Review of the Biology and Population Dynamics of the Blue Crab, *Callinectes sapidus,* in Relation to Salinity and Freshwater Inflow

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Task I

Reproductive Biology and Population Dynamics of the Blue Crab *Callinectes sapidus*

The blue crab, *Callinectes sapidus,* is an ecologically and economically important component of tropical, subtropical, and temperate ecosystems. The range of the blue crab is broad, extending from Argentina in the southern hemisphere to Massachusetts in the northern hemisphere. Blue crab occurrences in Nova Scotia, Denmark, Northern Adriatic, the Black and Mediterranean seas, and central Japan (Norse 1977, Williams 1974) have also been reported. Blue crabs are fundamental components of estuarine food webs, functioning as both predator and prey. The blue crab's role as predator is arguably, one of the most important biotic determinants of community structure in estuarine ecosystems (Mansour 1992, Guillory 2001 (b)).

Habitat selection of the blue crab is dependent on the particular physiological requirements of each life history state in its complex life cycle (Guillory et al. 2001 (a), Perry 1984). Blue crabs are present in planktonic, nektonic, and benthic stages, in habitats ranging from offshore to near-shore estuarine phases (Guillory et. al 2001 (a)). One of the most important habitats are the low salinity river and estuarine systems where mating occurs (Guillory et al. 2001 (a)).

Throughout the months of March to November, in the Gulf of Mexico (Johnson 1999), immature females who have not reached their pubertal molt, seek out low salinity estuaries (<15 ppt) with high densities of mature males for mating (Guillory et al. 2001 (a)). While in the brackish waters of the upper estuary the juvenile females will molt and subsequently mate (Johnson 1999). Following successful mating, the interval between mating and egg extrusion varies between two and nine months. When mating occurs in the spring and summer a two month interval is common. However, blue crabs that mate during fall and winter spawn during the following spring or when water temperatures rise to about 19ºC (Steele 1982). Year round spawning of Florida blue crab has been recorded with specific peaks in spring and fall. Mature mated female blue crabs are catadromous, migrating from hyposaline waters <30 ppt to higher salinity water in the lower estuary and offshore to spawn (Hines et al. 1987, Steele and Bert 1994). During the ebb tide females will take advantage of the outgoing waters and make their way out of the estuary within the spring, summer, and fall months (Perry and Stuck 1981, Steele and Perry 1990, Johnson 1999).

The movement of ovigerous females has been documented both out of estuaries and along the coast of Florida. In a 1989 tagging study, Steele, observed a single–gender specific migration North of Tampa Bay along the coast (Steele 1991). These findings are similar to studies of coastal areas south of the Apalachicola River conducted by Oesterling and Evink (1977). Originally, Oesterling (1976) hypothesized that females engaged in a mass migration to reach spawning grounds south of the Apalachicola River. This hypothesis presented a scenario where the low salinity flow from the Apalachicola River would transport larvae offshore to the Loop Current for redistribution of immature crabs to south Florida estuaries. Over turning this hypothesis was the documentation that newly hatched larvae require salinities in excess of 22 ppt (Costlow and Bookhout 1959, Sulkin and Epifanio 1975). Results of the 1989 Steel tagging study suggested the reduced salinity from the outflow of the Apalachicola River at Apalachee Bay acts as a freshwater barrier to the migrating females, preventing westward emigration rather than an offshore transport mechanism for larvae (Steele 1991).

The occurrence of female migration is not unique to the western coast of Florida. In northeastern Florida, mature females in the St. John’s River were tagged and their location documented upon capture. Their gradual movement out to sea was evidenced by collection throughout the spring and early summer months in which 96% of females were obtained downstream of the release point (Tagatz 1968). In addition, the highest abundance of egg bearing females was captured in July through September at distances of 5-6 km offshore of the river mouth (Tagatz 1968).

During the summer and fall months the arrival of a mature, mated and egg bearing females in the high salinity waters (>30 ppt) of the lower estuary stimulates the larvae of mature egg masses to hatch (Gunter 1950, Daugherty 1952, More 1969, Perry 1975, Tankersley 2002). Hatching occurs during ebbs tides, allowing larvae to be swept seaward (Epifanio et al. 1989, Tankersley 2002). Newly hatched larvae are transported from the lower estuary to offshore waters via surface currents (Johnson 1999).

Laboratory test have determined that while offshore, the larvae will complete seven zoeal life stages over approximately 30-50 days (Costlow and Bookhout 1959). Subsequently, the final zoeal larval stage metamorphoses to the megalopae stage which lasts from 6-20 days (Costlow and Bookhout 1959). Movement of megalopae back into the estuary is dependent on a variety of physiographic parameters, salinity regimes, tidal periodicity, long-term water level cycles, wind regimes, and coastal currents (Rabalais 1995, Guillory 2000). These physical factors or forces have been shown to affect the harvest of adult blue crabs in subsequent years (Johnson 1999, Heck et al. 2001). Megalopae are able to attain up-estuary transport through tidally-related vertical migration, also known as Flood Tide Transport (Tankersley 2002, Rablais 1995, Olmi 1994, 1995). This migration allows for up-estuary movement using tidal flood currents for settlement in shallow nearshore areas that are crucial for food and refuge from predators (King 1971, More 1969, Perry 1975, Perry and Stuck 1982, Johnson 1999, Heck et al. 2001).

Depending on the strength and timing of physical forces, the megalopae will be transported various distances into the estuary. This reinvasion of the estuaries occurs from March to November, with highest abundances in the late summer and early fall (Heck et al. 2001). The primary habitats where settlement and metamorphosis into first crab stage (approximately 2-3 mm in size) occurs are marshes and seagrass beds (Tagatz 1968). In fact, 90% of juveniles in any given area occur in seagrasses or marshes (Orth et al. 1990, Heck et al. 2001, Perry 1975), and up to 95% are less than 25 mm (Heck et al. 2001, Perry 1975). The highest abundances of juveniles occur in beds of submerged aquatic vegetation (SAV) which includes *Zostera marina, Ruppia maritime* and *Halodule wrightii* marshes. These appear to be the primary nursery habitats for the earliest juvenile instars. The occurrences of juveniles in sites with SAV are as much as five times higher than marsh sites containing *Spartina alterniflora* (Murphy et al. 2007, Heck et al. 2001, Moksnes and Heck 2006). In juvenile abundance studies performed by Heck et al. (2001) in the northern Gulf of Mexico the greatest abundance of early juveniles collected were in the lower bay sites with an average salinity of 23 ppt. Based on the increasing densities of larger juveniles in lower salinity waters, the data suggests movement up the bay toward lower-salinity waters into oligohaline marshes and SAV beds (Heck et al. 2001, Orth and van Montfrans 1987, Thomas et al. 1990, Williams et al. 1990). In general, juvenile distribution occurs over a broad salinity range, often times based on estuary location in the Gulf of Mexico. From Guillory et al. (2001 (a)):

> *Although juvenile crabs occur over a broad salinity range, they are most abundant in low to intermediate salinities characteristic of middle and upper estuarine waters. Daud (1979) found early crab stages (5-10 mm) in shallow brackish/saline waters and observed movement into fresher waters in larger juveniles. Swingle (1971), Perret et al. (1971), Christmas and Langley (1973), and Perry and Stuck (1982) determined the distribution of blue crabs (primarily*

juveniles) by temperature and salinity using temperature-salinity matrices (Table 3.1) [Table 1 in this review]. *Both Perret el al. (1971) and Swingle (1971) found maximum abundance in salinities below 5.0‰. In contrast, Christmas and Langley (1973) and Perry and Stuck (1982) found highest average catches associated with salinities above 14.9‰ in Mississippi. Based on one year of bag seine data, Hammerschmidt (1982) found no direct relationship between catches of juvenile crabs and salinity in Texas. Walther (1989) examined the relationship between recruitment of juvenile blue crabs (as measured by catch per unit of effort in 16 ft trawl samples) in Barataria Bay, Louisiana and salinity. He found a significant negative relationship between February-May blue crab catch per unit effort and salinity for the same time period ($R^2=0.80$). Although salinity influences distribution, factors such as bottom type, food availability and competition also play a role in determining distributional patters of juvenile blue crabs.*

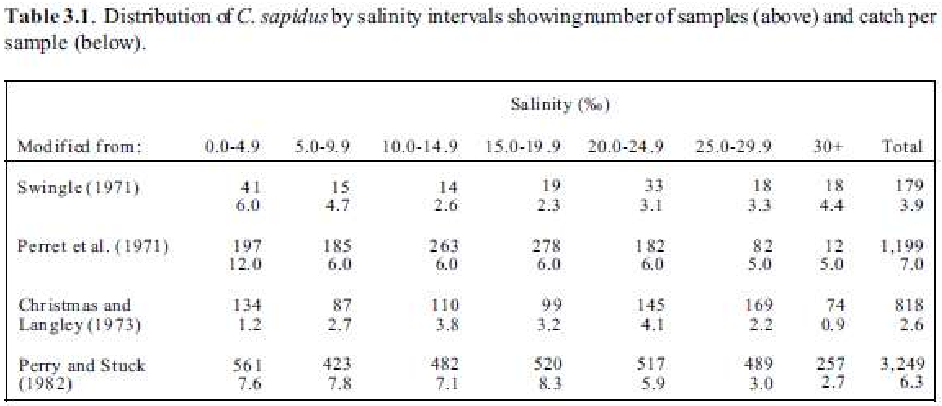

Table 3.1. Distribution of *C. sapidus* by salinity intervals showing number of samples (above) and catch per sample (below).

	Salinity (‰)							
Modified from:	0.0-4.9	5.0-9.9	10.0-14.9	15.0-19.9	20.0-24.9	25.0-29.9	30+	Total
Swingle (1971)	41 6.0	15 4.7	14 2.6	19 2.3	33 3.1	18 3.3	18 4.4	179 3.9
Perret et al. (1971)	197 12.0	185 6.0	263 6.0	278 6.0	182 6.0	82 5.0	12 5.0	1,199 7.0
Christmas and Langley (1973)	134 1.2	87 2.7	110 3.8	99 3.2	145 4.1	169 2.2	74 0.9	818 2.6
Perry and Stuck (1982)	561 7.6	423 7.8	482 7.1	520 8.3	517 5.9	489 3.0	257 2.7	3,249 6.3

Table 1. Juvenile Blue Crab Temperature-Salinity Matrices. (Reproduced from Guillory et al. 2001 (a)).

Habitat partitioning by juveniles is evident in many estuarine systems throughout the Gulf of Mexico. Seasonally, males and females will be distributed with respect to salinity and sex (Guillory et al. 2001 (a)). In Tampa Bay males are most abundant in the upper bay. Steele and Bert (1994) noted that the percentage of males is inversely related to the annual mean salinity.

These findings are consistent with studies in the St. John's River, Chesapeake Bay, and Louisiana coasts where male abundance is typically highest in the upper bay where lower-salinity regions occur (Tagatz 1968, Jaworski 1972, Hines et al. 1987).

Blue crabs utilize all salinity regimes of an estuary in order to complete their life cycle (Guillory et al. 2001 (a)). Therefore, the alteration of any one of these habitats may affect the blue crab populations. This includes habitat and hydrological changes that are prevalent in Florida and other Gulf coastal states (Guillory et al. 2001 (a)). From Guillory et al. (2001 (a)):

> *Low salinity marsh is an important nursery habitat for juvenile blue crabs and increased salinity may adversely impact the species (Rounsefell 1964). Marsh management by means of levees and weir, or other water control structures, is usually detrimental to fisheries in the short term because of interference with migratory cycles of estuarine dependent species (Herke 1979, Herke et al 1987, Herke and Rogers 1989).*

Disruption of estuarine salinity gradients associated with physical alterations may have adverse effects on blue crab populations (Guillory et al. 2001 (a)). In addition to physical alterations the change in freshwater inflow may have similar effects. From Guillory et al. (2001 (a)):

> *Changes in the amount and timing of freshwater inflow may have a major effect on the segment of the blue crab life cycle taking place in the estuary. Wetlands are maintained by rivers that transport sediment and nutrients. Reduction in freshwater inflow denies the nutrients to wetlands that are necessary for healthy growth. Activities affecting freshwater inflow include leveeing of rivers (eliminating overflow into surrounding marshes), damming of rivers, channelization, and pumping water for redistribution.*

Freshwater inflow also has significant affects on the disease prevalence associated with blue crabs and other crustaceans. In 2002, the blue crab fishery in Georgia suffered a dramatic crash in blue crab population abundance (Lee and Frischer 2004). This crash was caused by an outbreak of the parasitic dinoflagellate *Hematodinium* sp. *Hematodinium* is closely related to two other toxic dinoflagellates: *Gymnodinum brevis*, which causes red tide algal blooms; and the fish-killing *Phiesteria piscicida*. In 2002, Georgia experienced a drought that caused the average water temperature and salinity in several estuaries to increase to high levels (> 28 °C and > 30 ppt, respectively) (Lee and Frischer 2004). Laboratory studies conducted by Messick et al. (1999) suggest that salinity and temperature may strongly influence the presence and concentration of *Hematodinium*. Research conducted on populations of wild blue crab points to large catches being positively correlated with high river flow, suggesting that the availability of fresh water was beneficial to the health of the crab population (Sheppard et al. 2003).

Task II

Summary of Technical Literature Documenting Correlations of Blue Crab Abundance with Freshwater Inflow

Research into the relationship between freshwater inflow and blue crab abundance has attracted significant attention over the past two decades. The growing thirst of burgeoning human populations in the watersheds around the Gulf of Mexico has spurred numerous jurisdictional and legal battles over water rights. Various water management strategies have been developed to balance the needs of municipalities, agriculture, industry and fisheries resources of the region. Baseline research on the freshwater inflow requirements of estuarine ecosystems from Texas through Florida has been performed to varying degrees. Statistically significant correlations between freshwater inflow, blue crab abundance and commercial blue crab landings have been documented in the blue crab fisheries of Florida and adjoining states.

A review of key publications from adjoining Gulf of Mexico and southeastern US states revealed many statistically positive, negative and mixed correlations between freshwater inflow and blue crab abundance. In general, studies showing positive associations used long term life history based lagged inflow regressions applied over large regional data sets to identify significant associations. Negative associations were commonly generated from short term life history based lagged inflow regressions applied to data collected within an individual river. The studies presented in this review, include regional state-level investigations focusing on the broad contribution of freshwater inflow to blue crab abundance. The discussion of regional state-based studies is followed by summaries of a series of investigations specifically focused on the southwest region of Florida. Significantly different conclusions may be drawn from the different types of studies presented in this review. The intent of this report section is to compile the major findings of relationships between blue crabs and freshwater inflow, within Florida and the southeastern region, to help refine future investigations of this subject in Florida.

Specific studies of note finding significant relationships between freshwater inflow and blue crab abundance

Texas (Longley 1994, Hamlin 2005)

Over the past 30 years the demand on the freshwater resources of Texas has increased due to growing industry and population. A resource-based approach was employed to determine the freshwater inflow requirements of estuarine ecosystems and the associated fisheries of Texas bay systems. In 1994, Longley published a landmark document that provided the foundation for resource based water management of Texas bays and estuaries. Subsequent Texas publications used this resource based methodology to link beneficial fresh water inflows to fishery resources, defined by their commercial importance (Pulich et al. 1998, 2002, TPWD 2005). These baseline studies allowed for the modeling of freshwater inflow using the Texas Estuarine Mathematical Program (TxEMP) model (Matsumoto 1994) and resulted in minimum flows (MinQ) and maximum flows (MaxH) for Texas bay systems. These benchmark flow rates were based on maintaining the abundance of commercially important species within 80% of their mean historic levels (Hamlin 2005). Full descriptions of the functionality of the model can be found in Powel et al. (2002). The MinQ is defined as the minimum flow necessary for maintaining abundances and MaxH is defined as the inflow necessary to maximize the abundance of commercially important indicator species. Seven commercially important target species were used as indicators for management. Blue crabs were identified in the target species list due to the documentation of their population responding directly to freshwater inflows. Inflow hydrology is essential in understanding blue crab population dynamics (Longley 1994, Hamlin 2005).

The Texas legislature defined "beneficial inflows" with the Texas water code 11.147a for economically important estuarine species as:

> *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 and ecologically characteristic sport or commercial fish and shellfish species and estuarine life upon which such fish and shellfish are dependent* (Texas water code 11.147a in Hamlin 2005).

A full review of the development of Texas inflow water management policy to 2005 can be found in Hamlin (2005). Freshwater inflow management recommendations for other Texas estuaries are outlined in several reports, including those published on the Guadalupe River (Pulich et al. 1998), Nueces Bay (Pulich et al. 2002), Sabine Lake (TPWD 2005), and Matagorda Bay (Bio-West 2008). Two studies that provide a clear description of linkages between freshwater inflow, habitat, salinity and blue crab abundance on the Texas coast are Longley (1994) and Hamlin (2005), and are summarized for this review of relationships between blue crab abundance and inflows.

Longley (1994) utilized historical commercial harvest data and state fishery independent monitoring data (trawl and bag seine) from the Texas Parks and Wildlife (TPWD) to correlate inflow and bay system salinity records with specie abundance data of seven economically important estuarine dependent species. Adjustments were made to account for the environmental effects on growth and survival of crabs up to commercially exploitable size by using lagged freshwater inflows based on blue crab life history information. Regression analyses based on lagged inflows of one year and crab landings data indicated higher blue crab catches were associated with low salinity areas. Analysis of trawl data indicated that higher blue crab catches were associated with lower salinities (<22 $^{0}/_{00}$). Habitat use data suggested that blue crab densities were lowest in oligohaline areas and highest in mesohaline and polyhaline areas. Blue crabs were most abundant in trawl catches from areas where salinities ranged from 6 to 15 $^{0}/_{00}$. Juvenile blue crabs were most abundant in the vegetated habitats in the lower to mid estuary in salinity zones of 6 to 25 $^{0}/_{00}$ and avoided delta areas when freshwater inflow was excessive. Based on these and other findings included in their report, Longley (1994) recommend consideration of various life history requirements for multiple species when developing freshwater inflow management recommendations.

Research by Hamlin (2005) specifically focused on refining our understanding of the effect of freshwater inflow on juvenile and adult blue crab abundances in different salinity zones and habitat types within the Guadalupe estuary, Texas. This study used biological and ecological data to track changes in abundance and distribution over specific estuarine habitats. Statistical analysis of historic inflow, salinity, trawl and bag seine data were combined with geographic information system (GIS) technology to evaluate the population dynamics of the estuary from 1982-1999. Hamlin compared freshwater inflow (MinQ and MaxH) to juvenile and adult abundance based on GIS mapped salinity zone and habitat type to determine inflow effects based on these variables. Results of this work corroborate the findings of Longley (1994) and Pulich et al. (1998), where peak adult blue crab abundance occurred in salinities ranging from 5-15 $^{0}/_{00}$. This study found significant relationships between adult blue crab abundance and salinity zone. Hamlin reports that that adult catch per unit effort (CPUE) was significantly reduced when inflow was near MinQ freshwater inflow and salinity exceeded 20 $^{0}/_{00}$. Additionally, MinQ freshwater inflow was shown to be associated with spatially compact regions of elevated blue crab abundance located in the middle of the upper estuary where the salinity was <20 $^{0}/_{00}$.

During the study period, adverse salinity zones ($>20^{0}/_{00}$) for adults were found to extend over 70% of the bay estuary during Min Q flow and were limited to 30% of the bay estuarine habitat during MaxH inflow.

Hamlin further refined the work of Pulich et al. (1998) by using the critical growth season (January –June) as the critical inflow period for adults and demonstrated that inflow one month prior and continued through the early growth season (Dec – March) was the most statistically significant contributor to adult blue crab abundance. Investigation by this author into the juvenile critical growth season (March- July) found a significantly different season than the adult critical growth season (January – June). Results of this study indicated that the juvenile life stage demonstrated and estuary wide 55% increase in abundance during higher inflow cases. The author found increases in juvenile abundance were poorly correlated with salinity zone; however when the author used habitat types as a factor (seagrass and submerged aquatic vegetation in open bay) a significant increase in juvenile CPUE was found. The author suggests that future research should be devoted to spatial evaluation of blue crab abundance as it relates to estuarine bay features such as oyster and seagrass beds and design a sampling program to collect from brackish ($<20\ ^{0}/_{00}$) upper bay areas.

In Texas, populations of the endangered whooping crane reside in the Aransas National Wildlife Refuge. Research into habitat and diet reveal that two factors (freshwater inflow and blue crabs) are essential to their continued persistence in the refuge. Stehn (2008) suggests reductions in freshwater inflow are a major threat to whooping crane survival. Blue crabs are described to account for 80% of the diet and represent a significant portion of the dietary protein of cranes. Stehn suggests reduced freshwater inflow lowers blue crab populations resulting in a negative effect on the whooping crane population. Stehn (2008) associates the low blue crab production in the winter of 1993-1994 with lower fat reserves in cranes that caused a 37% reduction in crane nesting success the following spring. A larger investigation, commonly referred to as the 2009 SAGES report (Slack et al. 2009) also links freshwater inflow and whooping crane success in the Aransas National Wildlife Refuge. The section of the SAGES report on blue crabs has a flawed research design, limited use of key regional research and a lack of understanding of blue crab life history that result in faulty conclusions concerning blue crab abundance and fresh water inflow. A letter to the San Antonio River Authority (Blackburn 2009) sufficiently exposed these flaws and refuted their findings relating to freshwater inflow and blue crab abundance in the Aransas National Wildlife Refuge. This controversy aside, the SAGES study found the dominant food of cranes to be blue crabs and wolfberries. The abundance of these high energy food items is significantly affected by freshwater inflow, bay salinity, tides, and temperature (Slack et al. 2009).

Louisiana (Guillory 2000)

The loss of wetlands and the management of freshwater inflow to support wetland restoration prompted Louisiana to investigate correlations between river discharge and blue crab abundance. In 2000, Guillory investigated this relationship by utilizing data from long term (30 year) juvenile recruitment studies, commercial harvests and river monitoring stations where monthly mean discharge and salinity records were available. River discharge rates and salinity were correlated using a Pearson’s correlation for time frames of known blue crab life history parameters. Life history time frames for the blue crab were used to calculate the lag times for the associations (6 mo. for juveniles <40mm and 12 months for harvestable adults >127mm). This author found positive correlations between recruitment and monthly mean lagged late summer/early fall river discharge and negative correlations with salinity. Additionally, this author found a positive correlation of commercial harvest with unlagged river discharge and a negative correlation with salinity. Guillory (2000) specifically noted:

> *The reported correlations between blue crab recruitment or harvest and river discharge or salinity do not necessarily imply causality. The potential effects of environmental factors on the blue crab population size may be synergistic, intrinsic (physiological), or extrinsic (ecological) (Perry et al., 1984).*

While acknowledging that environmental factors associated with the inflow can influence the estuarine environment; this author chooses to focus on the effect of predation on juvenile crab populations. Guillory postulates that an effect of reduced salinities is the displacement of some marine fish predators such as red drum (*Sciaenops ocellatus*) that subsequently reduces predation on young crabs. Regardless of the causal mechanism(s) at play the author further suggests that reductions in salinity through freshwater diversion of the Mississippi river would be beneficial to the blue crab resource.

Georgia (Rogers et al. 1990)

A study was undertaken by Rogers et al. (1990) to investigate the effect of habitat management on the blue crab fishery. Georgia’s commercial fishing interests suggested that declines in landings observed from 1984 through 1987 were due to changes in the magnitude and timing of freshwater inflow by estuarine managers. Low landings during periods of “near record levels of nominal fishing effort” were cited by crab fishers as the indicator of this relationship. Data sets from fisheries independent monitoring (1974-1990), commercial blue crab landings (1950-1990), estuarine water quality and inflow from various sources from 1950-1990 were correlated using time structured blue crab life history parameters. Specifically, these researchers focused on the relationship between annual harvest and cumulative discharge from five rivers in Georgia and from rivers in the bordering states of Florida and South Carolina.

A range of 15 to 30+ year inflows were compared for the annual nine-month period of influence (September through May) on recruiting juvenile "young of the year" crabs. Few significant relationships were noted and those that were documented were not consistent among estuaries (e.g., annual harvest increased with increasing discharge in the Savannah River and decreasing discharge in the Satilla River) or were not observed for the entire time period examined (Alber and Flory 2002). Rogers et al. (1990) note that modeling the effect of freshwater inflow on blue crab populations should not be based on a single model for the region. They suggest the utility of a series of sub-models for the Georgia fishery. Additionally, they raise a number of issues concerning use of commercial landings as an indicator of abundance. For example, markets (pricing and availability) driving the commercial effort and resulting in periods of reduced landings could bias commercial landings data. Additionally, Rogers et al. note that regional crabs stocks in the late 1980s were 'fished down' to a level where they may have been supported by a single year class, resulting in populations more vulnerable to environmental fluctuations.

The Georgia blue crab fishery continued to decline into the early part of the current century. In 2003, landings were down by 80% as compared to historic averages (GEPD 2003). The cause of the decline was postulated to be due to severe regional drought and increased coastal salinities that allowed a parasitic infection of *Hematodinium* to overtake the population (GEPD 2003). The Georgia fishery was declared a fishery disaster in 2003 by the National Marine Fisheries Service due to drought and disease (GEPD 2003). The Georgia fishery illustrates how a severe drought can affect blue crab populations. Although this was a natural disaster due to drought and disease; one cannot overemphasize how essential the freshwater refuges (salinities <10 $^{0}/_{00}$) become for blue crabs during drought. These refuges provide regions where crabs can reduce the severity of these infections and survive to repopulate the fishery when freshwater inflow returns and high salinity abates.

Florida (Wilbur 1992 and 1994)

Wilbur (1992, 1994) documented the historical regional influence of Apalachicola, Suwannee, Ecofina, St. Marks and Ochlokonee river flows on the estuarine productivity of oysters and blue crab in northern Florida. In a paper published in 1994, Wilbur focused on blue crabs using the methods of Funicelli (1984), who correlated historical freshwater inflow in Texas to commercial landing of estuarine dependent species. For the study, Wilbur correlated 38 years of commercial landings to flows from the Apalachicola, Suwannee, Ecofina, St. Marks and Ochlokonee river systems. Flow parameters investigated for the study included 7 to 120 day maximum and minimum flows, monthly minimum, mean and maximums as well as mean monthly flows during critical blue crab growout periods developed from the Georgia freshwater inflow studies of Rogers et al. (1990). Regression and time series analysis of the inflow and commercial landing data for critical growout periods was used to demonstrate significant long term spatial and temporal relationships between flows and crab productivity. Wilbur (1994) positively correlated one year lagged historical (1952-90) Apalachicola River flows to Franklin County blue crab landings ($r^2=0.32$, $p<0.001$). The author further strengthened the correlation using only the most recent years of this data (1973-90) ($r^2=0.49$, $p=0.001$). Apalachicola River flows and Wakulla County blue crab landings were also correlated, using a one-year time lag ($r^2=0.52$, $p=0.001$). The extent of influence of the Apalachicola inflow beyond the northwest

Florida region was investigated by repeating the analysis on blue crab landings for other portions of the west coast, but no statistically significant associations were identified.

The 1994 Wilbur study suggests that the reduction in estuarine salinities from increased freshwater inflow increased the area of suitable habitat in the middle and perhaps lower estuary, where juvenile blue crabs can forage and develop (Livingston et al. 1976, Perry 1984 as cited by Wilbur 1994). These findings are similar to the aforementioned Texas studies with similar conclusions highlighting the benefit of large areas of water with salinity <20 $^{0}/_{00}$ occurring over adequate estuarine habitat during critical growout periods (Longley 1994, Pulich et al.1998, Hamlin 2005).

Wilbur (1994) notes that although salinity may be a good indicator of freshwater inflow to estuaries it may not be the sole contributor to changes in crab abundance. Inflows import more nutrient energy to the system resulting in enhanced food availability (Mattraw and Elder 1982). Wilbur suggests food availability may limit blue crab production at flows below a certain level but may not be limiting at flows above this level. The assertion is supported by the findings of Wilbur (1992), who report that moderate Apalachicola River flow, below 600 m^3/sec, were most closely related to commercial crab landing in Franklin and Wakulla counties. Other authors have suggested that food resource limitation at low flows increases cannibalism (Lipcius and Van Engel 1990) and predation (Guillory 2000, Guillory and Elliot 2001) by more saline tolerant predatory fish, including *Sciaenops ocellatus*.

Southwest Florida Studies

A series of studies, funded by the Southwest Florida Water Management District (SWFWMD) and the South Florida Water Management District (SFWMD), focused on habitat usage, patterns of seasonal abundance and assessment of the effect of freshwater inflows on fish and invertebrate communities within tidal river systems in the southwest region of Florida (Table 2). The river systems investigated vary from relatively short spring fed rivers in the north (Weeki Wachee through Chassahowitzka in Table 2) to longer rivers that drain large watersheds in the south (Alafia through Caloosahatchee in Table 2). The studies were implemented to support establishment of minimum flows and levels and develop methods for assaying the effects of management strategies on river biota.

System	Publication	Study Period
Weeki Wachee River	Matheson et al. (2005a)	1 year 8 months
Homosassa River	Peebles et al. (2009)	2 years
Chassahowitzka River	Greenwood et al. (2008)	2 years
Anclote River	Greenwood et al. (2006)	1 year
Hillsborough River	Mac Donald et al. (2006)	4 years 9 months
Tampa Bypass Canal	Peebles (2004)	6 years
Alafia	Peebles (2002 a) Matheson et al. (2005b)	3 years 7 years
Little Manatee River	Mac Donald et al. (2007) Peebles and Flannery (1992) Peebles (2008)	10 years 2 years (fish nursery use) 2 years (new analysis)
Manatee River and Gamble Creek	Greenwood et al. (2007)	10 years
Dona and Roberts Bay	Peebles et al. (2006a)	1 year 2 months
Myakka River and Myakkahatchee Creek	Peebles et al. (2006b)	1 year 8 months
Peace River and Shell Creek	Peebles (2002b) Greenwood et al. (2004)	2 years 2 months 8 years
Caloosahatchee *	Stevens et al. (2008a)	4 year
Estero Bay *	Stevens (2008b)	3 year

* South Florida Water Management District

Table 2. Studies of the Effects Freshwater Inflow on Fish and Invertebrate Communities of Coastal River Systems in the Southwest and South Florida Water Management Districts

The studies were based on long (>2 year) and short term (<2 year) sampling completed by the Florida Fish and Wildlife-Fisheries Independent Monitoring program (FWC-FIM) and the University of South Florida College of Marine Science. Stratified random sampling using trawls, seines and plankton tows was employed for most of the investigations. Sampling gear deployed in these studies were standardized for type, size and the duration deployed for defined river regions. Fish and invertebrate abundance and distribution data derived from the trawl, seine and plankton samples were regressed against a broad range of lagged inflows (one day up to 360 days) to investigate relationships between abundances and freshwater inflows.

Results from these studies suggest blue crab abundance response to freshwater inflow varies substantially between river systems of the region. A systematic review of major findings from each study follows with presentations based on a progression from the most northern (Weeki Wachee River) to the most southern (Estero Bay) system. In studies where the authors focused specifically on blue crabs, a review of their findings is presented without associated statistical values. For studies where no specific focus on blue crabs is presented, a review of the tables in their appendices is presented along with summaries related to the statistical significance of the originally reported relationships between inflows and crab abundances.

Weeki Wachee River (Matheson et al. 2005(a))

Matheson et al. (2005a) describe the Weeki Wachee River estuary as a short (12 km) spring-fed river with high water clarity and low organic load. They note that these characteristics result in fish and invertebrate abundance/inflow relationships which significantly differ from other southwest Florida tidal rivers. The conclusions of this study are focused on the overall species structure of the system, their collective response to freshwater inflow and the development of predictive regressions for individual taxa responses to inflow.

Matheson et al. suggest that changes in inflow from June to November would have the greatest potential negative effects on the majority of species collected from the river. Blue crabs were found to be concentrated in the river from late summer/early fall through spring. No specific description of the response of the blue crab to freshwater inflow is provided by Matheson and his colleagues.

Review of the salinity and lag inflows figures presented in the appendix of the Weeki Wachee River report was necessary for investigation of blue crab responses to inflows. The highest geometric mean abundance for blue crabs occurred in low mesohaline to oligohaline zones. Figures in the appendix of the report also indicate a quadratic response was observed for abundance of blue crab (≤35 mm when seine samples were compared with 77 day lagged inflows. Maximum Catch per Unit Effort (CPUE) of blue crab (≤35 mm) occurred in the mid-inflow range and minimum CUPE at low and high inflows ($p = 0.001$, $r^2 = .51$). The inverse appears to be true for abundances based on blue crab (>36 mm) trawl samples regressed against a 336 day lagged inflow. Graphs of these data show a quadratic response with high CPUE during low and high flow periods and low CPUE during the mid range flow ($p = 0.008$, $r^2 = .32$). The presentation of natural log transformed data in these authors data analysis precludes identification of specific inflow rates here; therefore inflows are described here as mid, high and low flows. These apparently contradictory results suggest that the information presented by Matheson et al. (2005a) for blue crabs may be inadequate for characterization of the response of blue crab abundance to freshwater inflow in the Weeki Wachee River system. Matheson et al. note that the short data collection period (20 months) may be a concern with regard to the reported findings. They also caution against use of their results for flow conditions outside the range of flows observed during the study period (flows significantly above the nine year mean).

Homosassa River (Peebles et al. 2009)

Peebles et al. (2009) investigated the effects of freshwater inflow on estuarine organisms of the Homosassa River estuary for a two-year period, from 2006 to 2008. The Homosassa River is a spring fed system consisting of the main Homosassa River (13 km) and secondary Halls River (4 km). Blue crabs constituted one of the ten most abundant taxa in the river system. Blue crab geographic mean abundance was observed in mesohaline zones. The authors found significant positive abundance responses to 182 day lagged inflow in both shoreline (p= 0.001, r^2= 0.56) and channel habitats (p= 0.002, r^2= 0.44) for blue crabs (≤ 30 mm). Blue crabs (>30 mm), from trawls in channel habitat, demonstrated negative abundance responses to 7 (p= 0.005, r^2= 0.36), 14 (p= 0.001, r^2= 0.570), and 70 (p=0.009, r^2= 0.320) day lagged inflow. It should be noted that problems associated with autocorrelation within the trawl data for blue crabs (>30 mm), suggest that findings based on these samples may be considered statistically invalid. The only statistically significant finding regarding blue crabs, in this report, is the positive response of blue crab recruits (≤30 mm) to 182 day lagged inflow. The short, two year, duration of this study provides a ‘snap shot’ of the effect of freshwater inflow on this system. Peebles et al. note that the use of these data in a predictive manner should be limited to the conditions encountered during this study. Long term studies are necessary to determine the implications of changes to freshwater inflow of this system especially in light of this documented lagged effect on recruitment.

Chassahowitzka River (Greenwood et al. 2008)

Greenwood et al. (2008) surveyed the Chassahowitzka River for a two year period (2005 through 2007) to study the freshwater inflow effects on habitat use by estuarine organisms. The Chassahowitzka River is a short (9 km) spring-fed river. Blue crabs were found to be one of the three dominant invertebrates collected by seine. Although no specific species ‘profile’ is provided for blue crab abundance and freshwater inflow for the Chassahowitzka River in Greenwood et al. (2008), the statistical output provided in the report appendix may be used to describe blue crab distributions within the river system and characterize abundance responses to inflows. Relatively high blue crab abundances were observed throughout the sampled portions of the river, where salinity ranged from <5 $^{0}/_{00}$ to 29 $^{0}/_{00}$. The geometric mean abundance of blue crab collected by seine, occurred in mesohaline zones. The response of blue crab abundance to freshwater inflows demonstrated negative responses for blue crabs (<30mm) from trawl data compared to 1 day lagged inflow ($p= 0.049$, $r^2= .15$). Seine data for blue crab (<30mm) abundance also revealed a negative response for 231 day lagged inflow ($p= 0.009$, $r^2= .46$). No statistically significant results for blue crabs (>30mm) are provided by Greenwood et al. (2008); a complete characterization of the relationship between blue crab abundance and inflows is therefore lacking for this system. Additionally, the trawl-based regressions are relatively weak, possibly due to inadequate sampling of small crabs with by trawl gear.

Further study of blue crabs in the Chassahowitzka River system is essential due to the lack of robust blue crab data sets from the limited two year study by Greenwood et al. (2008), the presence of the endangered whooping crane in the Chassahowitzka National Wildlife Refuge, and the documented reliance of cranes on blue crabs. This research could strengthen the statistical validity of findings reported by Greenwood et al. for their short-duration study (2 years) that was proceeded by and occurred during a period of low spring flows. Improved sampling of larger (>30 mm) crabs could also be implemented to provide a broader understanding of potential relationships between blue crab abundance and flows in the system.

Anclote River (Greenwood et al 2006)

The Anclote River is described by Greenwood et al. (2006) as a 55 km long tidal river that receives flow from a 190 km^2 watershed with sediments characterized as mud, sand, shell and limestone. These investigators studied the Anclote River for a one year period (2004–2005) during which time freshwater inflow ranged from 57 to 505 cfs. Few large blue crabs were collected in seines and trawls deployed for this study. No specific species ‘profile’ is provided by Greenwood et al. (2006) for blue crab abundance response to freshwater inflow for the Anclote River. Statistical output provided in the appendices of their report is used here to describe blue crab distribution within the river and characterize their response to inflows. The geometric mean abundance for blue crabs captured by seine was observed in low mesohaline zones (9.8-13.2 $^0/_{00}$) and in polyhaline zones (18.0-30.0 $^0/_{00}$) for trawls.

Analysis of the one year data set suggests negative responses of blue crab (≤40 mm) abundances based on trawl data using 210 day lagged inflow ($p= 0.035$, $r^2=0.49$) and based on seine data for 210 day lagged inflow ($p= 0.007$, $r^2=0.53$). However, the data used for development of the latter of these relationships has significant problems with autocorrelation, thus invalidating the significance of the finding. The most significant response observed for blue crab abundances in this river was a quadratic response for trawl-based data and 259 day lagged inflow (p= 0.019, r^2=.734). The response was a convex quadratic that clearly demonstrates higher abundances at intermediate flows. While some statistical relationships between crab abundance and inflow are suggested by the data reported by Greenwood et al. (2006), there are concerns with the relationships, based on: 1) short sampling period (one year); 2) the relatively small data set for large (>40 mm) blue crabs; and 3) autocorrelation within the abundance data.

Hillsborough River (Mac Donald et al. 2006)

The Hillsborough River is a controlled flow environment that was described by MacDonald et al. (2006) as a 72 km 'drowned river valley' that drains a 1,748 km^2 watershed into Tampa Bay. In 2000, MacDonald and his colleagues initiated a 57 month study of freshwater inflow on abundance of estuarine organisms in the Hillsborough River. In their 2006 report, they note that most species demonstrated a negative response to inflow over medium to long-term lag periods (90–365 days). However there was no specific description of blue crab response to freshwater inflow. A review of the appendices of this study revealed the highest mean abundance of blue crab (≤49 mm) collected in trawls and seines occurred in polyhaline and oligohaline zones. The 'best-fit' blue crab (≤49mm) abundance response for 240 day lagged blue crab trawl data regression appeared quadratic (p=0.044, r^2= 0.203) and showed significant problems of autocorrelation. Although MacDonald et al. (2006) do not provide significant descriptive or predictive relationships between blue crab abundance and freshwater inflow, their report does include information on spatial and temporal trends in crab recruitment and abundance for the Hillsborough River.

Tampa Bypass Canal (Peebles 2004)

The Tampa bypass canal is a controlled flow environment and flood-control structure that diverts flood waters from the Hillsborough River. Peebles (2004) sampled the system for four years (2000-2004) and evaluated flow-abundance relationships for several commercially harvested estuarine-dependent species, one of which was the blue crab. Peebles describes trawl-based blue crab abundance responses to flows as negative and highly irregular, but does not provide specific statistical evidence to support these assertions. The author does, however, suggest that further data collection and analysis of abundance responses relative to crab size, life stage and sex should be investigated for characterization of abundance-flow relationships.

Alafia River (Peebles 2002(a) and Matheson et al. 2005(b))

The Alafia River is described by the Peebles (2002a) and Matheson et al. (2005b) as a 54 km ‘drowned river valley’ that drains a 1,092 km^2 watershed. Sediments range from upstream rocky to fine grain downstream (Peebles 2002a). The 17 month study performed by Peebles (2002) started in 1998 did not specifically focus on the collection or analysis of blue crab data concerning the effect of freshwater inflow and blue crab abundance. A seven-year study initiated in 1996 (Matheson et al. 2005b) provides a ‘species profile’ for blue crabs and their response to freshwater inflow. Matheson et al. (2005b) found that blue crabs occurred in 58% of all samples. Blue crabs were found throughout the river, with highest abundances occurring in low mesohaline to euhaline waters.

Data used by Matheson et al. (2005b) for developing statistical relationships between inflows and blue crab abundances included lagged inflows for periods ranging from 0 to 365 days, and abundance data for <39 mm and ≥40mm blue crabs collected with seines and trawls. Their research demonstrated significant negative and curvilinear (quadratic) relationships for abundance and lagged freshwater inflow for both size classes. Matheson et al. (2005b) described the "abundances of small crabs in nearshore habitats and larger (≥40 mm CW) crabs in the channel exhibited statistically significant negative linear regressions with flows lagged from 0 to 365 (nearshore) or 0 to 90 (channel) days", with no indication in the text of the significance of the relationships. Review of appendix 2 and 3 of their report indicates that the only significant negative relationships ($p \leq 0.001$) are for near shore and channel abundance data and lagged flows ranging from 0 to 90 days. The strength of these negative responses should be acknowledged as non-robust due to the low r^2 values, none of which exceed 0.22 and most which are in the range of 0.11 to 0.15. Additionally, Matheson et al. (2005b) uncovered quadratic (concave) blue crab (<39 mm) abundance responses to nine inflow periods for lagged inflows of 45 days ($p<0.05$, $r^2=.27$), 60 days ($p<0.05$, $r^2=.26$) and 365 days ($p<0.01$, $r^2=.18$). These quadratic responses demonstrate an increase in abundance associated with low freshwater inflow and a decrease in abundance associated with high freshwater inflows for the lagged periods investigated. The authors also describe relationships between blue crab life stage, habitat and inflow that contribute to the understanding of crab abundance-flow relationships in the Alafia River.

Little Manatee River (Peebles and Flannery 1992, Mac Donald et al. 2007 and Peebles 2008)

The Little Manatee River is described by Peebles and Flannery (1992), MacDonald et al. (2007) and Peebles (2008) as an 18 km tidally influenced river with a 572 km^2 watershed. The

1992 Peebles and Flannery study was undertaken over a two year period to investigate the fish nursery function of the river in relation to freshwater discharge. This study and the updated data analyses presented by Peebles (2008) are specific to fish and make no reference to blue crabs. The study of the Little Manatee River by MacDonald et al. (2007) involved analysis of 10 years (1996 to 2006) of FWC-FIM data and three years (1988 to 1992) of data collected by the predecessor agency to FWC and FWRI which was the Florida Department of Natural Resources –Florida Marine Research Institute and funded through the Coastal Zone Management Program (CZM). These two data sets were used by MacDonald et al. (2007) to investigate relationships between freshwater inflow and fish and invertebrate populations of the river. This 2007 study provides a detailed description of the spatial and temporal changes in juvenile and adult blue crab abundance. Recruitment was found to be highest from October through March. Adult abundance peaked from May to July with the highest abundance of adult crabs in channel habitat where salinities were <18 $^{0}/_{00}$.

MacDonald et al. (2007) found significant relationships between freshwater inflow and blue crab abundance. Their analysis of the earlier data set (1988-1991) revealed large crabs (≥100mm) demonstrated a negative response to 14, 21, 30, 60 and 90 day lagged inflow. However, the 14 and 21 day-lagged inflows were subject to autocorrelation, significantly increasing the possibility of statistical error. Large blue crab moved downstream (16 km) in response to freshwater inflow ranging from 23 to 321 cfs. Their analysis of the 10 year FWRI-FIM data set revealed positive linear and complex quadratic responses to freshwater inflow. Newly recruited crabs (≤30 mm) in shoreline habitat demonstrated highest abundance during low and high flow periods for 120, 270, 300, 330 and 360 day lagged inflow with the lowest abundance occurring during moderate flows. The quadratic form of this response demonstrates the potential complexities associated with potential relationships between crab abundance and freshwater inflow. Positive linear responses for blue crabs were found for 360-day lagged inflow for 51 to 100 mm blue crabs in shoreline habitats and 90-day lagged inflow for >100 mm blue crabs in channel habitats. The response of blue crab to freshwater inflow in the little Manatee River appears to be variable and complex, with positive and negative linear responses and quadratic (concave) responses observed. The findings of MacDonald et al. (2007) suggest there are dynamic relationships at play in the Little Manatee River between blue crab abundance and freshwater inflow that deserve further study.

Manatee River and Gamble Creek (Greenwood et al. 2007)

The Manatee River and Gamble Creek are controlled flow environments of 58 km and 25 km in length, respectively, and drain an area of approximately 1,000 km^2. The Manatee River and Gamble Creek were studied from 1996 to 2006 by Greenwood et al. (2007). Blue crabs were present in more than 60% of their channel habitat trawls and represented the most commonly collected species. The geometric center of abundance for blue crab ranged from oligohaline to mesohaline zones.

Significant negative linear and quadratic responses were found for blue crab abundance under lagged freshwater inflow regimes during the study period. The center of blue crab ($\geq$ 50mm) abundance moved downstream (3.0 km) with 100 fold increases in inflow (8.5 cfs to 900 cfs) using 1day lagged inflow for the Manatee River (below the Braden River) and 63 day-lagged inflow below Gamble Creek. Similarly, inflow decreases of corresponding magnitude (815 cfs to15 cfs) were associated with upstream (5.5. km) movement of blue crab ($\geq$ 50mm) centers of abundance for 63-day-lagged flow. Relatively strong 28 day-lagged inflow quadratic responses were found for blue crab (≤ 50 mm). Greenwood et. al. suggest that the 'intermediate-minimum abundance' suggested by the quadratic response may indicate different processes occurring under high and low flow where abundance increases. They "advise caution" for use of these results for management purposes due to a number of discrepancies, including potential uncertainty regarding inflection points of the quadratic equations, lack of a wide range of flow data for model development, sample variance associated with crab abundance estimates, etc., that may weaken the robustness of the regressions. Overall, Greenwood et al. (2007) were able to describe only a few statistically significant relationships where blue crab abundance was displaced in short time frames due to large changes in inflow.

Dona and Roberts Bay (Peebles et al. 2006a)

The Donna and Roberts Bay systems are controlled flow environments receiving water from a canal with a water control structure that drains Cow Pen Slough and from another canal that diverts water from the Myakka River. A short term study performed by Peebles et al. (2006(a)) investigated the effects of freshwater inflow on fish and invertebrate abundance of the system from 2004 to 2005. These authors indicated blue crabs were among the dominant invertebrates captured in seines and trawls deployed for the study. Blue crab geometric mean abundance was highest in seine and trawls from oligohaline waters. While no specific discussion of the blue crab is presented by Peebles et al. (2006(a)), graphs presented for the seine and trawl 'pseudo-species' distribution responses in the report appendix show a significant positive response to freshwater inflow for blue crab (≤30mm) from seines using 147 day lagged inflow ($p=0.012$, $r^2=0.42$) and from trawls using 7 day lagged inflows ($p=0.002$, $r^2=0.72$). These positive responses suggest both short term environmental responses and longer term recruitment response to inflow. A significant quadratic abundance response was found for blue crabs (≤30mm) captured in shoreline seines using 1 day lagged inflow ($p=0.015$, $r^2=0.38$) and in channel trawls using 357 day lagged inflows ($p=0.002$, $r^2=0.80$). These responses indicated high abundance during low and high flow extremes and low abundance during moderate inflows. No information regarding relationships between inflow and large (>30mm) or adult blue crabs is included in the 2006 report.

Myakka River and Myakkahatchee Creek (Peebles et al. 2006b)

The Myakka River is approximately 100 km in length and drains approximately 1,500 km^2 of watershed. Investigations into the Myakka River and Myakkahatchee Creek (a tributary of the Myakka River) estuaries were performed for 20 months by Peebles et al. 2006a from 2003 thru 2004. Blue crab was found to be one of the four main invertebrates captured during the study. Blue crab geographic mean abundance was highest in mesohaline to polyhaline zones. A negative distribution response was reported for blue crab (≥35 mm) in the Myakka River using 175 day lagged inflow ($p=0.022$, $r^2=0.26$). A 'slightly' negative distribution response was noted for blue crab (≥35 mm) using 1 day lagged inflow (slope=-0.0174, $r^2=0.60$) and 273 day lagged inflow (slope -0.0276, $r^2=0.35$) for the Myakkahatchee Creek, however no significance value (p) was provided for this relationship. Review of report appendices indicated the reported negative abundance responses in the Myakka River, for all sizes of blue crab, included autocorrelation issues and should, therefore be considered invalid. Best fit seine and trawl data for crab pseudo-species (size classes of individuals collected with the seine or trawl nets) suggested quadratic responses, where lowest abundances occurred during high and low inflow for blue crab (≥35 mm) for 105 day lagged inflow ($p=0.040$, $r^2=0.23$) and for blue crab (≤35 mm) using 140 day-lagged-inflows (p=0.004, r^2=0.63). The data for blue crab (≥35 mm) using 105 day lagged inflow demonstrated high incidence of autocorrelation and should be considered invalid. The Peebles et al. (2006(b)) data for the Myakka River and Myakkahatchee Creek are therefore insufficient to characterize the blue crab abundance responses to freshwater inflow.

Peace River and Shell Creek (Peebles 2002 (b) and Greenwood et al. 2004)

Peace River and Shell Creek are approximately 170 km in length and drains an area of approximately 6,000 km^2. Peebles (2002 b) provides summary tables of a database of fish and invertebrate abundance information for the two systems, but does not include analysis of relationships between flows and blue crab abundances. A more recent seven-year study, performed by Greenwood et al. (2004), describes blue crab abundance and freshwater interactions in the Peace River and Shell Creek. According to Greenwood et al., blue crabs occur over the range of salinities encountered in the channel habitats of these systems and in salinities above oligohaline conditions in nearshore habitats. Complex responses between blue crab size, habitat, inflow and location within the river systems were observed. Blue crab responses to inflow are described generally as increases in abundance with decreasing freshwater inflow or occurrence of highest abundance during periods of moderate inflows. Specific relationships of interest are provided in the appendices of this report.

Within the Peace River, above the confluence of Shell Creek, negative responses of blue crabs in shoreline habitats were observed for all size classes, based on lagged inflows of 0-60 days. In channel habitats above the confluence, blue crabs (>39 mm) exhibited a negative response for 7-90 day lagged inflows and a convex quadratic response for 30-180 day lagged inflows. These results are suggestive of short term, down-river movement of larger blue crabs above the confluence with Shell Creek, followed by a longer-term complex (quadratic) response where abundance increases during moderate flows.

Relationships between blue crab abundance and inflow are also complex in Shell Creek. Large blue crabs (>39 mm) in channel habitat exhibited a negative response to 0-90 day lagged inflow. In the shoreline habitat of Shell Creek abundance of large blue crabs was positively associated with 0-60 day lagged inflows. These data suggest that fresh water inflow in Shell Creek may have led to the short term movement of large crabs from channel habitats to shoreline habitats. Small blue crabs (<40 mm) in shoreline habits of Shell Creek demonstrated a negative responses for 30-60 day lagged inflows and a positive response to 60-365 day lagged inflows. Consideration of observed responses of large and small crabs in Shell Creek habitats suggests a possible predation and flight response of smaller crabs to increasing abundance of the large crabs. The benefit of freshwater to recruitment is suggested by the positive response of small crabs to 60-365 day lagged inflows.

Caloosahatchee River Estuary (Stevens et al. 2008(a))

The Caloosahatchee River flow is regulated by water control structures and is part of a canal system that connects the east and west coasts of Florida. A four year study was performed by Stevens et al. (2008(a)) to investigate the effect of freshwater inflow on various species in the river system. Positive linear responses were found for the distribution of all size of blue crabs in channel habitat for 84 day lagged inflow and the abundance of blue crab (≤ 150 mm) in the shoreline habitats for 315 day lagged inflow. Stevens et al. found blue crab abundances were low in the channel habitat during intermediate flows and higher during high and low flows, based on 119 day lagged inflows. They suggest that these responses may be associated with water quality attributes of the inflowing freshwater. They also hypothesize that factors such as salinity and movement of crabs based on gender, maturity and mating behaviors are plausible explanations for observed abundance responses to flow. The need for additional studies focused on water quality, productivity and the role of this river system for blue crabs mating are implied in these hypothesese.

Estero Bay (Stevens et al. 2008(b))

Estero Bay receives freshwater inflow from small creeks and rivers (Estero River, Mullock Creek, Hendry Creek, Spring Creek, and Imperial River) that drain the approximately 1,100 km^2 watershed, which is influenced by the regulated discharge from the Caloosahatchee River. Stevens et al. (2008(b)) sampled fish and invertebrate nekton in the bay and several tributaries of the bay for a three year period, from 2005 through 2007.

Blue crab responses to freshwater inflow were found to vary based on habitat type and location in the system. Stevens et al. suggest possible reasons for the various observed responses to flow. A convex quadratic “recruitment response” was observed based on blue crab (≤150mm) abundance in shoreline habitat of tributaries associated with Estero Bay and 133 day lagged inflows. The quadratic response suggests highest abundances are found for intermediate flows (lagged 133 day flow of 200 cfs) and lower abundances for similarly lagged periods with higher or lower flows. Blue crab (≤150mm) abundance in bay shoreline habitat demonstrated a similar convex quadratic response for 1 day lagged inflow. Stevens et al. conclude that this represents a short-term distribution response by actively moving individuals or more passive displacement caused by the inflow. Blue crab abundance in deeper areas of the bay was contrary to the pattern observed for shoreline habitats. Abundance for 28 day lagged inflow was lowest in the deeper areas during intermediate flow (≈ 90 cfs) and higher abundances occurred during periods of low and high inflow. Stevens et al. identify several factors that may contribute to the complex flow-abundance responses observed for crabs in Estero Bay, including: water quality variability, variability in chemical signals that may serve as behavioral cues; flow-related physical displacement; and interaction between ecosystem productivity, physiochemical conditions, salinity preferences and migratory habitats of males and females. Complexity in the reported responses may also be related to the sampling of both Estero Bay and several of the bay tributaries. Other studies reviewed for this document were focused primarily on the river proper (source to mouth) and did not involve sampling of the broader associated estuary.

Discussion

The main differences in approach of the studies reviewed for this report are the breadth of focus. Texas and Louisiana chose to consider the entirety of the system from river channel to the point of estuary discharge into the Gulf of Mexico. Approaches used in these states have documented many significant positive relationships between blue crab abundance and freshwater inflow. The positive correlations are now an integral part of freshwater inflow management in both states. Recent approaches for managing the Texas coast include evaluation of data on daily minimum loading rates for nutrients, oxygen demanding compounds, effluent discharge, pollutants etc. and have resulted in an integrated resource-based management approach. Studies in Georgia were initially broadly focused on the entire Georgia coast and that subsequently identified the need for smaller regional models to address estuarine inflow management. It is the opinion of this author that Florida studies fall between these approaches. The water management district funded studies capture the 'within streambed' response of blue crabs. However, they fail to adequately address the broad reaching affects of freshwater inflow on river-associated bays and estuaries that are important habitats for blue crabs. The studies on northwestern Florida Rivers and associated regional blue crab abundance responses highlight the need to broaden recent investigations of blue crab productivity to regional levels.

Regardless of the approaches that have been used to investigate blue crab responses to freshwater inflow, it is ubiquitously expressed by authors of each reviewed report that limiting of the investigation of crab abundance to effects associated with inflow and salinity will always fall short of a comprehensive understanding of crab population dynamics. These systems are complex and deserving of broader and more complex studies involving evaluation of nutrient loading, productivity, pollution, predator displacements and their effects on habitat and blue crab populations.

Task III

Landings Monitoring

The economic value, landings and trip information for any commercial fisheries in Florida is available through the Commercial Landings Data center on the Florida Fish and Wildlife Research Institute website: http://research.myfwc.com/features/view_article.asp?id=19224 Specifically, Florida collects landings information (Trip Tickets) from commercial harvesters and dealers to generate data on the types of species landed and number of commercial licenses in use. These data are derived from trip ticket information which is the required paperwork submitted at the end of each fishing trip. Data are available for specific species of interest for quantities landed, location of catch, location of landings as well as the size and weight of harvested species. These data are divided into: state wide landings, state wide landings by month, landings by coast and landings by county for each fishing year. This data set is available from 1986 to present at the aforementioned hyperlink. Summary data examples for the 2009 fishing season are presented in Tables 3-6.

Species	Total Pounds	Total Trips	Average Price /lb.	Estimated Value
Blue Crab (Hard)	4,980,402	26,507	$1.21	$6,049,019
Blue Crab (Soft)	81,436	2,190	$7.78	$633,642

Table 3. 2009 Statewide Blue Crab Landings

Species	Jan. Pounds.	Jan Trip	Feb Pounds	Feb Trip	March Pounds	March Trip	April Pounds	April Trip	May Pounds	May Trip
Blue Crab (Hard)	329,643	1,858	321,159	1,812	379,063	2,403	481,030	2,632	488,517	2,730
Blue Crab (Soft)	1,203	124	1,313	127	12,097	297	14,973	349	12,770	232

Table 4. 2009 Statewide Blue Crab Landings by Month

Species	East Coast Pounds	East Coast Trips	West Coast Pounds	West Coast Trips	Inland Pounds	Inland Trips	Totals Pounds	Totals Trips
Blue Crab (Hard)	1,671,548	10,967	3,307,876	15,528	978	12	4,980,402	26,507
Blue Crab (Soft)	25,301	834	56,136	1,356	0	0	81,436	2,190

Table 5. 2009 Blue Crab Landings by Coast

Species	Bay Co. Pounds	Bay Co. Trips	Citrus Co. Pounds	Citrus Co. Trips
Blue Crab (Hard)	116,344	990	538,918	2,705
Blue Crab (Soft)	0	0	7,065	563

Table 6. 2009 Blue Crab Landings by County

Effort Management and Monitoring

The Florida Blue Crab Effort Management Program was implemented by the Florida Fish and Wildlife Conservation Commission (FWC) in July of 2006 to limit the number of commercial harvesters and traps allowed per endorsement. The program provides license endorsements for both hard-shell and soft-shell fisheries. This effort limitation dictates that no new endorsements are issued and only endorsement transfers are allowed. Annual requalification is required to retain the endorsement through documented landings from the previous fishing season. After the program's inception fishers are required to purchase FWC-issued trap tags for each trap fished. Prior to this program, there were no limits on numbers of harvesters or traps, no trap fees, and no qualifying or renewal criteria. With the implementation of this program an accurate account of the number of fishers in the industry and the number of traps available to the fishery exists (Table 7).

Fishing Season State Fiscal Year	Total Number of Trap Tags	Change in Number of traps from Previous Season	Number of Trap Endorsement Holders	Change in Number of Trap Endorsement Holders from Previous Season	Change in Landings from Previous Season	Change in Effort (Trips)
07/08	822,750*		1,171		-36.6%	-3.6%
08/09	290,699**	-64.7%	1,021	-12.8%	-18.3%	-18.5%
09/10	257,050	-11.6%	924	-9.5	-19.0%	-7.9%

*Trap Tag Required with no Fee on Traps
**First Year of fee Collected per Trap

Table 7. Number of Blue Crab Endorsements and Trap Tags for the 2008, 2009 and 2010 fishing seasons

The combination of trip tickets, trap tags, and endorsements provides for better assessments of effort and crabs landed in each region of the state. However, commercial landings alone do not give an unbiased picture of the blue crab population. Year to year effort is proving to be economically driven as opposed to supply driven. To obtain a better estimate of the fishable population and eliminate bias we recommend a focused fisheries independent monitoring assessment of the blue crabs using current gears/methods and commercial style crab pots to better calibrate the effect of freshwater changes on the abundance of blue crab and the effect on the commercial fishery.

Fishery Independent Monitoring

Currently, sampling and research efforts of the Florida Fish and Wildlife Conservation Commission Fishery Independent Monitoring Program are performed in multiple river systems and estuaries throughout Florida. Primary collection includes but is not limited to seining, trawling, and plankton tows for the assessment of fish and invertebrate communities. Although this broad-survey approach does yield useful information on blue crab abundance and distribution, it does not provide a complete understanding of the blue crab and its association with freshwater inflow.

Suggested Focused Studies on Blue Crab and Freshwater Inflow

These authors suggest specific studies focused on blue crab abundance and freshwater inflow to include:

Study 1.

Focused monitoring by the Crustacean Fisheries Research Program specific to juvenile (larval through first year) blue crabs, within the downstream associated estuaries of rivers in the region, is suggested. This program would be designed to detect seasonal recruitment periods and changes in juvenile and recruit abundance associated with freshwater inflow using megalopae traps, drop nets, seines and trawls applied in the downstream estuaries. These studies would follow similar methodologies of Longley (1994) and Hamlin (2005). This work would associate lagged inflows to changes in recruit and juvenile abundance, and delineate the spatial distribution of nursery grounds, salinity zones, submerged aquatic vegetation and salt marsh in the estuaries downstream of the major rivers of the region. Observation of the expansion and retraction of salinity zones over essential habitats such as SAV, correlations with freshwater inflow, and the effect on juvenile recruitment and adult abundance (Study 2) is essential to understanding the greater spatial and temporal effect of freshwater inflow on regional blue crab abundance.

Study 2.

A focused trapping program for adult blue crabs is advisable. The current FWRI-FIM program is not specifically focused on adult blue crabs; which is the life stage most closely associated with tidal rivers. Currently, the Crustacean Fisheries Research Program of FWRI administers such a program for stone crabs. A blue crab trapping program, similar to the blue crab studies performed by the Crustacean Fisheries Research Program in Tampa Bay from 1980-1983 (Steele and Bert 1994) and from 2002 through 2007 (FWRI unpublished data), would provide a more accurate species, size, gender and adult specific understanding of the regional blue crab population. Commercial traps that are specifically designed to select for blue crabs, reflect the gear used throughout the fishery, and can be deployed to provide data that will also serve as an independent gauge of the crab supply available to the commercial fishery. Using traps has been shown to be more effective on pre-adult and adult life stage blue crabs over seining or trawling. Swimming crabs have the ability to avoid nets, especially in clear waters (Rozas and Minello 1997). An avoidance response has been demonstrated in studies using otter trawls and push nets in studies of blue crabs (Miller et al. 1980).

To gain a better understand of the blue crab population response to fresh water inflow, we propose a sampling program utilizing traps at fixed sites along the length of several rivers and into the associated downstream estuaries; including but not limited to Homosassa, Chassahowitzka, Anclote, Alafia, Little Manatee, Peace and Myakka. Inclusion of several of the managed flow rivers should also be considered. Monitoring the effect of the managed flow on the fishery would be essential to our understanding of the blue crab abundance responds to this manipulation. Sampling should not be limited to where the river meets the bay or estuary but instead should continue into the estuary or bay to examine the effects of freshwater flow changes on the entire system. Any data collection should take place over a sufficient duration to capture the population response to the range of flows in the system throughout the year and from year to year. It is especially important to collect a long term data series for species that exhibit population fluxes of a cyclical nature, such as blue crabs. This allows for a more accurate representation of the affects of freshwater alterations on blue crabs. Regression models using time lag up to one year will be utilized to reveal any significant relationships of adult blue crab abundance to freshwater inflow in these associated rivers.

Study 3. The FWRI Crustacean Fisheries Research Program would additionally suggest a survey of historic regional landings for the blue crab fishery in an effort to correlate changes in landings and regional effort to freshwater inflow of the major rivers of the regions. This will be an expansion of the work of Wilbur (1992, 1994) for the Apalachicola River.

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