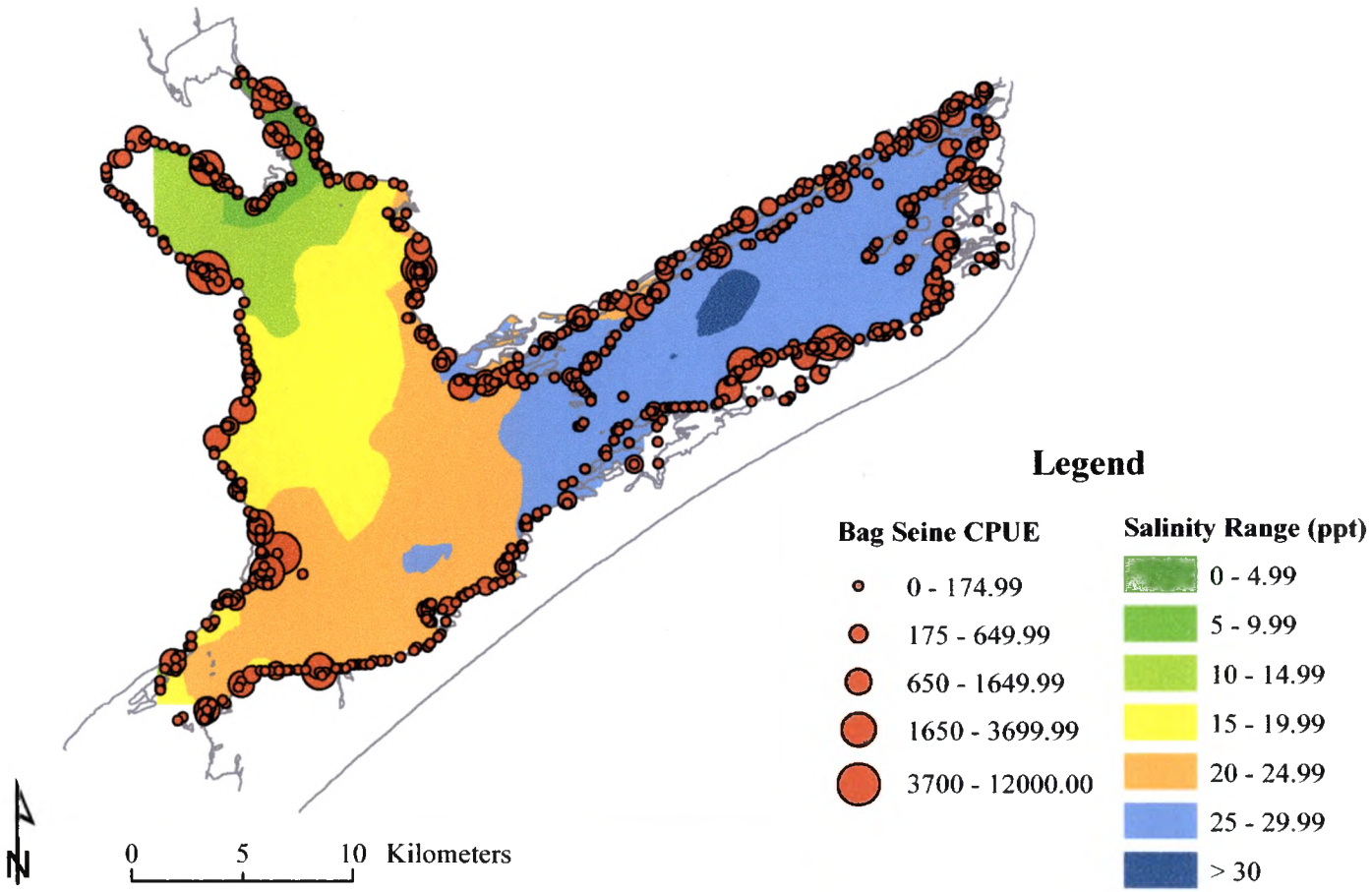
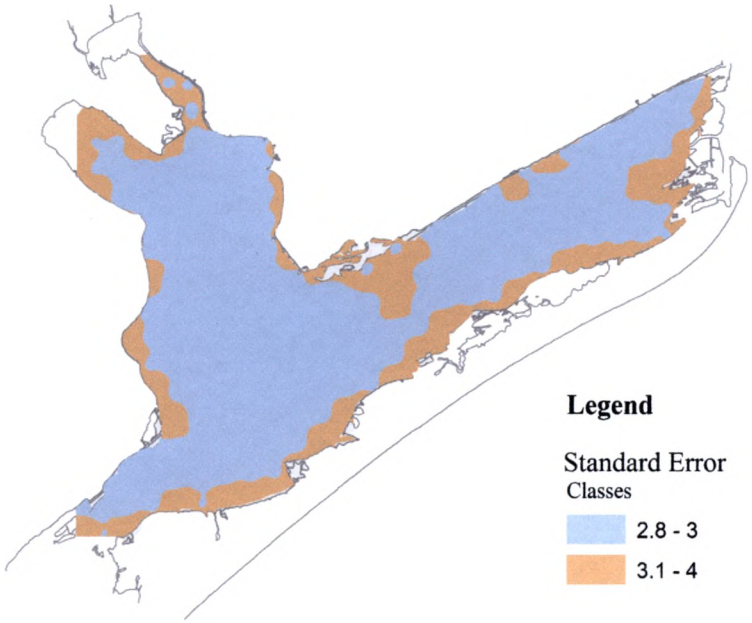


Figure 20. Higher-inflow Salinity Profile with Bag Seine (Juvenile) Blue Crab CPUE

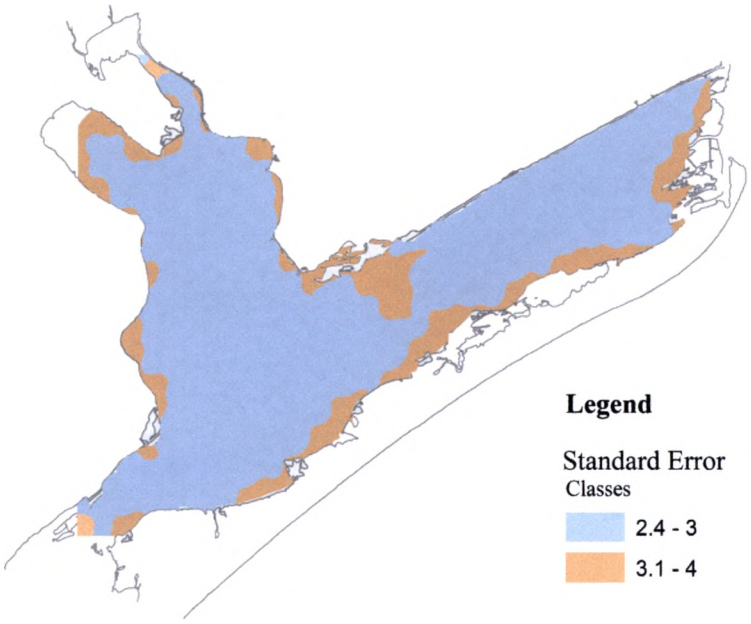
Estimate of Error and Variation of Salinity Data

Estimates of standard error that apply to the salinity profile results were generated for lower- and higher-inflow cases (Figure 21). The majority of the study area fell between 2.5 and 3 for both lower and higher-inflows, with areas around the edges on the higher end of that range. In general, errors inherent to the kriging method, from the method alone, consisted of slightly overestimating lower values and slightly underestimating higher values (ESRI 2001).

Interquartile range maps (Figure 22) were developed to illustrate the range of measured salinity values associated with the lower- and higher-inflow cases, since each inflow case is a collection of several years of data (eight years for lower, and ten years for higher-inflow case). When the two are compared, the lower-inflow case shows more variability in the upper estuary and much less in lower arms where there is less mixing of fresh and saline waters. The situation is generally reversed for the higher-inflow case where higher freshwater inflows create less variable salinity conditions in the upper estuary. Lower regions show higher variability since the additional volumes of freshwater travel farther into the bay and increase the area where fresh and saline waters mix.

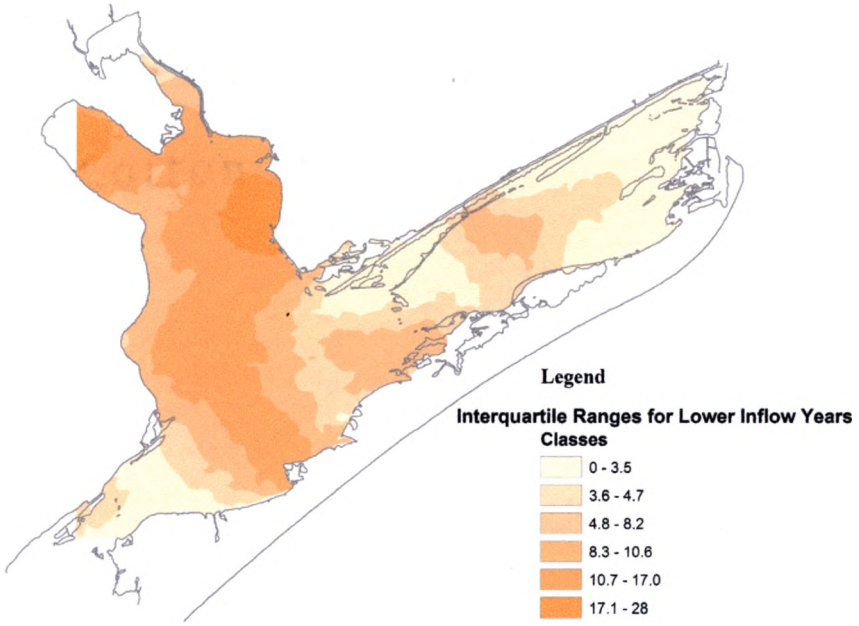


(A) Lower-inflow Case

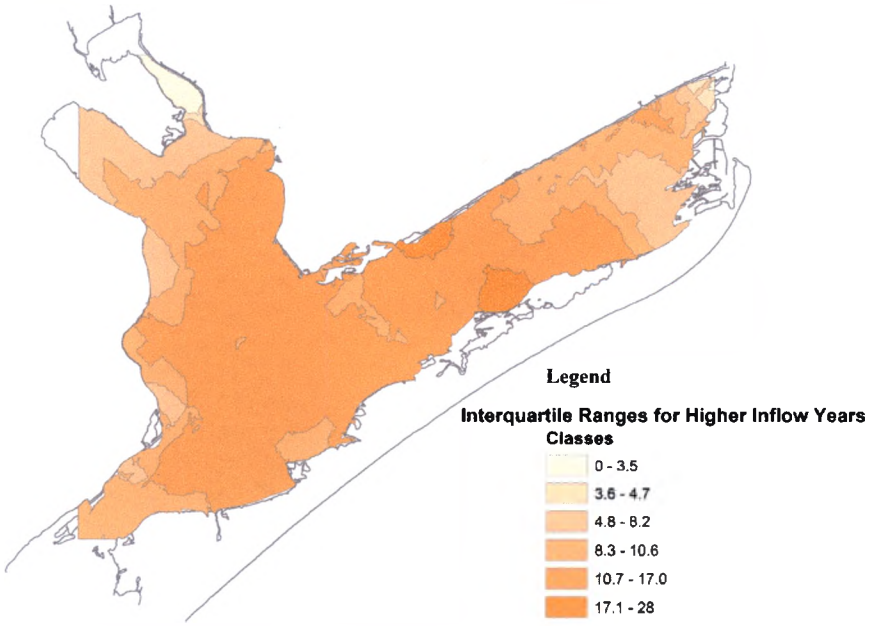


(B) Higher-inflow Case

Figure 21. Standard Errors for (A) Lower- and (B) Higher-inflow Cases



(A) Lower-inflow Case (parts per thousand saline)



(B) Higher-inflow Case (parts per thousand saline)

Figure 22. Salinity Interquartile Ranges for (A) Lower- and (B) Higher-inflow Cases

CHAPTER 6

STATISTICAL ANALYSIS

Descriptive statistics for trawl catch rates organized by two inflow cases and seven salinity zones are summarized in tables 11 and 12. A high number of samples with a zero catch rate contributed to differences between the zone mean and median values, particularly for higher salinity zones 5 and 6. It was anticipated these higher salinity zones would have a higher number of zero catches based on the findings of previous studies that identified an adult blue crab preference for lower salinity zones. The differences in mean and median catch rates indicate increased crab activity in areas where salinity levels are less than 20 ppt. However, the wide range of data values within these zones could indicate there are other important factors in addition to salinity, such as habitat type, that are influencing the presence or absence of crabs.

Table 11. Descriptive Statistics for Lower-inflow Trawl CPUE by Salinity Zone

Salinity Zone	N	Mean CPUE	Median CPUE	Std. Deviation	Std. Error of Mean	Min.	Max.
0	12	13.97	5.99	21.412	6.181	0	65.87
1	33	38.59	11.98	95.304	16.590	0	526.95
2	112	99.25	18.98	213.753	20.197	0	1281.44
3	284	128.92	35.93	342.939	20.349	0	4724.55
4	253	50.34	11.98	90.436	5.685	0	658.68
5	286	17.28	5.99	40.802	2.412	0	395.21
6	16	12.73	8.98	14.403	3.601	0	44.00
Total	996	67.32	11.98	208.558	6.608	0	4724.55

Table 12. Descriptive Statistics for the Higher-inflow Trawl CPUE by Salinity Zone

Salinity Zone	N	Mean CPUE	Median CPUE	Std. Deviation	Std. Error of Mean	Min.	Max.
0	212	61.71	17.96	127.401	8.749	0	1359.28
1	277	108.43	29.94	399.814	24.022	0	5898.20
2	273	80.71	23.95	164.295	9.943	0	1634.73
3	185	69.49	17.96	152.391	11.204	0	1041.92
4	259	25.19	5.99	86.020	5.345	0	1131.74
5	101	18.38	0	65.739	6.541	0	598.80
Total	1307	66.10	11.98	219.153	6.061	0	5898.20

Trawl CPUE Means Comparison Tests Among Salinity Zones

Salinity zones were then compared to determine if their mean CPUEs were significantly different from means of the other zones. Comparison of CPUE means between the groups began with a general analysis of variance test, the one-way ANOVA, to determine whether there was at least one group mean significantly different from other group means. Since there were violations of the ANOVA test's assumptions of normality and equal variances, further examination of the data was required in order to confirm the significant test result. These assumptions were tested using the Shapiro-Wilk test for normality and the Levene test for homogeneity of variance. The trawl catch data for both inflow cases were determined to be non-normal with unequal variances. This required that the trawl CPUE or catch data be transformed in order to approximate a normal distribution. A log10 transformation was performed followed by the nonparametric Kruskal-Wallis test to confirm the significant ANOVA result.

The high number of zero catches in both cases contributed to a positively skewed non-normal distribution. Since there are many options available to transform data, the log10 transformation was confirmed to be the best transformation by using SYSTAT's

Dynamic Explorer to interactively modify the distribution and match it with a log-linear plot. Using a method similar to the TPWD's freshwater inflow study, a constant was added to the CPUE data prior to transformation in order to prevent "zero catches" that resulted from empty net data from being log-transformed into missing values. Although the log-transformed QQ plots for both cases showed a nearly normal distribution visually, both cases failed the Shapiro-Wilk test for normality, with $p<0.0005$. Because the Shapiro-Wilk test indicated rejection of the null hypothesis that the data follows a normal distribution, both cases were subjected to the Kruskal-Wallis nonparametric test using a chi-square distribution with 5 degrees of freedom (higher-inflow), or 6 degrees of freedom (lower-inflow). These tests were significant at $p<0.0005$ with a test statistic of 142.11 for the higher-inflow case, and a test statistic of 113.96 for the lower-inflow case. This conclusion agreed with the ANOVA result, table 13, showing at least one salinity zone catch rate differed significantly from others.

Table 13. One-Way ANOVA Results for Trawl CPUE Data

Case		Sum of Squares	Degrees of Freedom	Mean Square	F	Significance
Lower-inflow	Between Groups	79.309	6	13.218	20.645	0.000
	Within Groups	633.230	989	0.640		
	Total	712.538	995			
Higher-inflow	Between Groups	101.489	5	20.298	30.849	0.000
	Within Groups	856.027	1301	0.658		
	Total	957.516	1306			

While both cases also failed the Levene test for equal variance, further testing was not required since the Kruskal-Wallis had already been performed and had produced a significant result. This condition was important, though, for selecting a multiple comparison test. Once it was confirmed there was at least one salinity zone with a significantly different CPUE mean, additional comparisons were necessary in order to identify which zones differ from others. For this purpose the nonparametric Games-Howell (GH) multiple comparison test (MCT) was selected. This test is recommended for group comparisons with an unequal number of samples and unequal variances (Toothaker 1993). In the GH test, the catch data is rank-transformed and a multiple comparison test is performed on the ranks. The experiment-wide error level was maintained at 0.05. Results for both inflow cases are shown in tables 14 and 15. The mean difference, column 3, is the difference between rank-transformed mean catch rates. The asterisk indicates a significant difference between zones at the $p<0.05$ level. The following paragraphs explain how these results were evaluated to identify zones with statistically significant differences.

Lower-inflow CPUE Means Comparisons

First, zones zero and six were dropped from the evaluation due to their low number of samples, 12 and 16 respectively. The remaining salinity zones were then separated based upon significance levels that identified which group CPUE means were significantly different from other groups at $p<0.05$. This step identified zones three, four, and five as significantly different from each other. Zones one and two required further evaluation since they were grouped in various combinations with the other three zones. After review of the significance levels, it was decided that zone one would be best

separated from two and three based on its significant difference ($p<0.05$) with zone three; even though it was not identified as statistically different from zone two. This confusing group relationship of zone one with the other zones was probably due to the lower number of samples (33) in comparison with the other groups which contained 100 or more samples each. Zones two and three were not found to be statistically different with $p=0.638$, and were therefore grouped together.

Higher-inflow CPUE Means Comparison

The same steps were followed for evaluating the higher-inflow matrix. All the inflow cases contained over 100 samples in each group and therefore none were dropped from the evaluation. Zone zero was separated from zone one since the significance level was 0.052, just two-thousandths above the significance cutoff value of 0.05. Table 16 summarizes these results in a stepwise fashion starting on the left with the lowest salinity zone in the upper estuary, and continuing in a downstream direction toward the highest salinity zones in Espiritu Santo Bay. The underlined zones in table 16 were determined not to be statistically different from each other.

In summary, there appears to be a consistent adult blue crab salinity preference of 10 to 20 ppt (boldface type); and this range most likely includes the 5 to 10 ppt after considering the uncertainty related to the low number of samples in zone one during the lower-inflow case. Figure 23 graphs these results in relation to the mean blue crab CPUE for each salinity zone, clearly illustrating the decrease in CPUE for both inflow cases when salinity concentrations exceed 20 ppt. Differences between the two inflow cases at salinity levels less than 10 ppt may be explained, in part, by the differences in

Table 14. Games-Howell Multiple Comparison Test of Trawl CPUE for the Lower-inflow Case

(I) Zone	(J) Zone	Mean Difference (I-J)	Sig.
0	1	-.31447	.831
	2	-.56483	.201
	3	-.72968(*)	.049
	4	-.37798	566
	5	-.02089	1.000
	6	-.02482	1.000
1	0	.31447	.831
	2	-.25036	.630
	3	-.41521(*)	.046
	4	-.06352	.999
	5	.29357	.283
	6	.28965	.820
2	0	.56483	.201
	1	.25036	.630
	3	-.16485	.638
	4	.18685	.486
	5	.54394(*)	.000
	6	.54001	.123
3	0	.72968(*)	.049
	1	.41521(*)	.046
	2	.16485	.638
	4	.35169(*)	.000
	5	.70879(*)	.000
	6	.70486(*)	.016
4	0	.37798	.566
	1	.06352	.999
	2	-.18685	.486
	3	-.35169(*)	.000
	5	.35709(*)	000
	6	.35316	.482
5	0	.02089	1.000
	1	-.29357	.283
	2	-.54394(*)	.000
	3	-.70879(*)	.000
	4	-.35709(*)	.000
	6	-.00393	1.000
6	0	.02482	1.000
	1	-.28965	.820
	2	-.54001	.123
	3	-.70486(*)	.016
	4	-.35316	.482
	5	.00393	1.000

* The mean difference is significant at the .05 level.

Table 15. Games-Howell Multiple Comparison Test for Trawl CPUE for the Higher-inflow Case

(I) Zone	(J) Zone	Mean Difference (I-J)	Sig.
0	1	-.22087	.052
	2	-.16284	.282
	3	-.01833	1.000
	4	.43944(*)	.000
	5	.57773(*)	.000
1	0	.22087	.052
	2	.05802	.964
	3	.20254	.114
	4	.66031(*)	.000
	5	.79859(*)	.000
2	0	.16284	.282
	1	-.05802	.964
	3	.14452	.450
	4	.60228(*)	.000
	5	.74057(*)	.000
3	0	.01833	1.000
	1	-.20254	.114
	2	-.14452	.450
	4	.45777(*)	.000
	5	.59605(*)	.000
4	0	-.43944(*)	.000
	1	-.66031(*)	.000
	2	-.60228(*)	.000
	3	-.45777(*)	.000
	5	.13829	.583
5	0	-.57773(*)	.000
	1	-.79859(*)	000
	2	-.74057(*)	.000
	3	-.59605(*)	.000
	4	-.13829	.583

* The mean difference is significant at the .05 level.

their spatial extents. Approximately 3% of the estuary experienced salinity concentrations less than 10 ppt for the lower-inflow case, as compared with 30% for the higher inflow case. The smaller region of low salinity resulted in fewer samples being collected within that zone.

From today's water policy and planning perspectives, the lower salinity threshold is not as immediately useful as the higher salinity threshold because today's most urgent goals are related to meeting future water demands in the region. A lower salinity threshold would be useful, though, for the purpose of predicting the spatial behavior of blue crabs in the event of large water releases from upstream dams. Low temperatures and dissolved oxygen levels, both of which are known to affect blue crabs might also be included as variables (Patillo et al 1997). The prediction of spatial changes in blue crab abundance would provide useful information applicable to the maintenance of whooping crane-protected habitats where blue crabs are a critical food source, and also for the commercial fishing industry that depends, in part, on blue crab harvests.

Comparisons with the 1998 Freshwater Inflow Recommendation Study

Results from the 1998 Freshwater Inflow Recommendation study showed that the mean CPUEs dropped significantly for salinity ranges above 15 ppt, and that the highest mean CPUEs occurred between 5 and 15 ppt (TPWD 1998). This study demonstrated a slightly wider peak CPUE range with the highest mean catch rates occurring between 5 and 20 ppt. Differences between the 1998 study and this one might be attributed to use of inflow-partitioned data sets used in this study.

Table 16. Games-Howell MCT Summary for CPUE Means by Inflow Case

Inflow Case	Salinity Zones Compared Flow Direction →	Corresponding Salinity Range (ppt)
Lower	1 **2 3** 4 5	(5–9.99) (**10–19.99**) (20–24.99) (25-29.99)
Higher	0 **1 2 3** 4 5	(0-4.99) (**5-19.99**) (20-29.99)

Notes: 1. Statistically similar zones are underlined.
2. Salinity range with the highest mean catch rate is boldfaced.

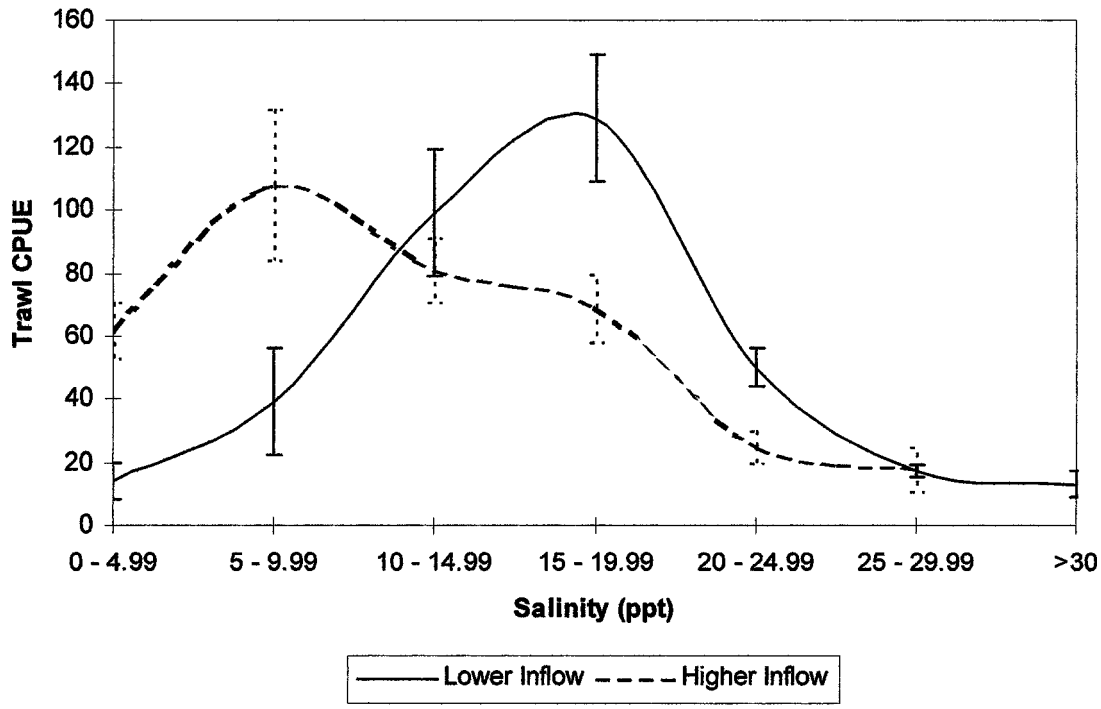


Figure 23. Adult Blue Crab Mean CPUE with Standard Error versus Salinity Range

Comparisons with other MCT Methods

Other MCTs were performed to see if they would produce a result different from the GH MCT. Other MCT tests applicable for groups with unequal variances include Tamhanes T2 (T2) and Dunnett's C (C), both of which are available using SPSS. Overall the results were very similar for the lower-inflow case, and identical for the higher-inflow case. For the lower-inflow case, GH results showed a slightly higher significance level between zone three (15 to 19.99 ppt) and the lower salinity zones, zero and one. This meant that zone three was less likely to have the same mean catch rate at salinity levels less than 10 ppt.

GH results for both cases were compared with another popular MCT method, Bonferroni, which is a test that assumes the comparison groups have equal variances and a similar number of samples in each group. It is also similar to Dunn's test that was used in the TPWD's 1998 analysis of catch rates by salinity zone. Review of the Bonferroni matrix produced the same conclusions as the GH test. For the lower-inflow case, the GH and Bonferroni separation of zones based on significance levels were the same when zones zero and six were excluded due to their low number of samples. For the higher-inflow case, the Bonferroni test identified zone zero as significantly different from zone one at $p<0.05$ while the GH test showed a significance level of $p<0.052$. The differences were minor and it was determined to be consistent with the GH result.

Adult Blue Crab Abundance by Salinity Zone

Thus far, blue crab abundance has been evaluated through CPUE, a catch rate. An alternate method for evaluating abundance is to extrapolate the mean catch rate CPUE into a total number of crabs per salinity zone by applying conversion factors derived from the sampling method. Mean catch rates were converted into a catch per area by using the speed of the trawling vessel, the width of the trawling net, and the length of time that samples were collected on average. As explained earlier, trawling nets 5.7 meters wide were towed for 10 minutes at a speed of 4.8 kph (3 mph), covering a distance of approximately 0.8 km (0.5 mile). Multiplying the trawling net width of 5.7 meters by the distance trawled (0.8km) produced an estimated 0.0046 square kilometers of trawled area per 10-minute sample. After converting mean CPUE (catch per hour) into catch per minute, they were multiplied by the factor 10-min per 0.0046 km^2 to obtain an estimated density in units of catches per square kilometer. This was multiplied by the area of each salinity zone to produce the total number of adult blue crabs in each zone (Tables 17 and 18).

This analysis demonstrated that salinity levels exceeded 20 ppt over approximately 70% of the estuary during lower-inflow years, resulting in a peak abundance area that is 30% smaller than the higher-inflow case. It is unclear how this would impact the ecology or life cycle of the blue crab and deserves additional study as an effect of reduced freshwater inflows.

Table 17. Lower-inflow Adult Blue Crab Abundance by Salinity Zone

Lower-inflow Salinity Zone	Area km^2 (mi^2)	Percent of Total Area	Population Density catch/km^2	Abundance Area x Density
0	4.96 (1.91)	1	30,400	151,000
1	10.65 (4.11)	2	83,900	894,000
2	44.06 (17.01)	9	215,800	9,508,000
3	105.99 (40.92)	21	280,300	29,709,000
4	149.62 (57.77)	29	109,400	16,368,000
5	186.09 (71.85)	37	37,600	6,997,000
6	7.07 (2.73)	1	27,700	196,000

Table 18. Higher-inflow Adult Blue Crab Abundance by Salinity Zone

Lower-inflow Salinity Zone	Area km^2 (mi^2)	Percent of Total Area	Population Density catch/km^2	Abundance Area x Density
0	56. 21 (21.71)	11	134,200	7,543,000
1	90.33 (34.88)	18	235,700	21,291,000
2	104.19 (40.23)	20	175,500	18,285,000
3	105.92 (40.90)	21	151,100	16,005,000
4	109.66 (42.34)	22	54,800	6,009,000
5	41.57 (16.05)	8	40,000	1,663,000

Spatial Evaluation Methods for Juvenile Blue Crab Catch Data

The original TPWD text-based bag seine data were converted into ArcView shapefiles using importing options along with the projection tools available within the Toolbox menu. Habitat types are based primarily on the 1992 National Wetlands Inventory (NWI). NWI submerged vegetation habitats were supplemented with TPWD seagrass data available through the Texas General Land Office (GLO 2004).

Preparation of Habitat Shapefiles

Two shapefiles were generated which separated submerged vegetation and marsh areas from a second group containing bare shoreline, mudflats, and open waters. These general groups were selected to differentiate between several types of habitats that exist in the estuary in relation to what is known about blue crab habits: beach and bare areas, marshes, submerged vegetation, and the open bay (Table 19).

Table 19. Bag Seine Habitat Classifications

Habitat Classifications	NWI Classes	Description
1. Estuarine Emergent Marsh 1 (Brackish Marshes)	E2EM, E2SS	Extreme upper estuary (very low salinity) marshes including emergent marshes and shrub-scrub wetlands
2. Estuarine Emergent Marsh 2 (Saline Marshes)	E2EM, E2SS	Remaining estuary marshes not included in habitat number 1
3. Beaches, Mud Flats, and Uplands	E1UB, E2US, PUB, PUS, M2US, U	Bare unconsolidated shorelines, mud flats and uplands
4. Open Bay	N/A	Beyond 46 meters (150 feet) from the shoreline
5. Submerged Vegetation	E2AB, PAB, LAB	NWI aquatic vegetation groups plus TPWD-based seagrass data

A buffer of 0.5 kilometer (0.25 mile) was created around the estuary shoreline to create a subset of the original NWI habitat type shapefile. NWI classes within the buffered region were then combined and renamed according to the habitat classes (Table 19). Next, a submerged vegetation and marsh shapefile was created and modified to include newer or more detailed seagrass data. First, the NWI aquatic vegetation and marshes habitats were selected from the NWI shapefile and saved to a separate shapefile. Seagrass locations were then combined with the NWI data using an overlay process,

completing the submerged vegetation and marsh habitats shapefile. The remaining habitats were then selected from the NWI file and saved as a separate shapefile.

Preparation of Bag Seine Catch Shapefiles

ArcView's "select-by-location" and "join" commands were used to identify and separate bag seine catch locations according to their distance from habitat locations. Two shapefiles were created that separated catch locations within 46 meters (150 feet) of a habitat type from those beyond 46 meters. To assign a habitat type to each catch location, the join command was used. It spatially related each catch location within 46 meters of the shoreline to the nearest habitat. Catch locations that fell more than 46 meters from the shore were classified as open bay. A few locations were manually associated with a habitat zone since they fell inland of the buffered NWI habitat shapefile. By falling inland of the buffered zone, they were incorrectly assigned to an open bay habitat. Since these locations were more than a quarter-mile inland, these errors could have been the result of field collection or data entry mistakes. Less than five catch locations for each inflow case were misclassified so the corrections were performed manually by consulting the original NWI file, the location coordinates and station identifier, and then editing the attribute table. The final processing step was to export the shapefile attribute tables into spreadsheet-compatible files. These steps were repeated for both inflow categories (tables 20 and 21).

Table 20. Number of Bag Seine Samples by Habitat Type for the Lower-inflow Case

Habitat Type	Number of Samples
Beach/Mud Flats/Uplands	99
Estuarine Marsh 1	18
Estuarine Marsh 2	144
Open Bay	159
Palustrine Marsh	8
Sub. Vegetation	120
Total	548

Table 21. Number of Bag Seine Samples by Habitat Type for the Higher-inflow Case

Habitat Type	Number of Samples
Beach/Mud Flats/Uplands	178
Estuarine Marsh 1	25
Estuarine Marsh 2	229
Open Bay	226
Palustrine Marsh	8
Sub. Vegetation	164
Total	830

Due to a low number of samples associated with palustrine marshes, it was dropped from further statistical analysis. Their locations in the middle and lower parts of the bay made it unclear whether they could be accurately reassigned to the upper estuary's brackish marsh group 1, or the estuarine salt marsh, group 2.

Descriptive Statistics for Bag Seine-collected Data

Descriptive statistics for bag seine catch rates grouped by habitat type are shown in tables 22 and 23. The difference in mean and median values is attributed to a high number of empty catches for both inflow conditions, similar to the adult samples. Mean CPUE's are similar for both cases with the exception of habitat 5, submerged

vegetation, where the higher-inflow catch rate doubled. The higher-inflow case shows more variation in catch rates with higher standard deviation for habitats 3, 4 and 5, which correspond to bare shorelines (beaches, mud flats, and uplands), open bay, and submerged vegetation. Salt marshes, habitat 2, showed a small increase in mean CPUE over the lower-inflow case, and a similar standard deviation.

Table 22. Descriptive Statistics for Bag Seine CPUE by Habitat Type for the Lower-inflow Case

Habitat	N	Mean CPUE	Median CPUE	Std. Deviation	Min.	Max.
1. Brackish Marshes	18	114.81	33.33	230.721	0	800
2. Saline Marshes	144	68.98	0	261.091	0	2900
3. Beach /Flats /Uplands	99	89.23	33.33	170.356	0	1300
4. Open Bay	159	86.37	33.33	200.499	0	1467
5. Submerged Vegetation	120	103.33	33.33	315.767	0	2667
Total	540	86.97	33.33	242.923	0	2900

Table 23. Descriptive Statistics for Bag Seine CPUE by Habitat Type for the Higher-inflow Case

Habitat	N	Mean CPUE	Median CPUE	Std. Deviation	Min.	Max.
1. Brackish Marshes	25	118.67	33.33	226.094	0	800
2. Saline Marshes	229	111.50	0	281.112	0	1967
3. Beach /Flats /Uplands	178	106.93	33.33	323.541	0	3733
4. Open Bay	226	121.39	33.33	382.777	0	3267
5. Submerged Vegetation	164	220.73	33.33	972.213	0	11900
Total	822	135.24	33.33	525.045	0	11900

Juvenile Blue Crab CPUE and Habitat Relationships

QQ plots of untransformed bag seine data revealed non-normal distributions (Figures 24 and 25). Log10 transformations produced reasonably normal distributions (Figures 26 and 27). However, they failed the Shapiro-Wilk test for normality and nonparametric testing did not discern any significant differences between groups. A rank transformation based on normal scores and the Tukey estimation formula produced approximately normal QQ plots (Figures 28 and 29). The five scattered data points on the left sides of these plots correspond to the zero values within the five habitat groups. Kruskal-Wallis analyses of variance on the ranks were performed. The Kruskal-Wallis tests were significant with $p<0.0005$: χ^2 (4,540) = 21.13 for the lower-inflow case, and χ^2 (4,817) = 20.48 for the higher-inflow case. This was followed by a means comparison test using a multiple-stage Kruskal-Wallis test. The purpose of this step was to determine if there was enough evidence to indicate a significant difference between catch rates for the juvenile blue crabs in relation to four different habitat types. The first habitat type (brackish marsh) was dropped due to the low number of samples collected, and also to simplify the means comparison test method by reducing the number of iterations performed.

Several considerations were used to select a nonparametric rank-transformation approach for multiple comparison tests of the bag seine abundance and habitat data. These were: 1) difficulty in finding a transformation that when applied to all groups resulted in a normal distribution that passed tests for normality, 2) the mean did not appear to be a good measure of central tendency, particularly for the salt marsh habitat;

and 3) the inability to achieve other parametric variance assumptions. A successful case might be made for using advanced multivariate parametric tests, such as discriminant analysis or canonical correspondence, based on the large number of samples in each group and an approximately normal transformed distribution. Additional time and study would be required to determine how best to apply them to this data set.

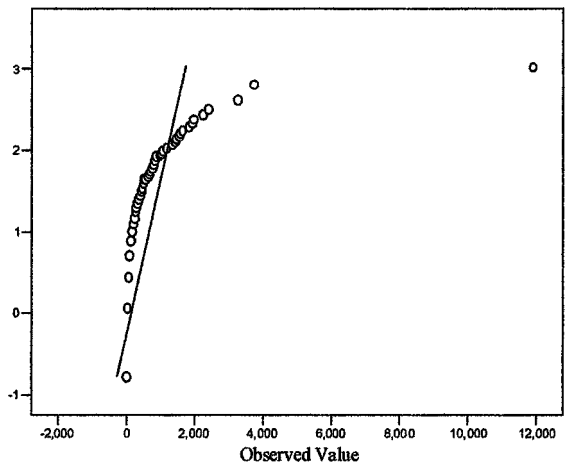


Figure 24. QQ Plot for Bag Seine Data, Lower-inflow Case

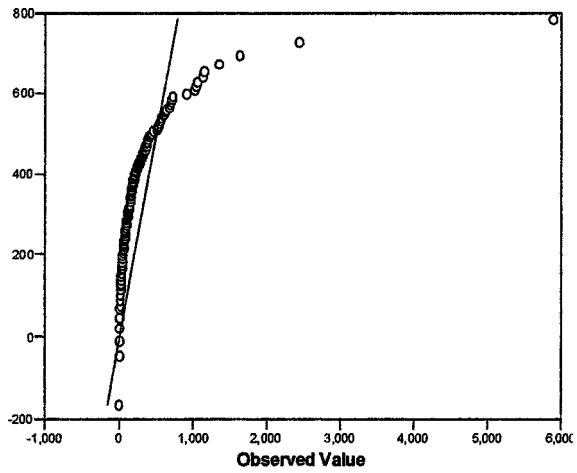


Figure 25. QQ Plot for Bag Seine Data, Higher-inflow Case

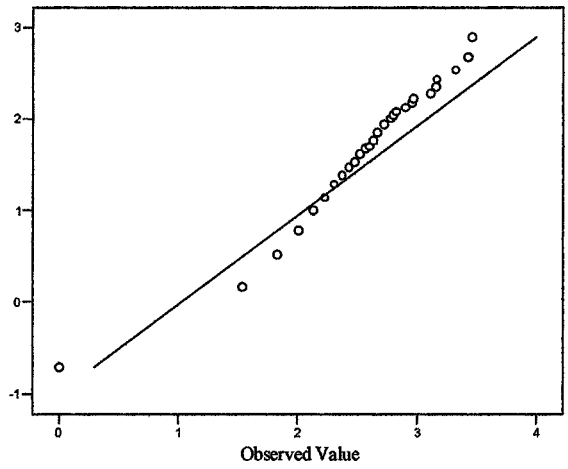


Figure 26. QQ Plot of Log10-Transformed Bag Seine Data, Lower-inflow Case

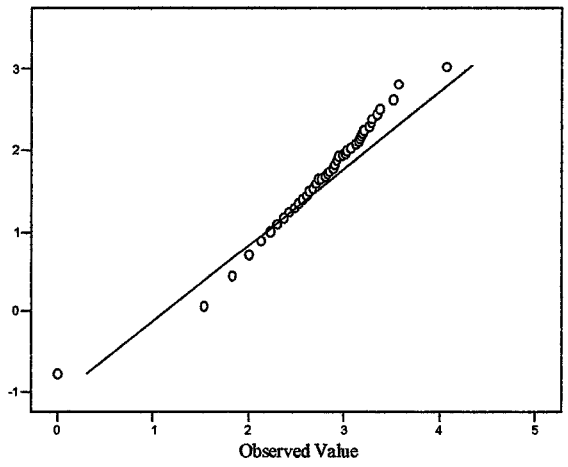


Figure 27. QQ Plot of Log10-Transformed Bag Seine Data, Higher-inflow Case

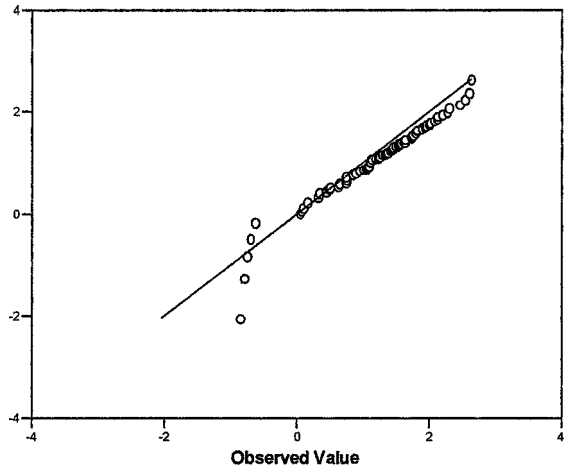


Figure 28. QQ Plot of Normal Scores Rank-Transformed Bag Seine Data, Lower-inflow Case

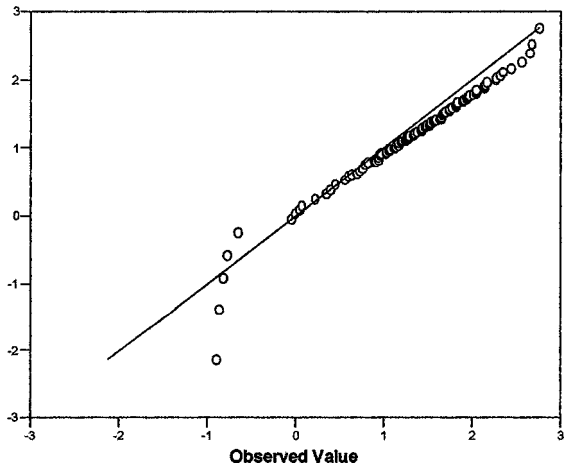


Figure 29. QQ Plot of Normal Scores Rank-Transformed Bag Seine Data, Higher-inflow Case

Juvenile Blue Crab Means Comparison Test

In order to determine which habitat group or groups were significantly different from other habitats, a multiple stage test using the Kruskal-Wallis statistic was employed (Helsel and Hirsch 2002). The first step was to perform a Kruskal-Wallis test for several independent samples with a significance level of 0.05. The independent variables were the CPUE catch rates that were rank-transformed within each habitat group. The dependent variables were the habitat types, 2 through 5. Using output from the test, the four groups (habitats) were ordered, ascending, by their CPUE mean rank. The result was 5, 4, 3, and 2 in ascending order. The next step in the evaluation grouped the three highest mean rank habitats (2, 3, 4), and the three lowest mean rank habitats (3, 4, 5) in order to form two subsets of habitat combinations for comparison. Both lower- and higher-inflow cases produced the same habitat-type combinations up to this point. New Kruskal-Wallis tests were performed and new habitat combinations all produced significant results indicating a difference in means in the habitat subsets. Iterations similar to the previous step were then performed, re-ranking the results from each subset, dropping duplicate comparisons, and followed ultimately by a 2-sample Kruskal-Wallis. The goal of this method was to find differences in the smallest possible subsets of habitat types. The significance levels were adjusted from 0.05 to 0.025 for all 2-sample comparisons in order to control the experiment-wide error rate. This method is explained in more detail in *Statistical Methods in Water Resources* (Helsel and Hirsch 2002). The iterative nature of this method combined with the overlapping habitat variables between subsets, produced duplicate habitat combination

evaluations. For clarity, only significant and non-duplicated test results from the multiple stage Kruskal-Wallis tests are shown in tables 24 and 25.

Table 24. Bag Seine Multiple Stage Kruskal-Wallis Significant Test Results for the Lower-inflow Case

Habitat Combination	Chi-square Test Statistic (df = 1, alpha = 0.025)	Significance
2 vs. 3	6.55	<0.010
2 vs. 4	15.01	<0.0005
2 vs. 5	7.44	<0.006
3 vs. 4	8.72	<0.003
4 vs. 5	10.01	<0.002

Table 25. Bag Seine Multiple Stage Kruskal-Wallis Significant Test Results for the Higher-inflow Case

Habitat Combination	Chi-square Test Statistic (df = 1, alpha = 0.025)	Significance
2 vs. 3	7.76	<0.005
2 vs. 4	14.43	<0.0005
3 vs. 4	12.76	<0.0005
3 vs. 5	9.118	<0.003
4 vs. 5	8.28	<0.004

Lower-inflow Means Comparison

The means comparison results do not reveal whether juvenile blue crabs are more or less likely to be found in one habitat over another, simply that the mean catch rates were determined to be statistically different. Significant differences in the mean catch rates were identified between the salt marsh habitat (2), and the other three habitat types, which are beach/mudflats/uplands (3), open bay (4), and submerged vegetation (5). In addition, significant differences were found between the open bay habitat and the other two shoreline-located habitats 3 and 5.

These results show that strongly significant differences in abundance exist between the open bay habitat and those located closer to shore. Different life stages of the still developing juvenile blue crab may explain this result. Other significant differences were detected between the salt marsh habitat and the other two types of habitat that are close to shore. Although a significant difference was not detected between the submerged vegetation habitat versus the beach and other bare shoreline habitats, the chi-square statistic was just shy of significance at 4.17 (with the critical value being 5.02).

Higher-inflow Means Comparison

Though results for the higher-inflow were similar to the lower-inflow case, there were a couple of differences that needed further examination. Habitats 3 and 5 were detected as significantly different, which did not occur in the lower-inflow case. Examination of the chi-square result revealed that the comparison between habitats 3 and 5 was just short of being significantly different in the lower-inflow case as described above. Another difference between the lower- and higher-inflow means comparison test was that no significant

difference was detected between habitats 2 and 5, whereas a difference was detected in the lower-inflow. Further evaluation revealed a relatively low, but still significant, test statistic of 7.44 for the lower-inflow case and a nearly significant test statistic of 4.65 for the higher-inflow case; the critical statistic being $\chi^2_{0.975,(1)} = 5.02$. Again, both cases were relatively close to the critical statistic and may indicate that the salt marshes (2), and submerged vegetation (5) habitats are relatively similar from the CPUE catch rate perspective. This conclusion seems reasonable since juvenile blue crabs have been reported to utilize both seagrass and salt marsh habitats (Pattillo et al 1997).

CHAPTER 7

CONCLUSIONS

This study analyzed 18-years of coastal fisheries sampling data from the Texas Parks and Wildlife Department in order to evaluate relationships between freshwater inflow conditions and the abundance of blue crabs in the Guadalupe estuary. The results show a significant relationship between a higher abundance of adult blue crabs and specific salinity zones. This is significant because the geographic extents of these zones are affected by the quantity of freshwater inflow into the estuary. This study demonstrated a drop in the mean CPUE catch rates for adult blue crabs when salinity concentrations exceeded 20 ppt. Lower-inflow conditions, when freshwater inflows were near or below the MinQ target, produced large areas of higher salinity in the estuary. This resulted in a compacted region of elevated blue crab abundance located in the middle to upper estuary where salinity concentrations were below 20 ppt. Conversely, a significantly larger portion of the estuary fell below 20 ppt. for the higher-inflow case, which resulted in a preferred salinity region that extended into the lower estuary around parts of Espiritu Santo Bay, Welder Flats WMA, and the Aransas NWR.

Evaluation of salinity surface profiles revealed that the lower-inflow case, which was associated with an inflow target below MinQ, exceeded the 20 ppt salinity threshold in over 70% of the estuary, as compared with just 30% for the higher-inflow case.

Numerous oyster beds which are known to be important as a shelter for blue crabs and also as a food source are also located in the middle estuary and may have contributed to the increased abundance found there. Both inflow cases showed a similar response as salinity levels exceeded 20 ppt and therefore salinity concentration is probably the stronger influence. Further study of oyster bed habitat areas and blue crab abundance could provide a better understanding of this relationship.

The freshwater inflow report that was published in 1998 for the Guadalupe estuary had concluded that peak abundances of adult blue crabs occurs in the 5 to 15 ppt salinity range, which is very similar to the 5 to 20 ppt range established in this study (TPWD1998). At that time a comparison of salinity surface profiles for a less-than-MinQ case had not been performed and therefore, the spatial differences in abundance demonstrated in this study were not observed. The January through June critical growth season, which corresponds to the months of the year when blue crabs were most abundant in the estuary, was identical with results from the 1998 study. And while the earlier study used the critical growth season as the critical inflow period, this study showed that inflows occurring early in the growth season, plus one-month prior, were the most statistically significant. Inflows during the last month of the critical growth season were shown to be less significant.

The juvenile critical growth season, March through July, was found to be slightly different than the adult season, January through June. The two peak abundance periods overlap, however the shape of each distribution is very different. Adult blue crab CPUE catch rates gradually increase toward a March peak and then decrease over several months to the lowest abundance months of August, September and October. Juvenile

blue crabs, on the other hand, appear in great numbers during March and April, with a smaller secondary peak during May, June and July.

Estuary-wide mean and median CPUEs for adult blue crabs were nearly identical for both inflow cases, however, the geographic distributions were significantly different between the two cases. This study showed that in addition to a preferred salinity zone of less than 20 ppt for adult blue crabs, fewer large catches were located along the shoreline in the lower parts of the estuary, some of which border the Aransas NWR and other marsh regions where whooping cranes have been observed to feed. These results suggest that it is important that estuary modeling include a geographic component for the maintenance of salinity zones as an addition to current methods that employ estuary-wide harvest levels. The benefits of which would be a larger harvesting region for commercial fishing, and an increase in abundance in the lower estuary, particularly along shorelines that border the NWR and WMA marshes.

Unlike the adult blue crab result, juvenile CPUE catch rates showed an estuary-wide 55% increase for the higher-inflow case. There were very poor statistical relationships between juvenile blue crab abundance and the seven salinity zones used in this study, suggesting a different salinity structure should be used or the presence of other influencing factors of which the major one could be habitat type. The abundance of juvenile blue crabs was therefore evaluated in relation to several different types of estuarine habitats: 1) open water, 2) beach, mudflats and uplands, 3) seagrasses and other submerged vegetation, and 4) salt marshes. Most catch rate increases occurred around two habitat-type locations: the seagrasses and submerged vegetation habitat, and the open bay habitat.

Most of the habitats were found to have at least one significantly different CPUE catch rate when evaluated against other habitat types. Means comparison testing for both inflow cases showed the open bay habitat was significantly different from all other habitats located close to the shoreline. This might be explained by the different life stages of the still developing juvenile blue crab. Two areas known to be utilized by juvenile crabs, salt marshes and areas of submerged vegetation, had mixed results with means comparison testing. The lower inflow case detected a significant difference between the two habitats, while the higher inflow case did not. Both cases were relatively close to the critical statistic for significance, which may indicate the presence of another factor or that the two habitats are relatively similar from a catch rate perspective.

Identification of an adult blue crab lower salinity threshold was problematic due to the low number of samples were collected during lower-inflow years in areas where concentrations were 10 ppt or less. This is likely related to the small estuary region that experienced low salinity when freshwater inflows were low. Only 3% of the estuary study area had salinity concentrations less than 10 ppt under lower-inflow conditions. Increasing the number of samples for these conditions would be challenging since it would require prior anticipation of a lower-inflow season, and modification of the random sampling program to ensure samples were collected in the upper third of the estuary. A lower salinity threshold could be useful for the purpose of predicting spatial behavior in the event of large water releases from upstream dams. The impact on blue crab spatial abundance would be useful information applicable to the maintenance of

protected habitats where blue crabs may be a critical food source, and also for the commercial fishing industry that depends, in part, on blue crab harvests.

From today's water policy and planning perspective, however, the lower salinity threshold is not as immediately useful as the higher salinity threshold because current planning goals are, for the most part, related to the diversion of waters from the basin in order to meet future water demands of the region. Water resource managers require data and tools to evaluate proposed projects and their impact on downstream estuaries, among other places. With the knowledge that adult blue crabs do not thrive under higher levels of salinity, managers can evaluate proposed inflow modifications in order to ensure that salinity levels are kept below 20 ppt in as large an area as possible. This study has shown how geographic analysis, when combined with biological monitoring data and ecological information, can be used to assess changes in the abundance and distribution of estuarine-based species that utilize specific geographic areas as habitat. Further research could be devoted to the spatial evaluation of blue crab abundance as they relate to estuary features such as oyster and seagrass beds, and the design of a sampling program to regularly collect samples in the brackish upper estuary.

APPENDIX

Table A-1. Projection Summary for GIS Layers

Texas State Mapping System (TSMS)	
Spheroid	Clarke GRS 80
Datum	North American Datum of 1983 (NAD93)
Longitude of Origin	100 degrees West (-100)
Latitude of Origin	31 degrees 10 minutes North (31.16_)
Standard Parallel #1	27 degrees 25 minutes North (27.416_)
Standard Parallel #2	34 degrees 55 minutes North (34.916_)
False Easting	1,000,000 meters
False Northing	1,000,000 meters
Units of Measure	Meters

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VITA

Lynne Hamlin, B.S.C.E., graduated from high school in Mesa, Arizona, where she was a competitive swimmer, coach, and lifeguard. After spending three years in central Germany where she and her husband were stationed with the U.S.A.F., she entered Florida International University in Miami, Florida, where she earned her Bachelor of Science degree in Civil Engineering (B.S.C.E.) focusing on water resources and transportation. While at the university, she interned with the Florida Everglades National Park Research Center where she assisted with the development of a hydrologic model by collecting field data, performing statistical analyses, and developing hydrologic maps. During the following seven years she was employed with the state of Texas as a transportation planner and environmental modeler. In her final position as an urban airshed modeling specialist, she designed and implemented projects that utilized geographic information systems (GIS) to study transportation-based emissions. She lives on a ranch south of Austin, Texas, with her husband Dave, a pilot with Delta Air Lines. In January 2000, she entered the Graduate College of Texas State University-San Marcos where she continued her studies in the fields of environmental planning and GIS within the Geography Department.

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