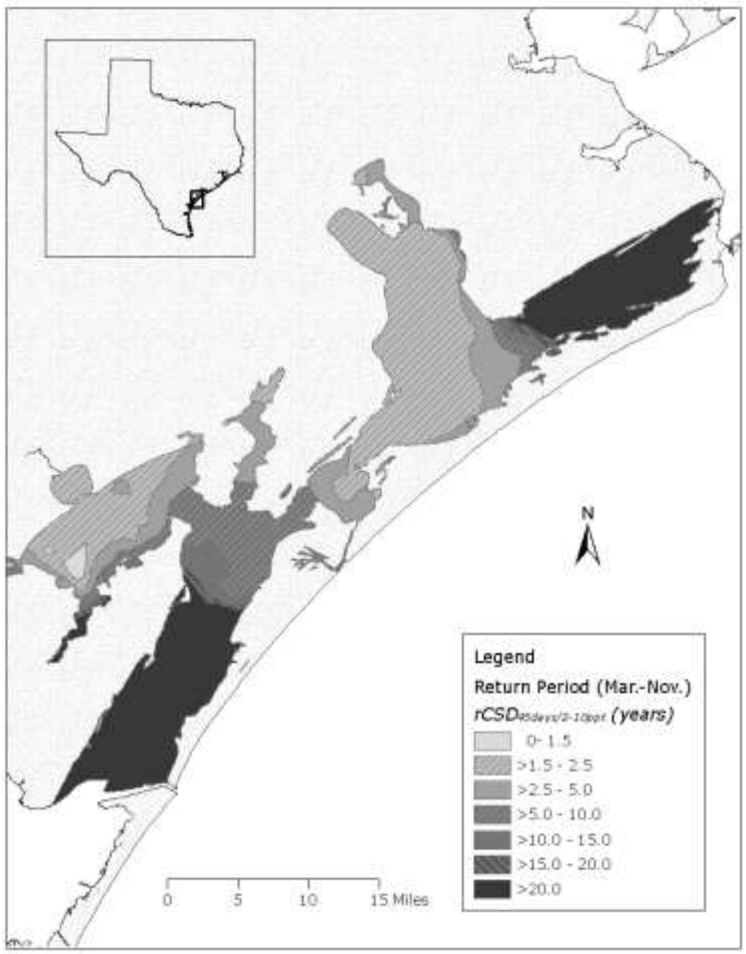
Examining Bay Salinity Patterns and Limits to *Rangia cuneata* Populations in Texas Estuaries



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1 Executive Summary

The brackish water clam Atlantic Rangia cuneata (*Rangia cuneata)*, is an important native species in the upper portion of most Texas estuaries. Rangia cuneata clams are of ecological significance because of their role as a filter feeder, converting detritus and phytoplankton into biomass and serving as an important food source for fish, crustaceans, and water fowl (LaSalle and de la Cruz, 1985). Previous research, executed in other states, indicates that *Rangia cuneata* has strict short-term salinity requirements for reproduction (Cain, 1973). These needs, as opposed to aspects of adult physiology, are thought to be the primary control on the habitable range for the species (Hopkins and others, 1973; Cain, 1975). Because of the importance of the species and the ability to relate salinity needs to the flux of freshwater reaching an estuary, *Rangia cuneata* has recently become one of the primary indicator species for establishing freshwater inflow regimes for Texas estuaries (e.g. GSMA-BBEST, 2011). However, despite this new-found focus on *Rangia cuneata* in Texas, there has been little specific study of this species and the factors which appear to limit its occurrence and distribution in the state's estuaries.

This study utilizes a novel approach to characterize salinity patterns, focusing on those which may limit *Rangia cuneata* distribution in Texas estuaries. This new approach to describe salinity patterns integrates salinity magnitude (e.g. 2-10 parts per thousand), duration of occurrence (e.g. 30 days or longer), and periodicity of re-occurrence (e.g. re-occurring at least once per five years). Specific magnitude, duration, and re-occurrence values are examined that would appear to be explanatory for the geographic distribution of *Rangia cuneata* based on scientific literature relating studies of the species' reproduction and life history information in other locales.

The study uses the interlinked Guadalupe Estuary (also generally known as San Antonio Bay) and Mission-Aransas Estuary (also known as the Mission-Aransas Copano Bay system) as the focal area. The new integrative salinity variable is developed at selected points in these estuaries using the salinity predictions of the Texas Water Development Board's TxBLEND model for the 1987-2009 period. The point data are then mapped and contoured to develop spatial pattern data which can be examined for their correspondence to the apparent area of *Rangia cuneata* population. The goal is to achieve a better understanding of long-term re-occurring patterns of salinity that may exhibit a controlling influence on *Rangia cuneata* in Texas estuaries.

Several re-occurring salinity patterns that would appear to be necessary to support *Rangia cuneata* reproduction and recruitment were examined. The primary salinity examined was the widely-cited range of 2-10 parts per thousand needed for larvae of *Rangia cuneata* to survive immediately after spawning (e.g. Hopkins and others, 1973). Also of prime importance were periods of 15 or 30 days in which salinity was continuously in that range, with these periods chosen based in inferences from other studies of *Rangia cuneata* indicating the duration of the salinity-sensitive larval stage (Cain, 1973). Although these were the key salinity range and durations, others were tested for completeness.

The study found that when salinity patterns are characterized in this way, there is an expected drop off in the frequency of occurrence of favorable conditions for reproduction and recruitment of *Rangia cuneata* as one moves from the upstream portions of the examined estuaries towards the higher-salinity points of tidal exchange with the Gulf of Mexico. However, seemingly

favorable salinity conditions of sufficient duration are so widespread and of such frequent re-occurrence that they alone do not appear highly explanatory in describing the limit to the population distribution of *Rangia cuneata* in the examined estuaries. In other words, *Rangia cuneata* appear to inhabit a much more restricted portion of the estuaries than the salinity patterns that would initially appear limiting can explain. These findings are, of course, given with the caveat that the data available for the spatial distribution of *Rangia cuneata* may be somewhat inadequate.

In addition to these primary searches for explanatory salinity patterns, the study also examined the possible role that another salinity-based reproductive requirement may play: the need for an abrupt salinity change to initiate spawning as was found in a single study in Virginia (Cain, 1975). While the early larvae of *Rangia cuneata* would still require the supportive salinity conditions described above (salinity and duration), such a spawn-initiating episode would essentially constitutes a “pre-condition.” For this study, the “pre-condition” was based on salinity change rates (rise / fall magnitude over certain number of days) that may initiate spawning based on the Virginia study. Comparisons of the frequency of re-occurring favorable salinity patterns of appropriate salinity and duration were made, with and without the pre-condition. The results show that this additional “pre-condition,” as tested in the Guadalupe and Mission-Aransas Estuaries, appears to be very restrictive and may have additional explanatory power regarding the limits on *Rangia cuneata* population distribution. This needs more investigation than was possible in this study. Such abrupt changes, if indeed controlling spawning, may indicate the need for pulses of freshwater inflow as opposed to stable inflows that hold salinities in a specific range.

Additional factors that may play a role in the long-term limit on the population distribution of *Rangia cuneata* in areas further removed from freshwater sources could include predator-prey relations, competition, disease and parasites, or simply lack of a favorable substrate for burrowing.

Even areas typically having a high abundance of *Rangia cuneata* may experience occasional population setbacks. As observed during first-hand field observations following the record-setting drought of 2011, there was widespread mortality of *Rangia cuneata* in the upper portion of the Guadalupe Estuary in areas that are typically heavily populated with rangia. This may or may not have been caused by the probable extended period of drought-induced high salinities in this area. Although *Rangia cuneata* adults have been observed to withstand up to 30 ppt in laboratory settings (Pattillo and others 1995), they are seldom found in areas with salinity above 15 ppt very often (Hopkins and others, 1973; LaSalle and de la Cruz, 1985). However, there do not appear to have been explicit long-term field studies of the effects of high salinity exposure. Any potential role of high salinity in limiting the population distribution of *Rangia cuneata*, is likely expressed in an interacting fashion with effects from other variables such as temperature and duration of exposure (Pattillo and others, 1995).

If there does exist an upper limit of salinity tolerance by *Rangia cuneata* adults, even if it must co-occur with other environmental stressors, this may limit the habitable area on the seaward side. This would be in opposition to long-standing opinions (Hopkins and others, 1973; Cain, 1975) that salinity-based limits on reproduction and recruitment are the main or only control on the population distribution of *Rangia cuneata*. Obviously, there is ample need for additional Texas-specific studies of Rangia cuneata to investigate the specifics of their apparent salinity-modulated reproduction and recruitment at early life stages and the controls that salinity and other environmental parameters may exert on the adult population.

2 Introduction

The brackish water clam Atlantic Rangia cuneata (*Rangia cuneata)*, is an important native species in the upper portion of most Texas estuaries. *Rangia cuneata* is generally found in the portion of an estuary where salinity typically is less than 15 part per thousand (ppt) (Hopkins and others, 1973). The ecological significance of *Rangia cuneata* lies in its role as a filter feeder, converting detritus and phytoplankton from the water column into biomass and serving as an important food source for fish, crustaceans, and water fowl (LaSalle and de la Cruz, 1985).

Previous research, executed primarily in Atlantic seaboard and other Gulf states, indicates that *Rangia cuneata* has strict salinity requirements for reproduction and recruitment of larval stages into the adult population. These needs, as opposed to aspects of adult physiology, are thought to be the primary control on the habitable range for the species (Hopkins and others, 1973; Cain, 1975). Because salinity can be related to the flux of freshwater reaching the estuary, *Rangia cuneata* has recently become one of the primary indicator species for establishing estuarine inflow regimes for Texas estuaries. For example *Rangia cuneata* was used by four of the Senate Bill 3 (SB3) Basin and Bay Expert Science Teams in their work to develop a schedule of inflow quantities to maintain a sound ecological environment for their respective estuaries (SN-BBEST, 2009; TRSJ-BBEST, 2009; CL-BBEST, 2011; GSMA-BBEST, 2011).

Despite this new-found focus on *Rangia cuneata*, there has been little Texas-specific study of this species. The factors which limit Rangia cuneata distribution in Texas estuaries are unknown, though generally, their abundance tends to decrease as distance from the source of freshwater inflow (*i.e*., the river mouth) increases (TPWD, no date). Therefore, it is probable that Rangia cuneata populations are limited by the lack of favorable salinity conditions as distance increases from the mouth of rivers although other factors such as predator-prey relations, competition, disease, or lack of a favorable substrate may also play a role.

This study rigorously examines the frequency and duration of reoccurring spatial salinity patterns which may limit *Rangia cuneata* distributions in Texas estuaries. The study relies on the interlinked Guadalupe Estuary (also generally known as San Antonio Bay) and Mission-Aransas Estuary (also known as the Mission-Aransas Copano Bay system) as the focal area (Figure 1). To examine salinity patterns on a spatial basis, this study developed a novel map-based method of characterizing key re-occurring salinity patterns utilizing a frequency of re-occurrence approach. This new approach to describing salinity patterning develops a salinity variable at many specific points in the estuary system. The new variable integrates salinity magnitude (e.g. 2-10 parts per thousand), duration of occurrence (e.g. 30 days or longer), and periodicity of re-occurrence (e.g. re-occurring at least once per five years). These point data are then mapped and contoured to examine the correspondence between this new salinity pattern variable and the known area of *Rangia cuneata* population in an example Texas estuary. This new technique for portraying salinity may also prove of general utility and a suite of maps are provided in an appendix.

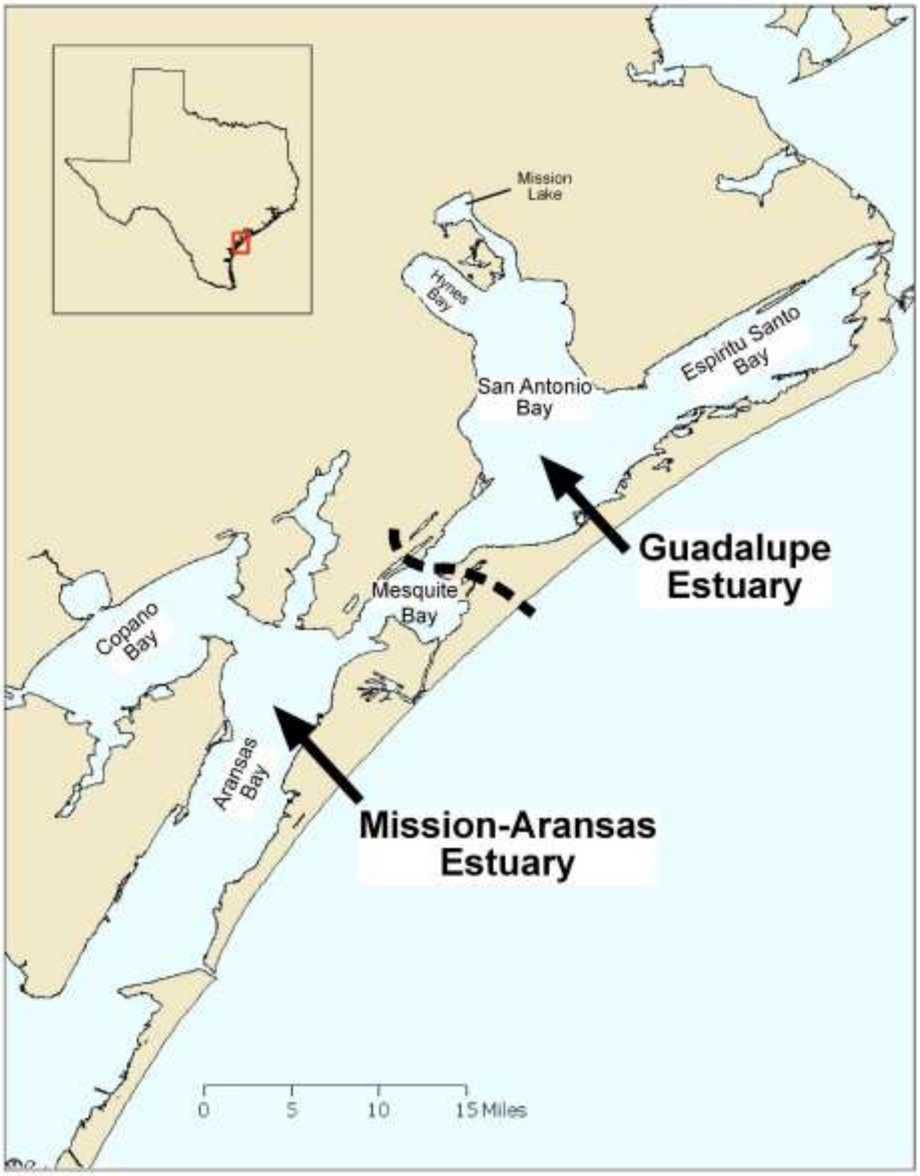

Figure 1. **The Guadalupe and Mission-Aransas Estuary system located along the central Texas coast.**

The longevity and strict salinity-controlled reproductive requirements of *Rangia cuneata* combine to make an ideal test case for examination of the potential for how periodically suitable environmental parameters might act to condition the spatial distribution and abundance of sessile estuarine organisms. Furthermore, by determining the salinity magnitude, duration, and re-occurrence factors that appear to limit the extent and persistence of *Rangia cuneata*, this study will provide a better understanding of one of the mechanisms by which altered freshwater inflows may impact an estuary.

3 Uncovering Key Salinity Patterns in the Guadalupe and Mission-Aransas Estuary System

The objective of this study is to examine if key re-occurring salinity patterns, which would appear necessary for reproduction and recruitment of *Rangia cuneata*, can explain the population distribution of the species in the interlinked Guadalupe and Mission-Aransas Estuaries. These interlinked estuaries were selected as the focus of this effort because of the presence of *Rangia cuneata* (GSMA-BBEST, 2011). The inter-linkage between these estuaries refers to the fact that the salinity behavior in much of the Mission-Aransas Estuary is closely tied to the freshwater inflows occurring into the adjacent Guadalupe Estuary as found by the GSMA-BBEST (2011). These estuaries are also more-or-less in the middle of the Texas coast and exhibit pronounced variability in salinity which is an ideal setting to examine the role that salinity may exhibit on controlling the population distribution of *Rangia cuneata*. Also contributing to this choice of focal area is that the Texas Water Development Board's (TWDB) TxBLEND salinity transport and circulation model, the primary source of salinity data for the study, was recently recalibrated (Guthrie and others, 2010a and 2010b) and inflow estimates refined for this estuary system (Guthrie and Lu, 2010).

The recent efforts of the Guadalupe, San Antonio, Mission, and Aransas Rivers and Mission, Copano, Aransas, and San Antonio Bays Basin and Bay Expert Science Team (GSMA-BBEST, 2011), analyzing TPWD data (TPWD, no date) clearly showed that *Rangia cuneata* and a similar species *Rangia flexuosa* (Brown rangia) have been found in a large portion of these estuaries (see Figures 2 and 3). There is very limited literature available on *R. flexuosa*. However, the fact that the two species commonly co-occur geographically suggests that they have similar ecological requirements and the GSMA-BBEST ended up lumping the two species together as will be done in this study. For the remainder of this discussion specific environmental requirements for *Rangia cuneata* are utilized with an assumption that they may also apply to the apparently intermingled population of *Rangia flexuosa* .

There are some significant features of this TPWD rangia data that are important to highlight. One is a caveat that the GSMA-BBEST (2011) discussed: the abundance and extent of habitable area for both *Rangia* species in these estuaries, and the others in Texas, are not directly known. The characteristics of the *Rangia* population can only be inferred from "accidental catch" in the sampling data of the Coastal Fisheries Resource Monitoring Program of the Texas Parks and Wildlife Department (TPWD). The *Rangia* information in the TPWD database (TPWD, no date) is from trawl equipment that is dragged along the bottom and occasionally digs into the sediment layer and gathers specimens of this burrowing species. While this data is clearly far from ideal, in the absence of a targeted and comprehensive sampling study, it is the best available and is thought to be generally indicative of the population distributions for the two *Rangia* species (GSMA-BBEST, 2011).

Also important to consider is the time scale of the field sampling data that are available. Since these figures are the composite of all samples taken over the entire 28 years of sampling, it is quite possible, given the biology of *Rangia cuneata* reproduction and recruitment (discussed briefly above and more below) that not all of the rangia found through time would be found continuously. The abundance, especially for *Rangia cuneata*, in the upper portion of the

Guadalupe Estuary may indicate that it is a permanently occupied area, but some other samples in what are typically more saline, may be outliers due to sporadically suitable reproduction conditions. Examining the potential role that salinity patterns may play in limiting the population distribution is, of course, the focus of this study.

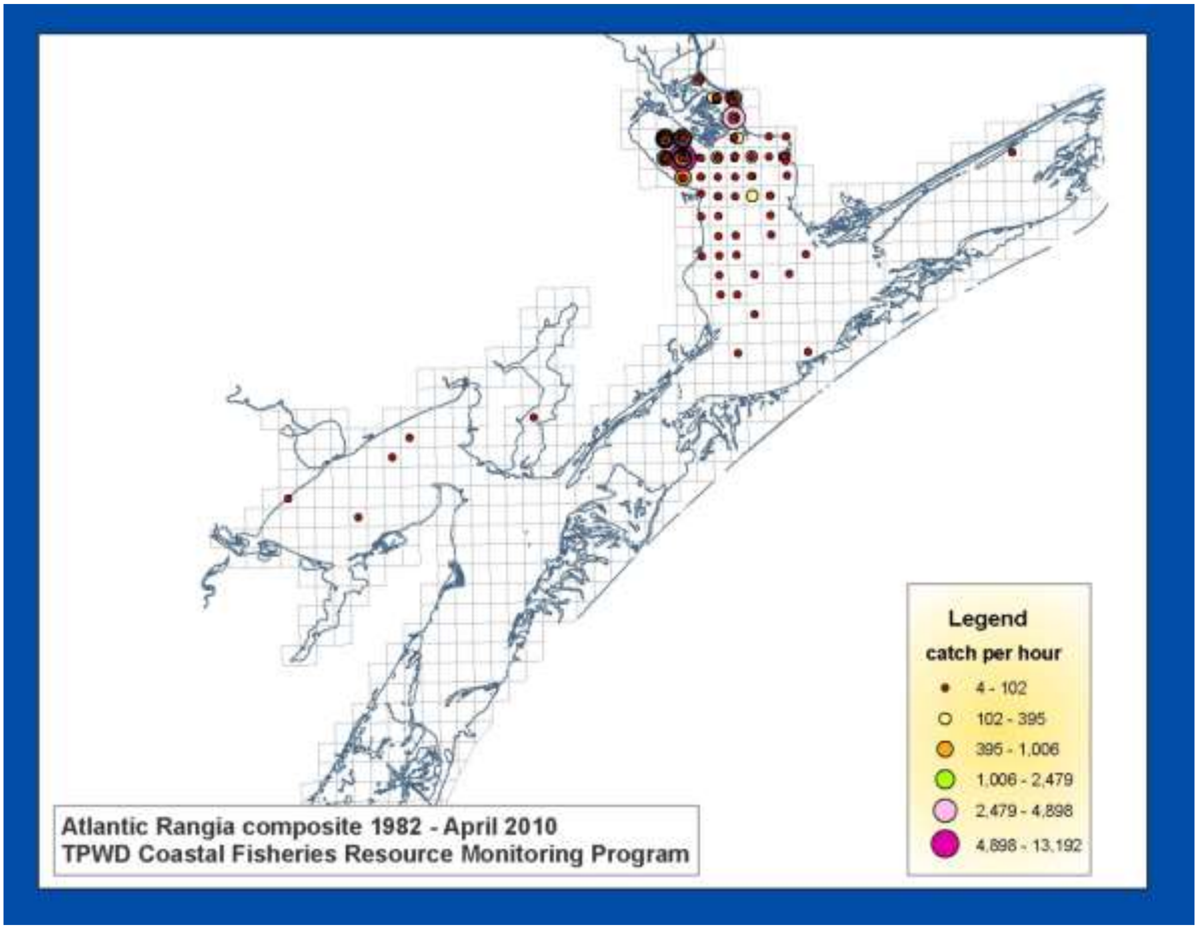

Figure 2. Atlantic Rangia cuneata (*Rangia cuneata*) in the Guadalupe Estuary and Mission-Aransas Estuary based on the data from Texas Parks and Wildlife Department's Coastal Fisheries Resource Monitoring Program (TPWD, no date). Figure from GSMAC-BBEST, 2011.

Understanding the relationship between salinity patterns and *Rangia cuneata* population distribution is complicated by the high variability of salinity in most Texas estuaries over the course of a season and among years (Longley, 1994) and the life history characteristics of *Rangia cuneata* itself. Salinity variability, and indeed the frequent occurrence of unfavorable reproductive conditions, may still allow for a viable *Rangia cuneata* population as pointed out by previous researchers (e.g. Hopkins and the others, 1973; Cain, 1975). This is possible due to several factors, the first being that the clams' average life span appears to be four to five years (Fairbanks, 1963), with a maximum of perhaps ten to fifteen years, (La Salle and de la Cruz, 1985; Hopkins and others, 1973). Second, only the early larval stages appear to exhibit the rigorous low-salinity needs; adults are tolerant of a much broader range of salinity (Cain, 1973). Thus, ideal conditions supporting reproduction and requirement do not have to be met each year to maintain a viable population.

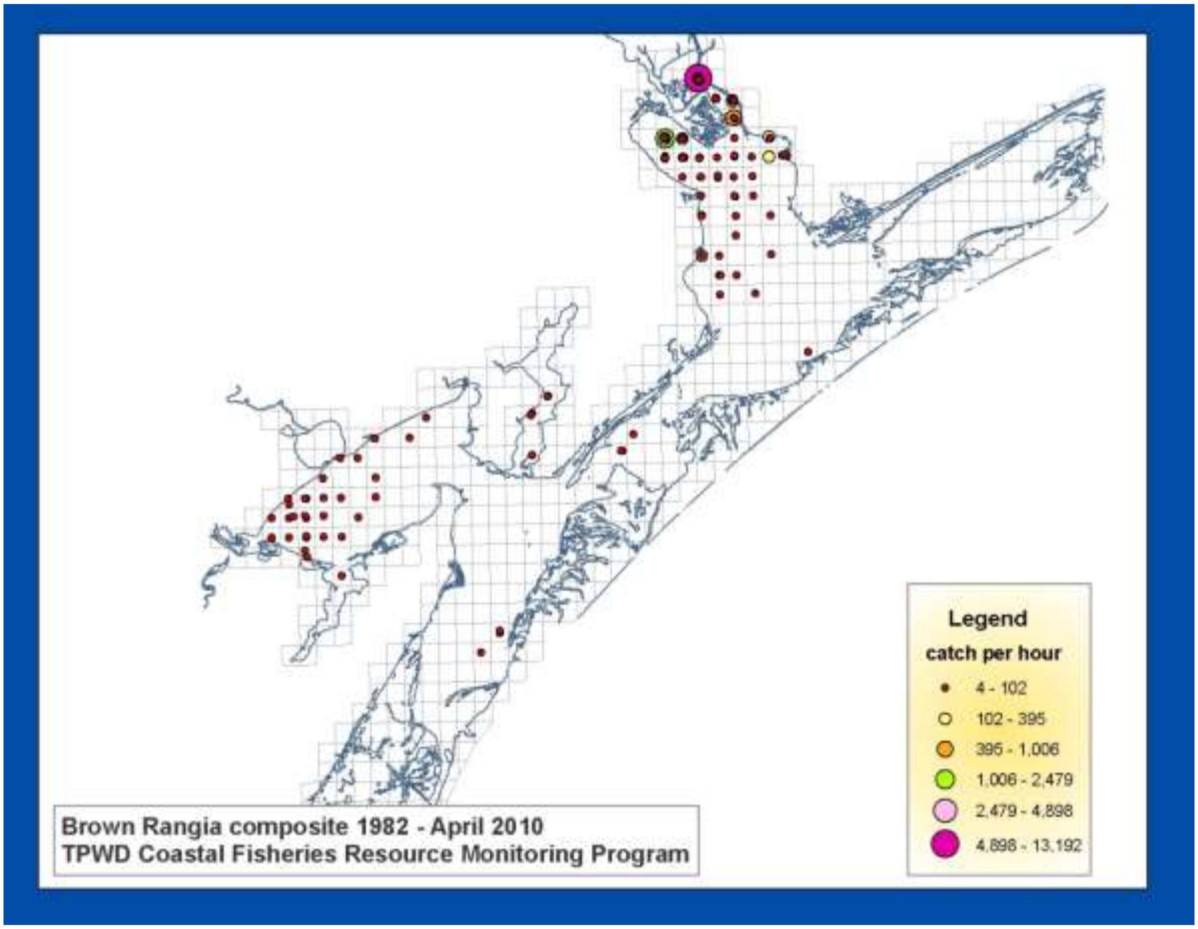

Figure 3. **Brown Rangia cuneata (*Rangia flexuosa*) in the Guadalupe Estuary and Mission-Aransas Estuary based on the data from Texas Parks and Wildlife Department's Coastal Fisheries Resource Monitoring Program (TPWD, no date). Figure from GSMAC-BBEST, 2011.**

An added complexity in relating salinity patterns and *Rangia cuneata* distribution is due to the potential spatial variability of salinity through multiple spawning seasons; the area of larval survival could shift spatially among years leading to confusion about the "core" area of permanent habitation versus those in an area with suitable reproduction and recruitment conditions met only very infrequently.

3.1 Biologic Underpinnings

Establishing an explicit spatial linkage between reoccurring salinity patterns and *Rangia cuneata* distribution requires not only the analyses of a robust set of salinity data of broad areal coverage (described below) but also a focus on the particular characteristics of salinity that appear biologically significant. As alluded to earlier, the totality of studies on the salinity needs of *Rangia cuneata* for reproduction and recruitment were executed outside of Texas. These apparent salinity-modulated reproductive needs will serve as the default values for this study, although some attention will be given to their suitability for Texas.

The basic requirement of salinity in the range of 2-10 parts per thousand (ppt) for early larval survival is a frequently-cited reproductive characteristic of the species (e.g. LaSalle and de la Cruz, 1985; Harrel, 1993). This is a highly simplified finding of the rigorous work of Cain (1973) who tested embryonic (a.k.a. "early larvae") and "late larvae" survival or *Rangia cuneata* over a broad range of temperature and salinity conditions. Cain tested temperatures from 8 to 32 °C, in equal increments [8, 16, 24, 32 °C], and salinity conditions ranging from 2 to 20 ppt in equal 6 ppt increments [2, 8, 14, and 20 ppt]. Additional test were performed with 0 ppt salinity. Cain found that the embryonic stage, up to just 48 hours after spawning, was far the most sensitive to salinity conditions. Survival rates for this stage were 0% for salinities below 2 ppt or above 14 ppt regardless of temperature. The optimum conditions for embryos was concluded to be 6 - 10 ppt in combination with temperatures between 18 and 29 °C. Both the stated salinity and temperature limits were apparently developed by interpolation using a bi-variate "response surface" equation relating survival to the various combinations of temperature and salinity. The experiments with late larvae, from 2 - 7 days of age, found a broader optimum conditions range covering from 2 - 20 ppt over the entire tested temperatures range of 8 and 32 °C.

In later field-based research, Cain (1975) examined the apparent environmental controls on *Rangia cuneata* spawning. His research in the estuarine portion of Virginia's James River, found that spawning was triggered by a rapid increase or decrease in salinity. Cain found that *Rangia cuneata* in lower salinity portions of their habitat (nearer the freshwater source) spawned after a rapid rise in salinity while those at the other habitat extreme behaved in the opposite fashion. Cain postulated that these responses appear to be a mechanism for accomplishing synchronous release of eggs and sperm. This spawning under abrupt changes in salinity would also appear to maximize the potential for the larvae to recruit into new areas if the favorable salinity conditions temporarily extend upstream or downstream. Once the larvae settle and begin to develop a shell, they can tolerate completely fresh water conditions at the upstream end and much higher salinity at the downstream limits. Although Cain did not give precise figures for the rise or fall magnitude necessary (e.g. 10 ppt) and over what time frame, he did find that a rise or fall to an endpoint of 5 ppt appeared "operative". Others have interpreted Cain's (1975) results and state that the upstream clams required an increase of about 5ppt while clams in the downstream portions of the habitat needed a decrease of 10 to 15 ppt to spawn (e.g. LaSalle and de la Cruz, 1985). Based on interpretation of the original figures presented in Cain (1975) it would appear that salinity changes on the order of 5 - 10 ppt over an approximate one to two week period was effective for inducing spawning in the James River estuary. The interpretation by the GSMA-BBEST (2011) was an approximate 5 ppt change, but over what time frame was not specified.

These fairly detailed environmental requirements for reproduction and recruitment of *Rangia cuneata* have been distilled to a fairly general level in the previous use of the species as an estuarine indicator in Texas. The recent efforts of the SB3 Basin and Bay Expert Science Teams and contributors, took as a given the 2-10 ppt requirements for early larvae and then determined the inflows necessary to support such a zone within the estuary for a duration on the order of one to two months (e.g. NWF, 2009; SN-BBEST, 2009; TRSJ-BBEST, 2009; GSMA-BBEST, 2011). Consideration of the year-upon-year frequency that such a favorable salinity zone must re-occur in order to support the *Rangia cuneata* population was not addressed in any detail, although the long-term historical occurrence level of the supporting inflow was considered. Other potential reproductive requirements such as the need for a rapid change in salinity to induce spawning, as described by Cain (1975) for *Rangia cuneata* in Virginia were not taken into account computationally although the GSMA-BBEST (2011) did note these.

Clearly, for *Rangia cuneata* there is a multifaceted array of spawn-inducing and larval survival traits that are salinity-controlled. While these salinity controls and durations are derived from studies in other geographic locations, the basic physiologic influences that salinity exerts on *Rangia cuneata* are quite probably applicable in Texas as well, though the specifics may vary.

3.1.1 Primary Biologic-Based Pattern Searches

The primary approach to salinity pattern identification in this study utilizes an integrated search for a fixed favorable salinity range, such as 2-10 ppt, that occurs continuously for some number of consecutive days, such as 15 days. The motivation for this pattern search is based on the biologic underpinnings of *Rangia cuneata*. The method maps favorable salinity areas that persist for a long enough duration to assure larval survival and recruitment into the adult population. Additionally, the issue of the frequency that these favorable patterns must re-occur is pivotal in this study. Therefore, the study will also rigorously examine the characteristics of re-occurrence of what appear, from other studies, to be the favorable salinity conditions for reproduction and recruitment.

3.1.2 Second Tier Biologic Conditions / Limitations

Given the influence that sharp changes in salinity appear to have on spawning in *Rangia cuneata* in other locations, a second tier of effort in this study was to examine the potential role that this trait may also exert on the geographic range of *Rangia cuneata* in the Guadalupe and Mission-Aransas Estuaries. After the initial spawn-inducing event, the subsequent period must also present the early and late larvae with the apparent conditions that support their survival and recruitment into the adult population as described above as “primary.” Thus this search is essentially a “look back” approach in which salinity must rise or fall by a specified amount over a specified number of days as a pre-condition to the favorable salinity conditions for larvae. Much more specific information on how these two salinity patterns are examined is presented below.

3.1.3 Seasonal Limits

Previous research on *Rangia cuneata* in Florida, Virginia, and Mexico (as summarized in LaSalle and de la Cruz, 1985) found that most spawning occurred in two periods corresponding more or less to spring and late summer - fall. However, these may be more of a reflection of the necessary salinity change conditions, and LaSalle and de la Cruz (1985) point out that spawning potential may be continuous. Cain (1975) found that the production of reproductive cells began when water temperatures rose to 15°C.

For the purposes of this study the 15°C threshold was used to indicate the portion of the year in which reproduction might take place. Water temperature data for the Guadalupe Estuary from the TPWD Coastal Fisheries Resource Monitoring Program of the Texas Parks and Wildlife Department (TPWD, 2012) was analyzed. Figure 4 presents the analysis results showing that the period from February through November generally has median temperatures to support *Rangia* *cuneata* reproduction. However, special consideration of the month of February is in order since it is so close to the threshold. First, since these are median values, half of the samples for February for both the Upper and Lower portions of San Antonio Bay would not be at or above 15°C. Furthermore, the "Whole Bay" data appear to be highly influenced by the Espiritu Santu Bay results, while much of San Antonio Bay itself is just exactly at 15°C. Thus, in this study the period used to indicate temperatures suitable for reproduction and recruitment was from March through November.

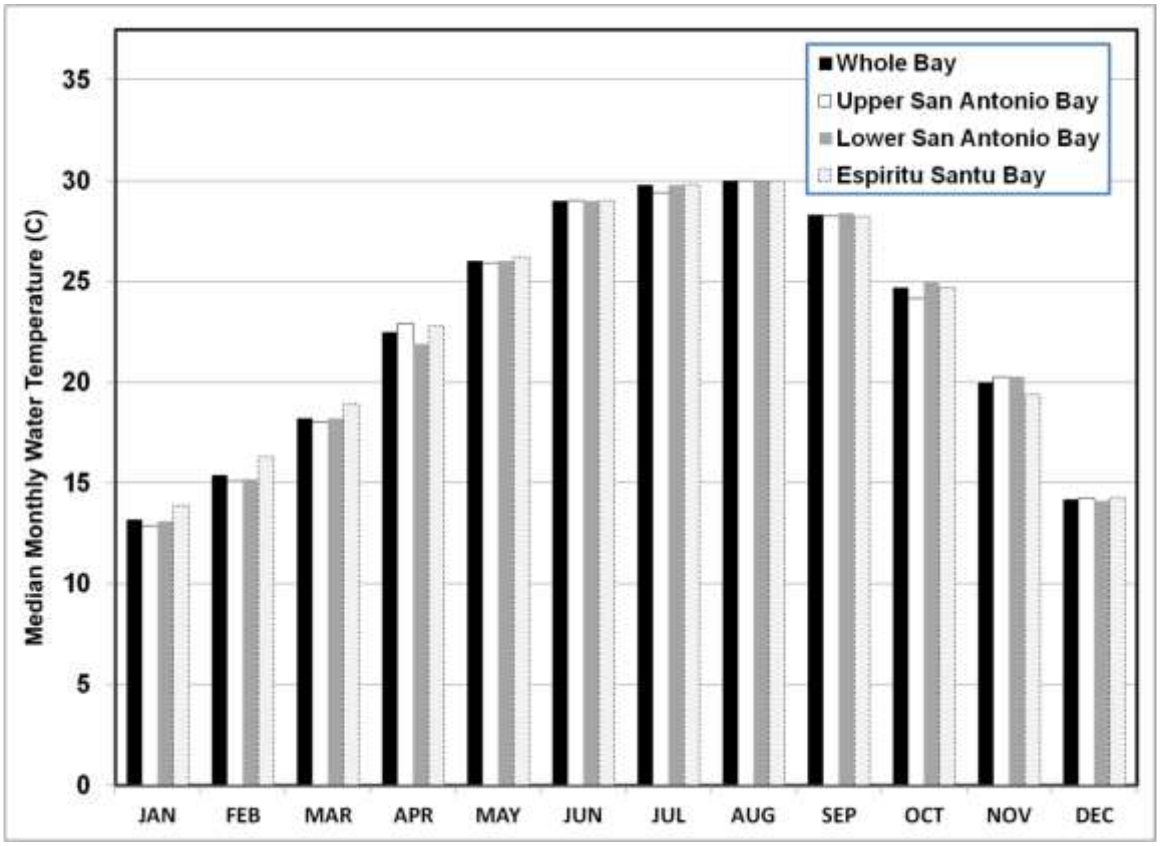

Figure 4. **Summary of monthly median water temperature values for the Guadalupe Estuary based on the data from Texas Parks and Wildlife Department's Coastal Fisheries Resource Monitoring Program (TPWD, 2012).**

3.2 Salinity in the Guadalupe and Mission-Aransas Estuary System

Clearly from the above discussion, salinity data are fundamental to this study. Broadly speaking, there are salinity data available falling into two categories: a) field-measured values and, b) those predicted salinities from a hydrodynamic model or from statistical (regression) approaches. While actual field data would be the first choice for pursuing the analyses herein, there are only a few sites in the Guadalupe and Mission-Aransas Estuaries with permanent salinity monitoring (see GSMA-BBEST, 2011). Additionally, the period of record for some of these sites is very short and thus pose great limitations.

Fortunately, there are means of predicting salinities, either at times or locations where field data are not available. The Texas Water Development Board (TWDB) maintains a mathematical model, known as TxBLEND, which simulates the hydrodynamics and salinity transport within the Guadalupe and Mission-Aransas Estuaries (and Matagorda Bay at the northern end) based on inflows and other variables (e.g. tides and winds). The period of record covered by TxBLEND is January 1987 - October 2009. TxBLEND subdivides the estuary into a fine mesh of nodes and simulates the salinity at each with a time step of 3 minutes with output generated at one hour intervals. More important for this study is that TxBLEND provides a fine spatial scale which facilitates the search for spatially-based re-occurring salinity patterns. This model was recently calibrated and updated to include revised inflow estimates (Guthrie and others, 2010a and 2010b; Guthrie and Lu, 2010). The GSMA-BBEST (2011), based on examination of TWDB's calibration and verification efforts, found that the TxBLEND model performs with a reasonable level of accuracy with some noted concerns for portions of the Mission-Aransas Estuary.

This study relies fundamentally on output of the TxBLEND model covering the two estuaries and using a time-scale resolution of daily average values. While the TxBLEND model has several thousand nodes, for this work a subset of 162 well-dispersed nodes were selected as shown in Figure 5. This level of resolution was found to be adequate to cover the entirety of the interlinked Guadalupe and Mission-Aransas Estuary system and yet provide good coverage for the contouring and mapping exercises. Of those selected nodes, fifteen were reserved for validation purposes in the contouring of salinity pattern data (described below). Appendix A documents the nodes utilized in greater detail.

Figure 6 illustrates an example of the TxBLEND model's time-series prediction of daily salinity for the 2004-2005 period at two highlighted points within the Guadalupe Estuary (locations shown on the previous figure). At both locations there is a clear response of lowered salinity during the periods of high to very high inflows that occurred in May - June 2004 and again in late Nov.-through December 2004. However, the lowermost point, BB, consistently maintains a higher level of salinity due to its location farther down the estuary.

While the salinity predictions of TxBLEND are of fundamental value to this study, the search for explanatory salinity patterns relies on several further computational steps to derive certain specialized variables based on the underlying salinity itself. The derivation of these variables and the extensive use of these for map-based pattern recognition and comparison to the geographic extent of the *Rangia cuneata* population are the topics of the next section.

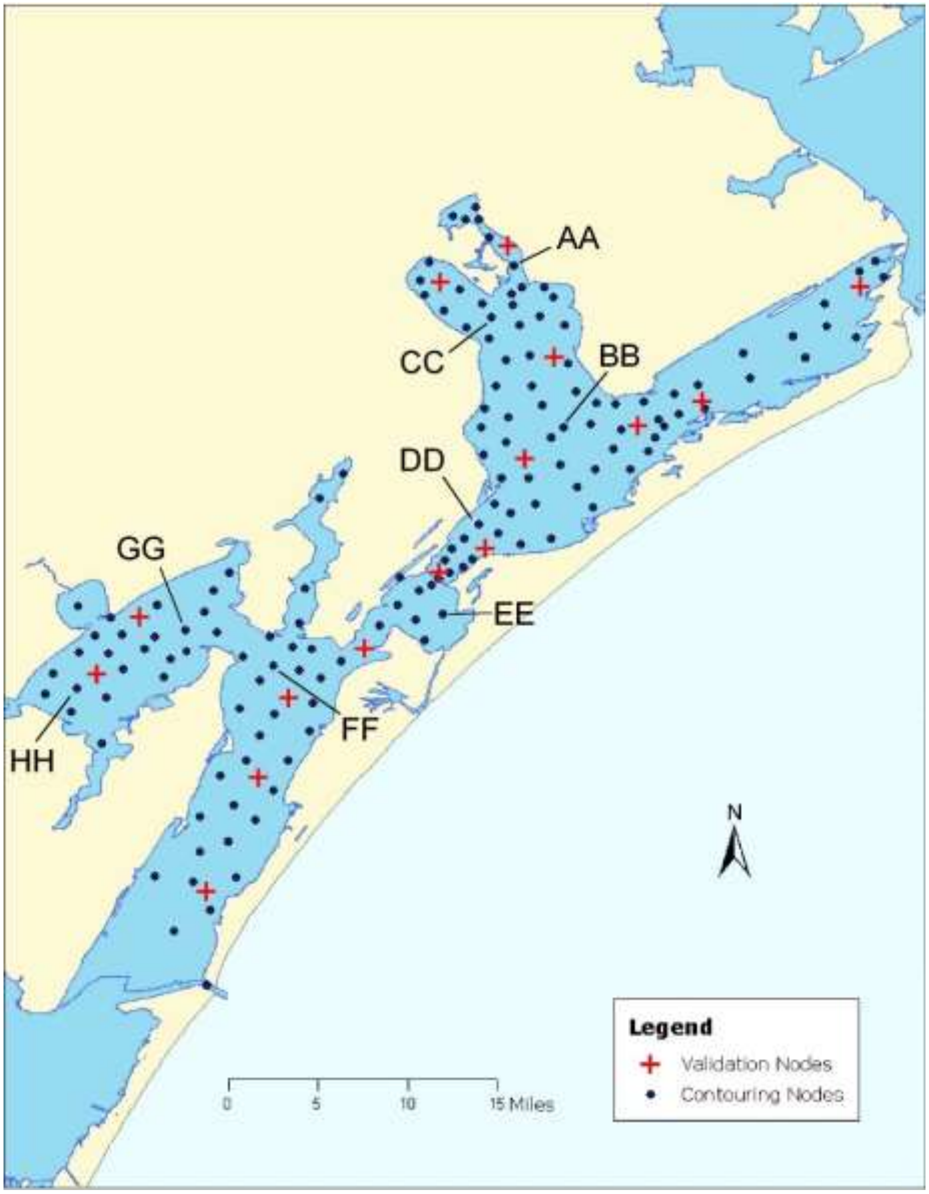

Figure 5. The points utilized for salinity pattern examination within the Guadalupe and Mission-Aransas Estuary system. Each point (dot or cross) corresponds to a computational node of the TWDB's TxBLEND hydrodynamic and salinity transport model. Labeled points (e.g. "AA") will be referred to within the report and in other figures. (see Appendix A for more details on nodes).

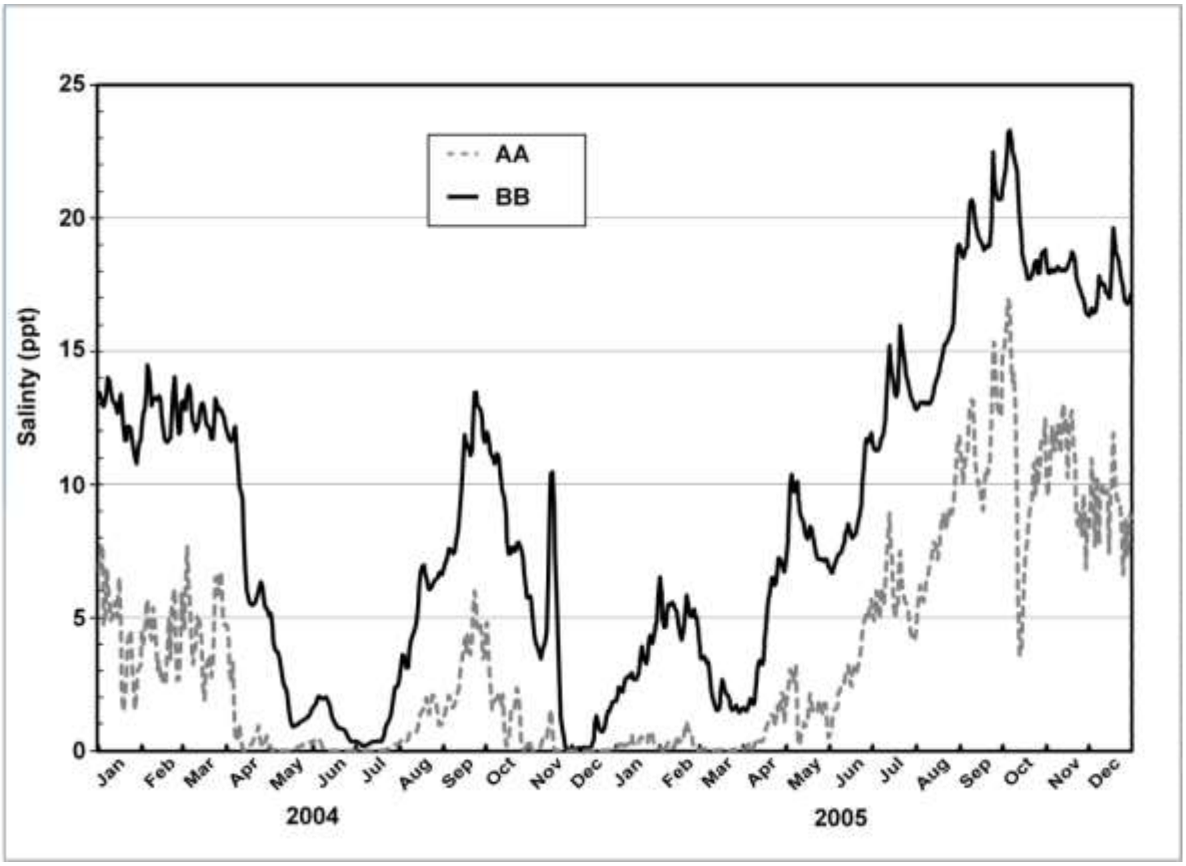

Figure 6. **Illustration of the TxBLEND model's prediction of salinity at points AA and BB (locations shown in previous figure) for the period of 2004-2005. The period illustrated contains a high degree of variability of salinity within the Guadalupe Estuary due to highly ranging inflow conditions.**

3.3 Specific Salinity Searches - Computational Pathway

Because of the apparent large role that salinity plays in controlling the reproduction and recruitment of *Rangia cuneata*, several specialized variables were developed in this study to describe salinity patterns of potential significance.

3.3.1 Primary Pattern Searches

Because survival of *Rangia cuneata* larval stages depend on salinity being maintained within a certain range for a minimum duration, the first new variable integrates this combination of salinity magnitude and duration. The variable CSD (consecutive salinity days) is introduced to denote consecutive days in which salinity is within a certain fixed range. Thus, the variable CSD_{0-10} denotes a count of consecutive days in which salinity is within the range of 0 to 10 ppt at a fixed point in the estuary system. Figure 7 illustrates this variable as derived from the salinity data at point BB as shown on previous figures above for just the years 2004-2005. For these initial explanatory purposes, at this point no seasonal limitations on the occurrence of CSD are considered except that a string of consecutive days may not continue past the end of a year.

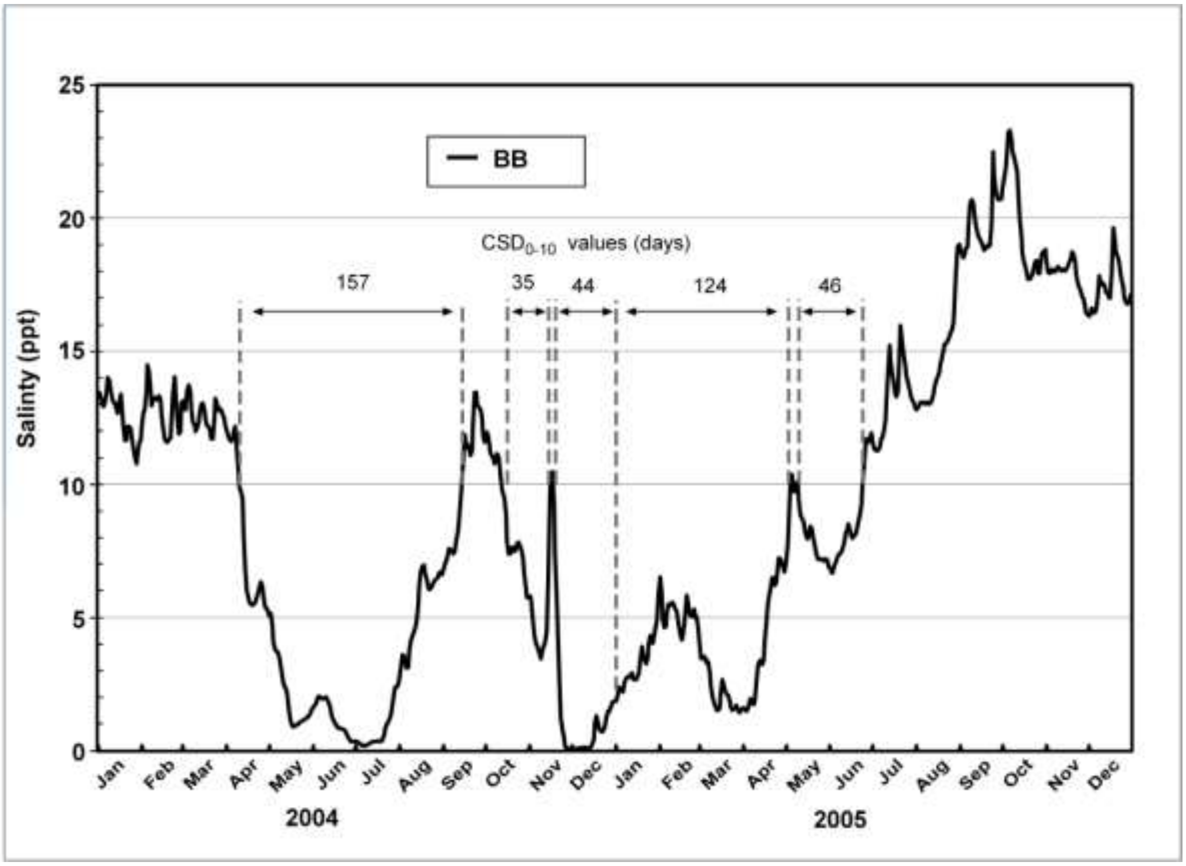

Figure 7. **Illustration of the variable consecutive salinity days (CSD) for salinity in the range of 0- 10 ppt for the 2004-2005 period at the point BB (previously located).**

Because of the focus on comparing *Rangia cuneata* and salinity patterns in a spatial context, for this study it is useful to recast the point-by-point CSD variable as derived above into a form that can be portrayed on a map. For the purposes of finding CSD values that are of adequate length to support reproduction and recruitment, the maximum annual CSD value at each point for each year is utilized (e.g. 157 days for 2004 and 124 days for 2005 at point BB). Again, for illustrative purposes at this point, the whole year's salinity is considered. For a given year, the suite of such values, one for each node depicted in Figure 5, can be used as the basis for a contour map of CSD. More details on the method of contouring the point CSD data into a map view is given in Appendix B. As shown in Figure 8 this map of CSD_{0-10} is just for the year 2005, which had a more-or-less average yearly total of inflow (2.36 million acre-feet, 12th rank) in the TxBLEND model's 23 year record covering 1987-2009. Figures 9 and 10, respectively, show the same depiction of CSD_{0-10} for both the wet year 2004 (5.50 million acre-feet, 3rd rank) and dry year of 2008 (0.84 million acre-feet, 20th rank) to contrast to the average year 2005.

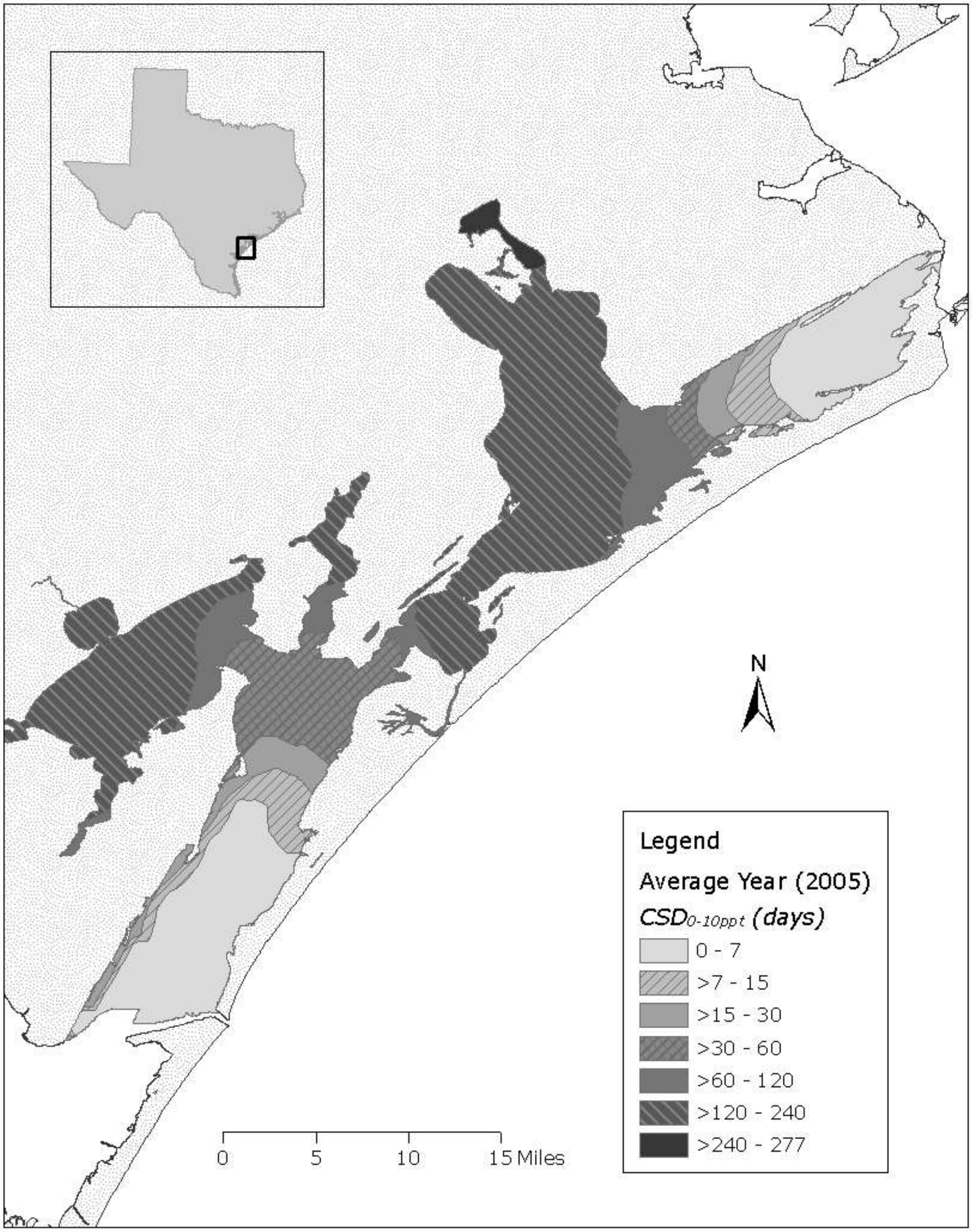

Figure 8. **A map view of the maximum annual value of CSD_{0-10} throughout the Guadalupe and Mission-Aransas Estuary systems for the year 2005, a year of nearly average inflow within the range for the 1987-2009 period.**

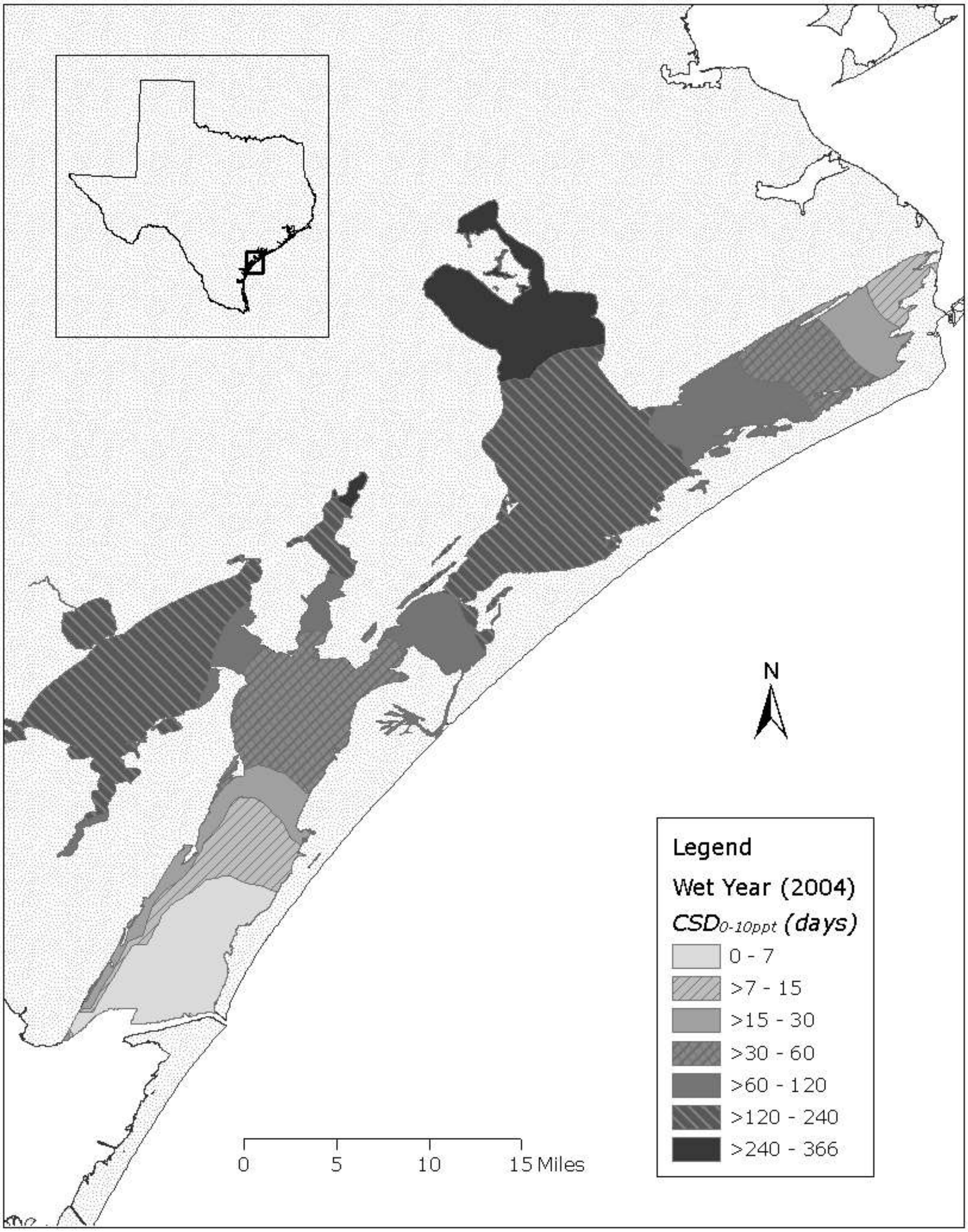

Figure 9. A map view of the maximum annual value of CSD_{0-10} throughout the Guadalupe and Mission-Aransas Estuary systems for the year 2004, a year of high inflow within the range for the 1987-2009 period.

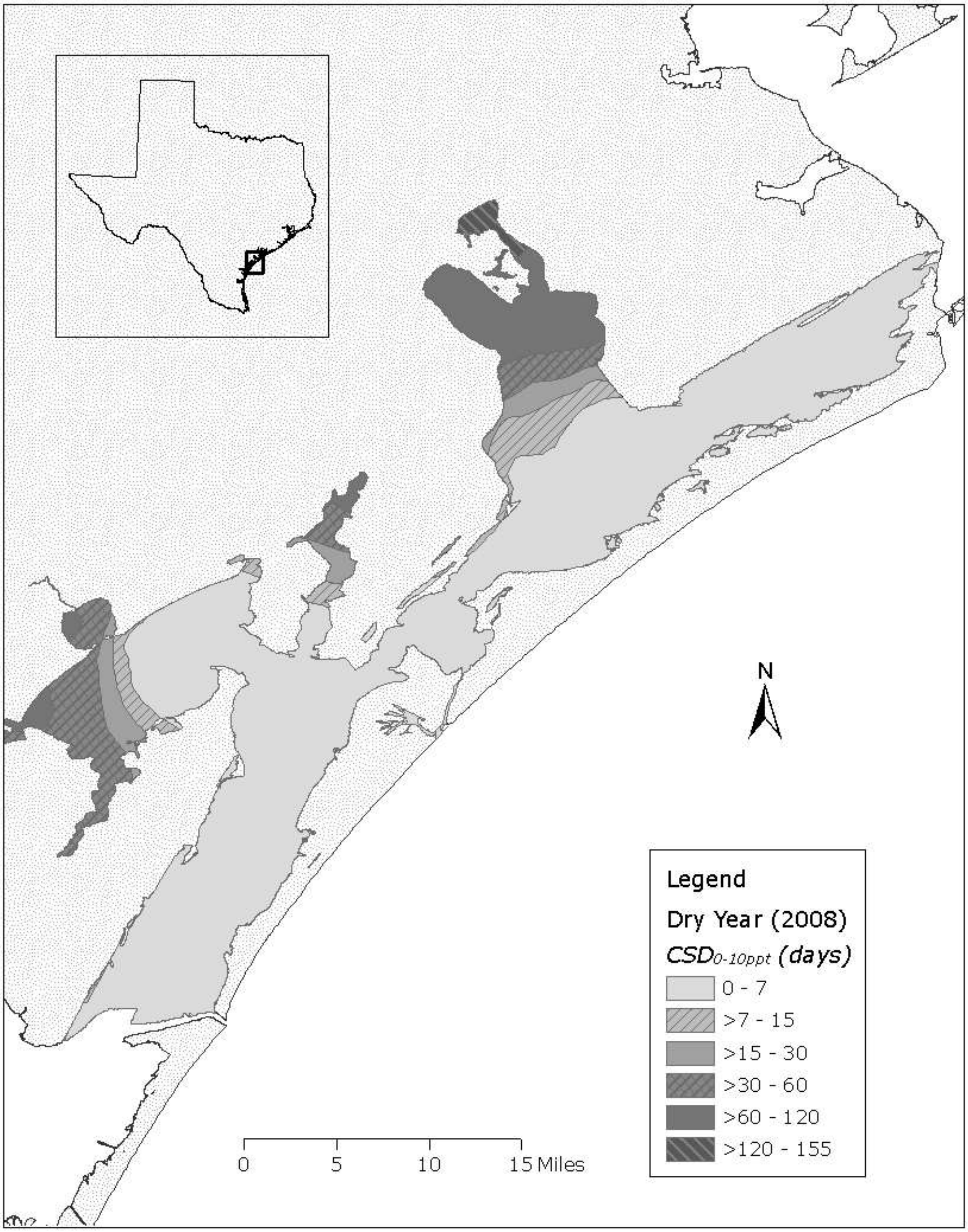

Figure 10. **A map view of the maximum annual value of CSD_{0-10} throughout the Guadalupe and Mission-Aransas Estuary systems for the year 2008, a year of very low inflow within the range for the 1987-2009 period.**

Figure 11 illustrates the derivation of a set of CSD values but with a non-zero lower bound and again without limitation to the time of year, except the same CSD termination at the end of a year as above. These CSD values are for the salinity range of 2-10 ppt at the same point BB and for the same time period as used above. The influence of the lower salinity range bound of 2 ppt is clearly evident with much shorter durations for CSD_{2-10} and a greater number of periods.

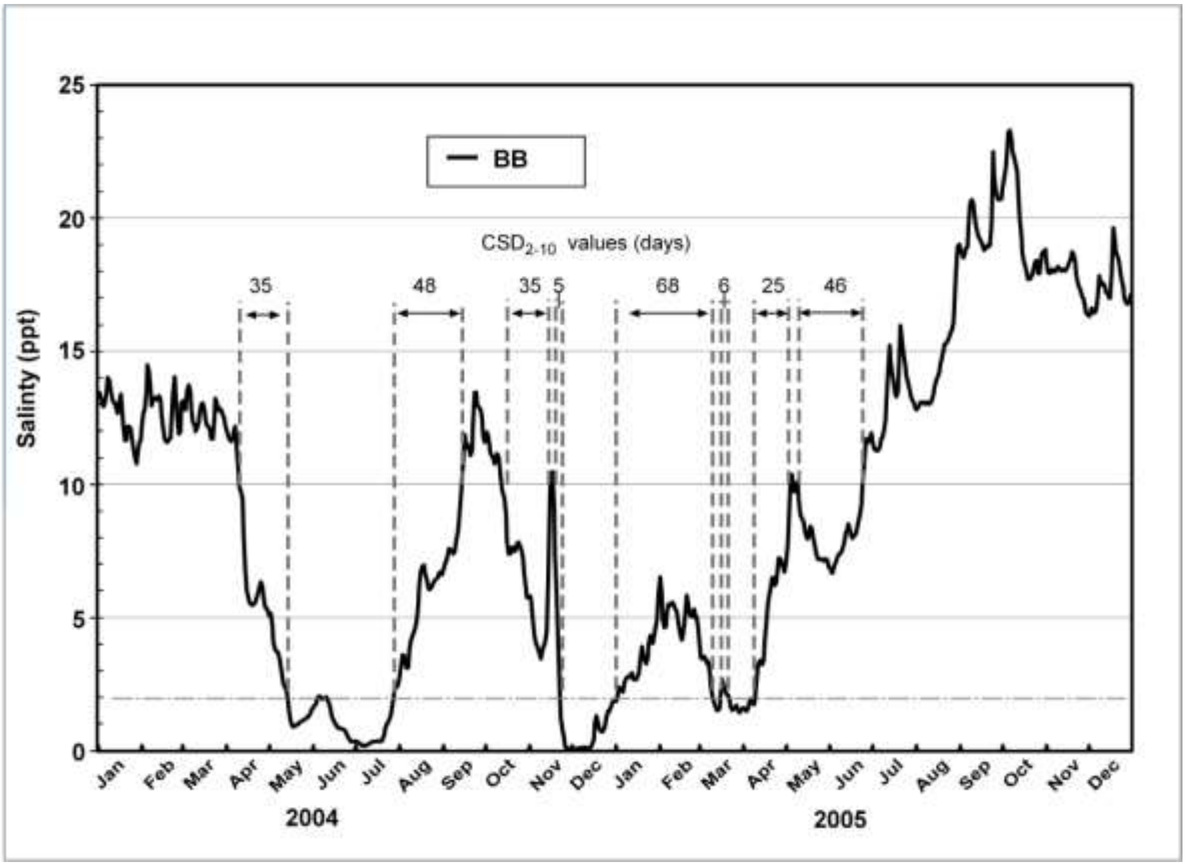

Figure 11. **Illustration of the variable consecutive salinity days (CSD) for salinity in the range of 2- 10 ppt for the 2004-2005 period at the point BB (previously located).**

Analogous to the spatial portrayal of CSD_{0-10} previously, Figures 12 through 14 present the spatial view of CSD_{2-10} values for the average (2005), wet (2005), and dry (2008) years, respectively. A particularly relevant feature associated with the non-zero lower bound of 2 ppt emerges in these figures. In contrast to the spatial behavior of the CSD_{0-10} variable, there is a clear "sandwich effect" for CSD_{2-10} due to the non-zero lower bound of 2 ppt. For example in Figure 12, CSD_{2-10} values peak in the >120 days bracket over just a limited area more-or-less corresponding to Mesquite Bay, the transition zone between the Guadalupe and Mission-Aransas Estuaries, before declining again as one moves into the core of the Guadalupe Estuary. This effect is also evident in the middle and upper portions of Copano Bay.

This effect is the result of these "fresher" areas of the estuary system being more likely to fall below the 2 ppt lower cutoff. Of course, these same areas are more likely to maintain salinity below the upper limit of 10 ppt, which would tend to increase CSD lengths, but as shown in

Figure 12, on balance, there is a definite decrease in overall likelihood of staying within the 2 - 10 ppt range in the upper portions of either estuary during this average inflow year (2005) compared to the 0-10 ppt range (see Figure 8). A similar effect, although with differing CSD_{2-10} lengths, is evident for the wet year as shown in Figure 13. For the dry year plot of CSD_{2-10} in Figure 14, the effect is barely discernable, with the contour intervals used, but is evident in the very upper portion of the Guadalupe Estuary. For the dry year, over much of the upper half of the Guadalupe Estuary the peak in CSD_{2-10} falls in the range of 60-100 days, but then exhibits a decline back into the 30 - 60 day range at the very top of the estuary. At the contour intervals used the effect is not evident in the upper portions of the Mission-Aransas Estuary for the dry year example although examination of the actual point-specific data does show a slight decrease in CSD_{2-10} in this area.

Another notable feature of the series of maps for CSD_{2-10} presented in Figures 12 - 14 is that the maximum values of CSD are found in the average year not the wet year. More specifically, in the average year most of San Antonio Bay exhibited CSD_{2-10} in the range of 60-120 days whereas for the wet year much of the lower half of the bay was in the 30-60 days range. Again these are the net effects of the lower non-zero bound wherein salinity in many areas during the wet year falls below the 2 ppt lower salinity limit.

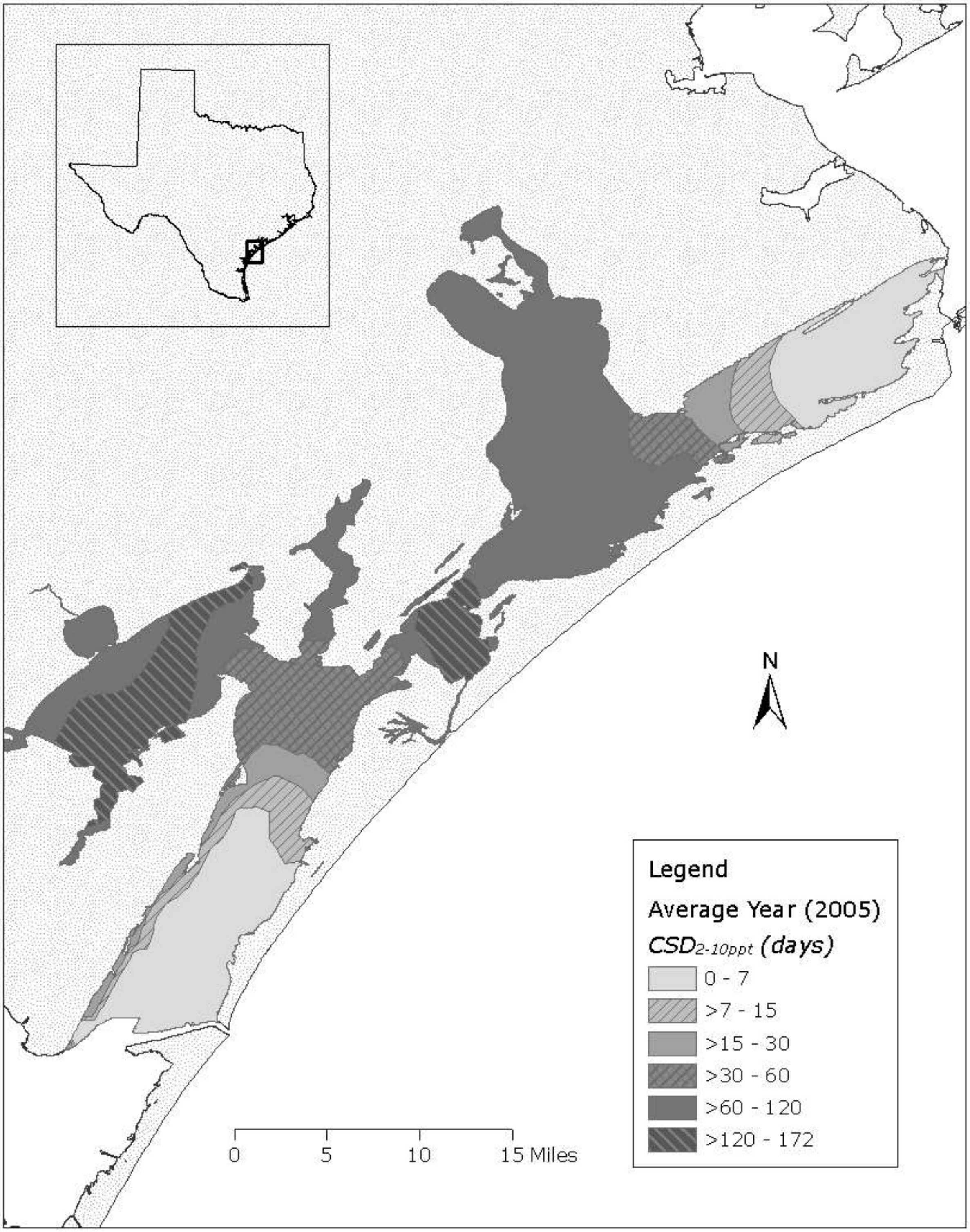

Figure 12. **A map view of the maximum annual value of $CSD_{2\text{-}10}$ throughout the Guadalupe and Mission-Aransas Estuary systems for the year 2005, a year of nearly average inflow within the range for the 1987-2009 period.**

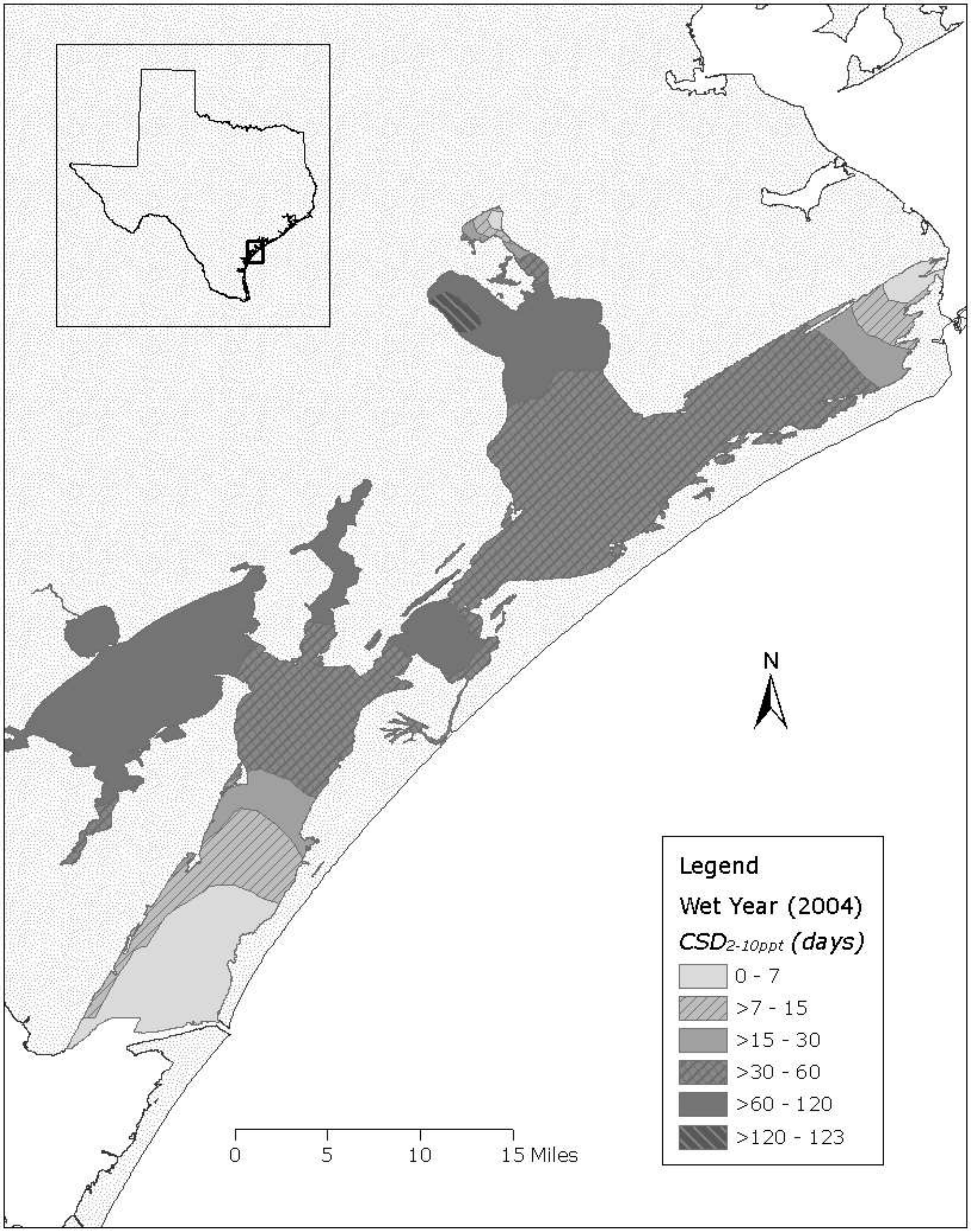

Figure 13. **A map view of the maximum annual value of $CSD_{2\text{-}10}$ throughout the Guadalupe and Mission-Aransas Estuary systems for the year 2004, a year of very high inflow within the range for the 1987-2009 period.**

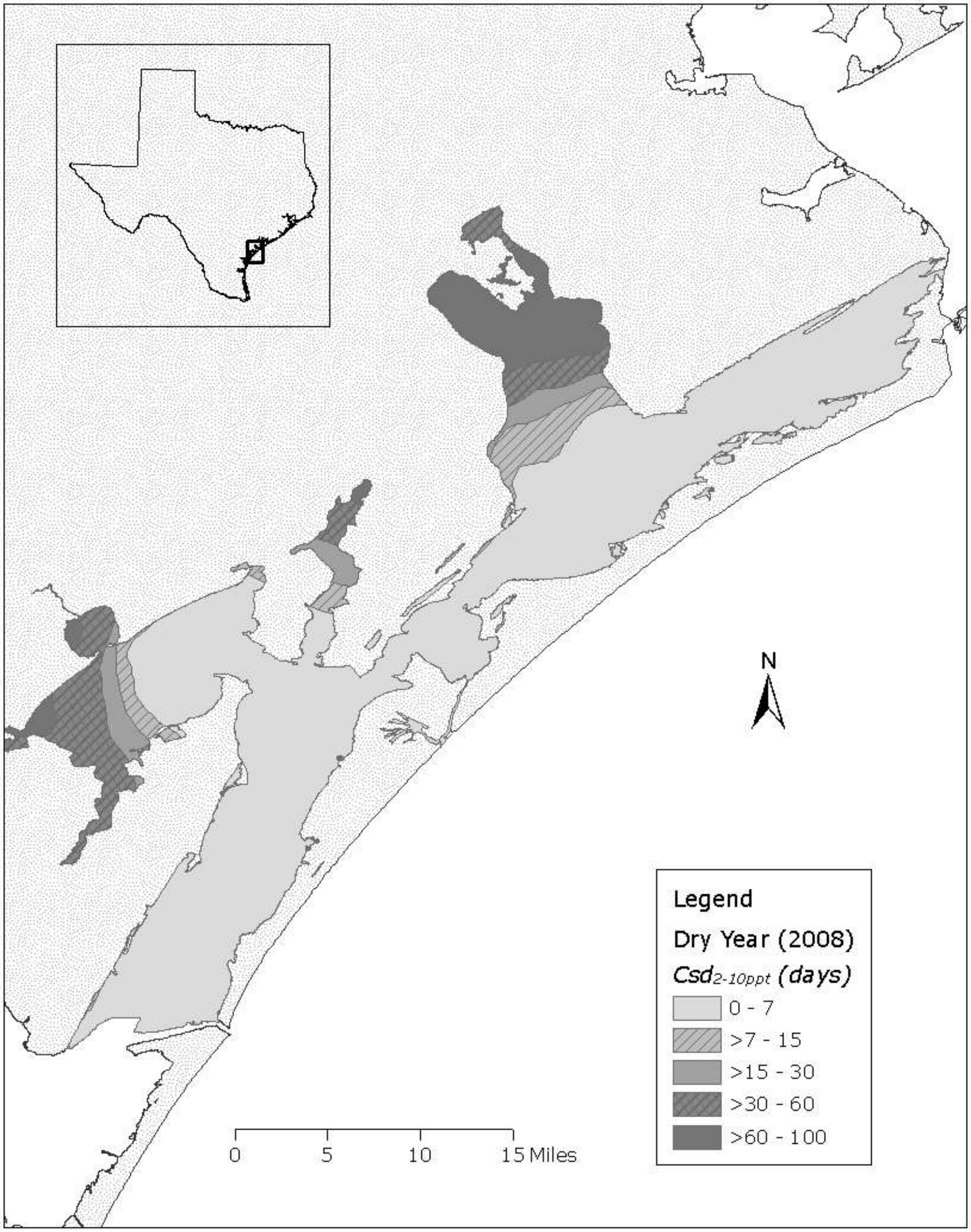

Figure 14. A map view of the maximum annual value of $CSD_{2\text{-}10}$ throughout the Guadalupe and Mission-Aransas Estuary systems for the year 2008, a year of very low inflow within the range for the 1987-2009 period.

3.3.2 Examining Spawning Limitations

As mentioned in the Biological Underpinnings section above, the primary searches for consecutive salinity days within specific salinity ranges is most suitable for implications on larval survival and recruitment of young clams into the adult *Rangia cuneata* population. The other key salinity-controlled process, at least based on Cain's (1975) results from the James River in Virginia, is the need for an abrupt salinity change to induce spawning. Thus, the occurrence of a favorable salinity condition for larval survival, as captured by CSD above in the primary searches, may also have what is essentially a "pre-condition" for successful reproduction to occur. A string of consecutive salinity days that also follow an abrupt salinity change (defined below) will be labeled CSD*.

Though somewhat beyond the initial scope, some additional effort was made in this study to examine to what extent the CSD occurrences found via the primary search also meet such presumed pre-conditions for spawn initiation and become CSD* values of sufficient length and frequency. Cain's (1975) figures indicate that salinity changes on the order of 5 - 10 ppt over an approximate one to two week period were effective for inducing spawning.

Figure 15 illustrates how the normal $CSD_{2\text{-}10}$ determination from above (Figure 11) is further conditioned by examining if some portion or all of the periods of CSD follow an abrupt salinity change. In this portrayal, all CSD values are tracked on the right axis and, as before, are not limited by seasonal constraints. Since CSD accumulates day-by-day these plot as sawtooth shapes when they occur. The original values for $CSD_{2\text{-}10}$ are shown with the solid green line. Also shown, in blue are the $CSD^*_{2\text{-}10}$ values for an abrupt salinity change assessment. The parameters used to define "an abrupt salinity change" in this example are indicated by the parameters rise and fall (R and F) for the magnitude of change in salinity and the period over which it must occur (in days). Thus CSD*2-10 [R5/F5/7day] indicates a string of continuous days with salinity in the range 2-10ppt, but also following a salinity change of at least 5ppt over a 7 day period. In this case the rise and fall magnitude are the same (5ppt), but that is not a necessary condition. The striking feature of this figure is how many of the original periods of $CSD_{2\text{-}10}$ did not have the necessary pre-condition for an abrupt salinity change, using parameters roughly in line with what Cain (1975) found. Of the six original $CSD_{2\text{-}10}$ occurrences in 2004-2005 that were over 20 days in length, only one had the necessary abrupt change pre-condition. More on the significance of this facet of *Rangia cuneata* reproduction will be given below in the findings section.

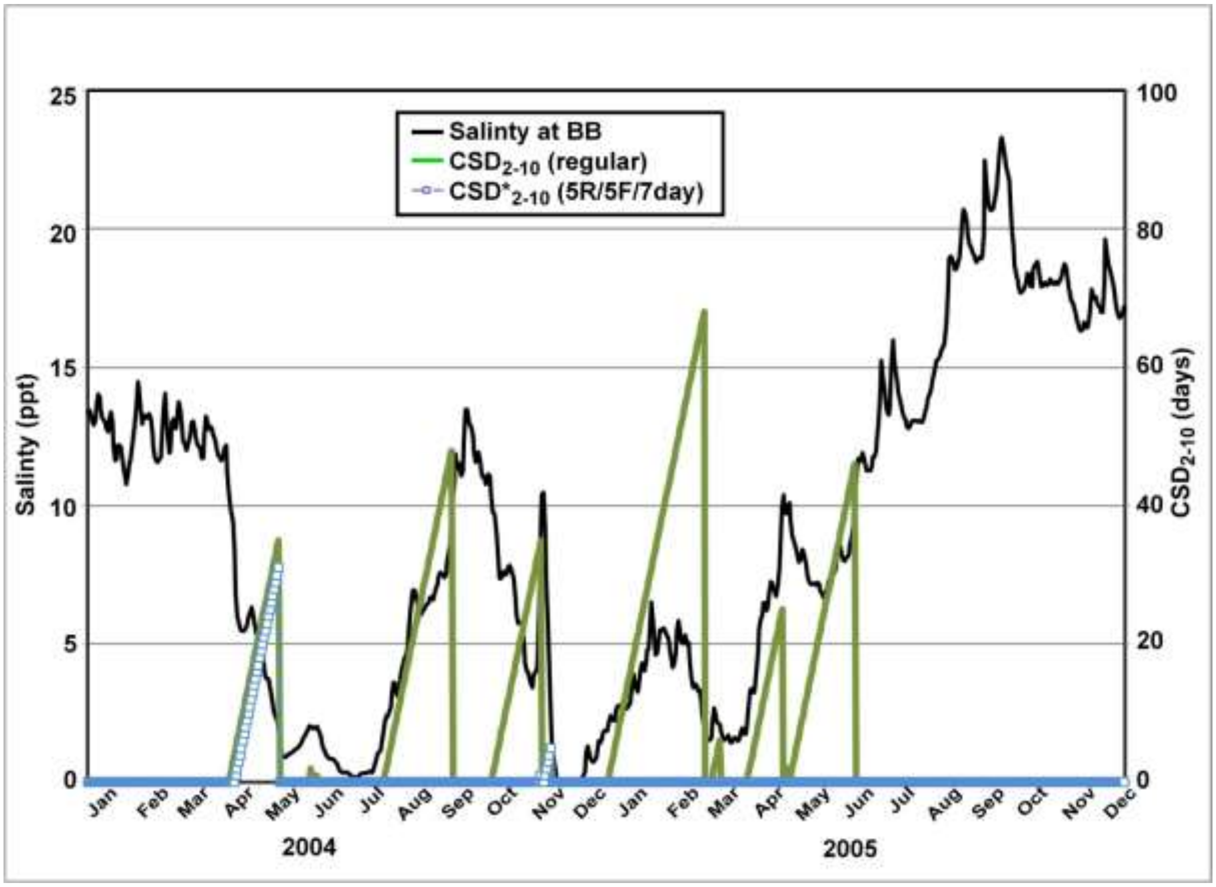

Figure 15. **Illustration of the how the number of occurrences of consecutive salinity days (CSD) for salinity in the range of 2- 10 ppt is greatly diminished if a pre-condition of abrupt salinity change is added. Shown are results for the 2004-2005 period at the point BB (previously located).**

3.3.3 Return Periods

While the variable CSD integrates both the magnitude of salinity (e.g. in the 2 - 10 ppt range) and the duration of salinity within that range, there is still the need to incorporate a measure of the frequency with which these or other apparently favorable salinity conditions occur. This is motivated primarily by the life history characteristics of *Rangia cuneata*, alluded to above, in which a favorable period for reproduction and recruitment would not have to occur every year to sustain the population. Thus, a variable which captures how often a favorable salinity condition or "event" occurs was developed in this study.

The variable rCSD is introduced to denote the *return period* for consecutive salinity days (CSD). This calculated variable is a measure of the frequency with which a certain salinity "event" re-occurs over a long period of time. In this study, each "event" is the occurrence of a specific period of consecutive salinity days that fall above a benchmark value, such as 15, 30, or 60 days. The calculation method finds events that occur on average once per 5 years, or once per 10 years, etc. As such, it is an analog to those used in hydrology to find return periods for certain flow values, usually high-flow events (Chow and others, 1988).

Figure 16 illustrates the concept beginning with the sequence of annual maximum values of CSD_{2-10} events at the point BB, which range from 0 in several years to 136 days in 2003. Those events that are greater than 60 days in length are highlighted in grey. For the example there are 9 qualifying events with at least 60 day length. The *re-occurrence intervals* (or *return intervals*), the time between such events greater than 60 days, are shown near the top of the figure (e.g. 4 years between 1987 and 1991). Thus the *return period* for CSD_{2-10} events of 60 day length is, mathematically, the *expected value* of time between the events over a long time period. The shorter the return period, the more frequently occurring the event is. One approximation method for the return period is to use the total span of years containing the qualifying events divided by the number of events. For the example this would be a total period of 21 years (from 1987 - 2007) /9 events = 2.33 years. For this study however, in order to avoid a potential low bias in return period length determination, the entire period length of 23 years was used for all return period calculations. Thus for the example here for CSD_{2-10} events of 60 day length, the return period is 2.56 years or in a more formal mathematical form the $rCSD_{60days/2-10ppt}$ at point BB = 2.56 years. In a more colloquial form, we can say that at point BB we would expect salinity to remain in the 2-10 ppt range for 60 consecutive days about one time in each 2.56 years. Table 1 presents a suite of rCSD values determined for the point BB in the Guadalupe Estuary for several benchmark length values.

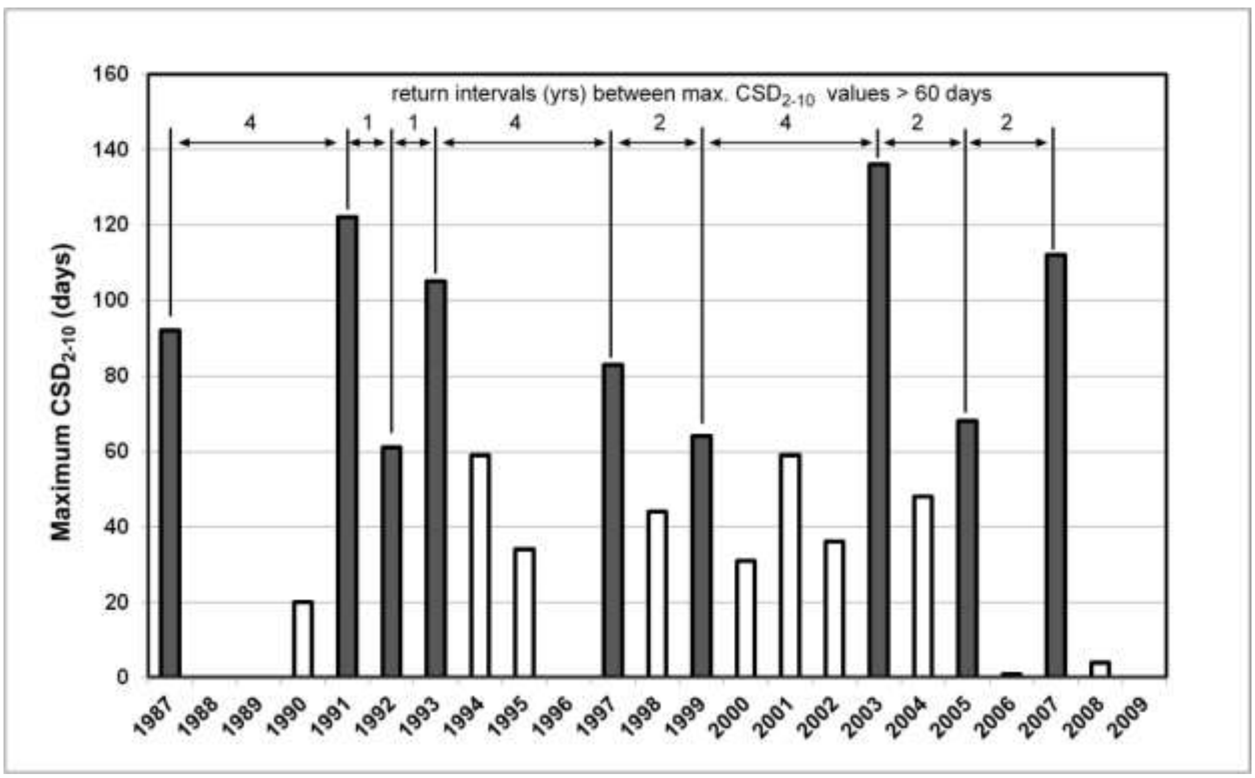

Figure 16. **Illustration of the derivation of the return period for CSD_{2-10} events greater than or equal to 60 days in length a the location BB (previously located).**

Table 1. Illustration of using the annual maximum series of $CSD_{2\text{-}10}$ at a fixed point to derive the return period for a specific benchmark duration.

benchmark length (days)	number of qualifying events	return period (years)
7	17	1.35
15	17	1.35
30	16	1.44
45	12	1.92
60	9	2.56
90	5	4.6
120	2	11.5

As noted above, these return period calculations utilize the whole 23 year period of the TxBLEND model. In the opinion of this author, this avoids the potential for a low bias and better reflects the actual rarity of certain events. For instance in the calculation of $rCSD_{120days/2\text{-}10ppt}$ there are only two qualifying events separated by just 12 years (1991 and 2003 in Figure 16). Using the entire period of 23 years gives the return period result of 11.5 years in Table 1. The alternative using just the 12 years between the events would yield a return period estimate of 6 years. This is an important consideration in this study because of the particularly short overall period of record of just 23 years. In the field of hydrology and meteorology, the typical application of the return period calculation methodology, the periods of record for underlying data are generally on the order of 100 years.

Through the procedure given above, the rCSD values for any particular salinity range and duration can be found. If this is done for each of the spatial nodes presented in Figure 5, it is once again possible to portray the results in a contoured map-based view. Figure 17 presents the results for the 60 day duration of $CSD_{2\text{-}10}$, again with no limits for the time of year of occurrence. Though this is apparently a novel approach for portraying salinity patterns in an estuary, this spatially-explicit procedure is an analog of techniques long employed in meteorology to describe the geographic behavior of precipitation extremes. A good example is the contour maps of Herschfield (1961) which portray maximum precipitations accumulated over a certain standard duration (from 1 hour to several days) that re-occur with specific frequencies (e.g. 1 per year through 1 per 100 years).

Some discussion/interpretation of this type of salinity map (Figure 17) is in order since this type of depiction of re-occurring salinity patterns is of pivotal importance in this study. At the point BB we may now say that salinity in the 2 - 10 ppt range and maintained for 60 consecutive days and without regard to the time of year, re-occurs with a return period of about once per 1.5 - 2.5 years. The return period, again, is a measure of frequency, with the lower the number the more frequent the event. The return period at point BB is much closer to 2.5 years because of its proximity to the next contour band for 2.5 -5 years.

Overall, this map shows that over a broad swath of the Guadalupe Estuary and most of Copano Bay in the Mission-Aransas Estuary, one would expect that salinity in the 2 -10 ppt range will be maintained for at least 60 consecutive days fairly often since most of these areas are covered by the 1.5-2.5 and 2.5-5 year zones. By contrast, areas in Espiritu Santo Bay and the lower most portion of Aransas Bay toward the Aransas Pass would not be expected to maintain salinity in this range for a consecutive 60 day period very frequently. The >20 year contour represents areas with either one occurrence or none in the 23 period of record.

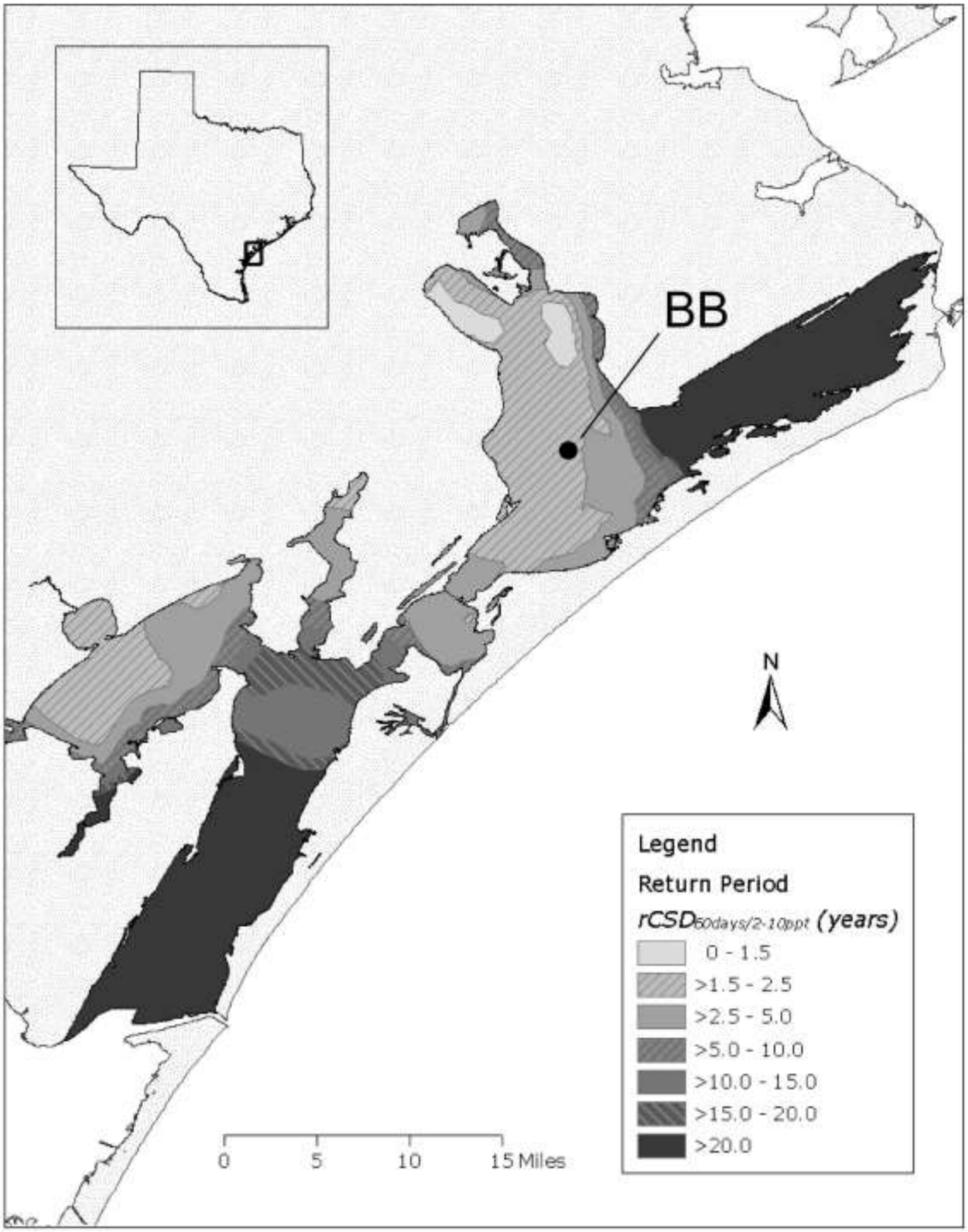

Figure 17. Map view of the return period results for $CSD_{2\text{-}10}$ of 60 day duration throughout the Guadalupe and Mission-Aransas Estuary systems for entire 1987-2009 period.

4 Findings

With the creation of the specialized variables based on salinity as described above, it is now possible to examine if certain salinity patterns that appear to be biologically significant for *Rangia cuneata* do, in fact, explain the apparent population distribution. The initial presentations of CSD, CSD* and rCSD in Section 3 were intended for explanatory purposes only and thus were not constrained by any time-of-year considerations. In the searches for explanatory salinity patterns undertaken from here on, the time of year for reproduction and recruitment is based on water temperature and taken as March - November (see Figure 4). The important findings are organized according to the type of salinity pattern search employed to examine a limit on the *Rangia cuneata* population distribution. These are either a primary search, just based on consecutive days in a favorable salinity range, or the second tier level in which a spawn-initiating salinity change “pre-condition” also must occur.

4.1 Primary Pattern Searches - Regular Consecutive Salinity Days

Given the apparent need for salinity to be maintained in specific ranges for *Rangia cuneata* larvae survival, the primary pattern searches here are based on the consecutive salinity days variable. Literature values for the favorable range of salinity form the foundation for pattern identification. The initial evaluations here were made using the widely-cited salinity range of 2 - 10 ppt (e.g. Harrel; 1993). The other biologically important aspects of a salinity pattern to support reproduction and recruitment are the duration and frequency of re-occurrence. The durations evaluated here are informed primarily by the work of Cain (1973). The initial favorable salinity condition must be of sufficient length to allow larval growth to the stage at which they settle and start to form a shell, at which point the clams begin to be less sensitive to salinity (Cain, 1973). In the very controlled laboratory setting of his work, in which food was not limited and temperature was tightly controlled, Cain found that larvae mature to the point of settling in approximately 8 days. For the evaluations here, examining actual estuarine survival prospects, a minimum of 15 days was used as the beginning point for salinity pattern identification. Again, all the pattern searches here are limited to the March- November period.

For the frequency of re-occurring favorable salinity, as indicated by the return period, in this study it is assumed that a return period of less than 5 years is a rough guide for an upper bound that would be necessary to support a healthy *Rangia cuneata* population that reproduces and recruits fairly regularly. This is based on studies indicating an average age of about 4-5 years (Fairbanks, 1963). Since some individuals may live longer, a less frequent re-occurrence might support a population, but it should be marked by just a few very even age classes as pointed out by previous investigations (Hopkins and others, 1973).

Figure 18 portrays the patterns of $rCSD_{15days/2\text{-}10ppt}$ across the Guadalupe and Mission-Aransas Estuaries, limited to the March-November period. This is a depiction of how often, using the 1987-2009 period, the favorable salinity range 2 - 10ppt occurred for a minimum of 15 days continuously in the months March-November. For instance in the vicinity of the point BB (shown on Figure 17), this favorable salinity range for reproduction and recruitment is maintained for 15 consecutive days very frequently; it re-occurs about every 1.5 years over the long term. In fact most of the Guadalupe Estuary, with the exception of Espiritu Santo Bay, would experience this favorable salinity pattern that would appear to support *Rangia cuneata* reproduction and recruitment with a fairly high regularity, with return period measures generally less than 2.5 years. This is also true for most of Mesquite Bay and the entirety of Copano Bay. In the upper end of Aransas Bay adjacent to Copano and Mesquite Bays, this favorable salinity pattern re-occurs a bit less frequently falling into the 2.5 - 5 year category. The frequency of this favorable pattern declines markedly as one progresses on down the length of Aransas Bay toward the Gulf inlet at Port Aransas.

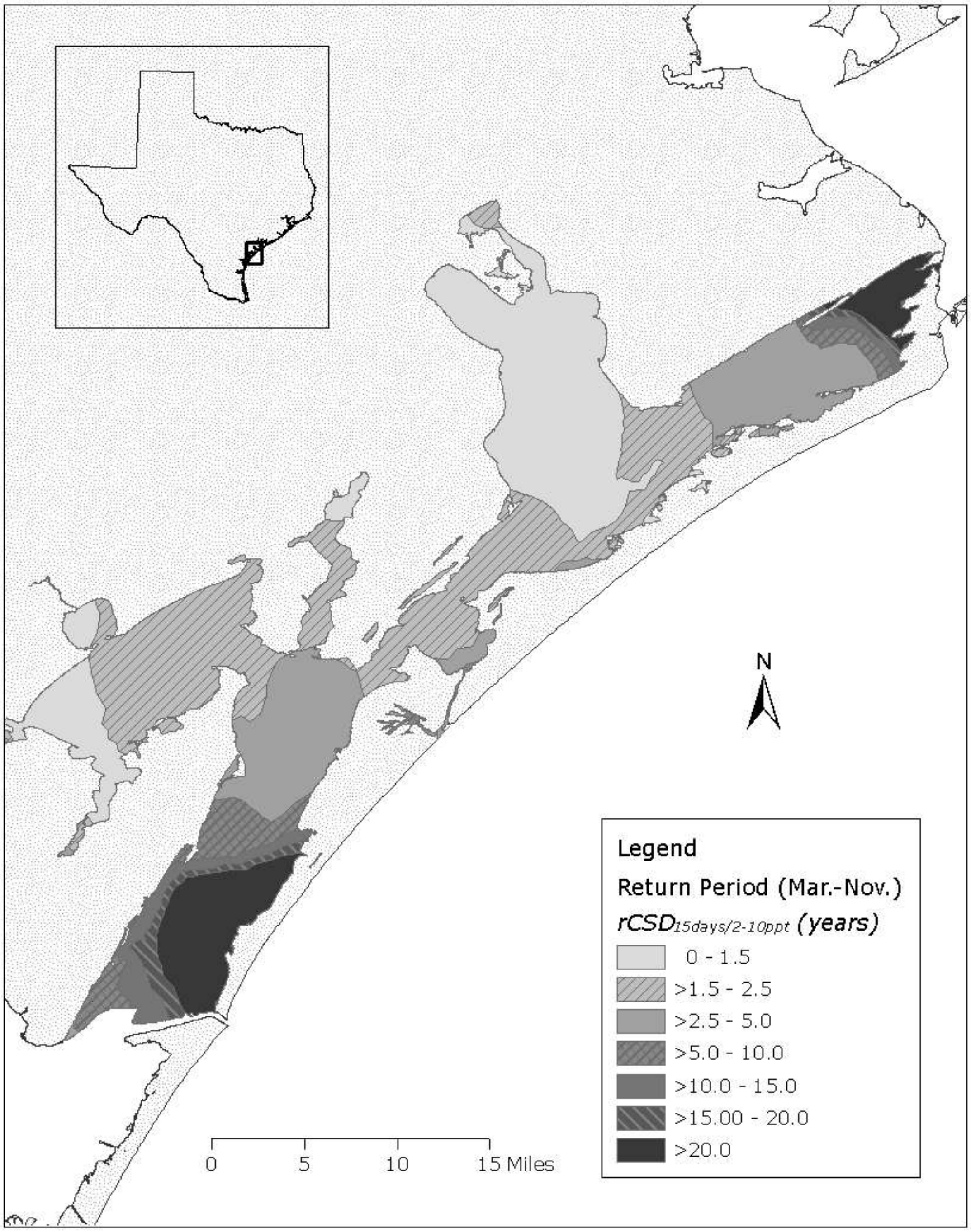

Figure 18. Map view of the return period results for CSD_{2-10} of 15 day duration, limited to the Mar.-Nov. period in years 1987-2009.

This finding regarding the CSD_{2-10} for 15 days was not expected; the principal investigator expected that this favorable salinity condition with a high frequency of re-occurrence (low return period), would not be so widespread if it is an effective control on the *Rangia cuneata* population distribution. For instance, the finding here is that Mesquite Bay would appear to support *Rangia cuneata* reproduction and recruitment, with a requisite 15 day duration, nearly as often as the upstream end of the Guadalupe Estuary. However, only the upper portion of the Guadalupe Estuary is where field observations and/or TPWD sampling confirm a normally high concentration of *Rangia cuneata* (Norman Boyd, personal communication, January 31, 2011); *Rangia cuneata* has only been sporadically found in Mesquite Bay (Figure 3).

The results above were for the 15-day duration, but it is possible that longer durations in the favorable salinity range are necessary in the estuary for the growth and maturation of the larvae. With this prospect, Figure 19 presents the same favorable salinity range, 2 - 10 ppt, but with a 30-day duration. The results, even with a doubling of the requisite duration, still show that such a favorable salinity occurs quite frequently over an extensive area. Still, most of the Guadalupe Estuary down to Mesquite Bay and the bulk of Copano Bay are covered by the 0 - 1.5 year and 1.5 - 2.5 year return period contours. Much of Mesquite Bay and upper Aransas Bay are still in the 2.5 - 5 year contour. While this salinity pattern seems plausible as a limit on reproduction and recruitment of *Rangia cuneata*, it is still much more widespread than the area of high abundance of the clams which is limited to the upper Guadalupe Estuary (see Figure 2).

For thoroughness, longer duration events were also evaluated and the results for 45-day and 120-day events are shown in Figures 20 and 21, respectively. The map for the longest duration of 120 days of salinity in the 2 - 10 ppt range yields some intriguing results in that a couple of highly-localized "target" areas emerge that exhibit lower return periods than other adjacent areas both closer to the freshwater sources and closer to the seaward exchange. These do correspond spatially to some known areas of high *Rangia cuneata* population, especially for *Rangia cuneata* in the Hynes Bay portion of the Guadalupe Estuary. While this spatial alignment is striking, the actual frequency of occurrence values in those "target" areas are quite low, with only a small area in Hynes Bay in the 5 - 10 years return period class. Based on the apparent high levels of *Rangia cuneata* in this area and the wide range of size classes indicating frequent successful reproduction and recruitment (as indicated by TPWD samples and direct observations, Norman Boyd, personal communications) this low frequency level would not appear sufficient to sustain the population characteristics in this area.

Finally, one additional possible favorable salinity range was evaluated: 6 - 10 ppt. This was indicated as the "optimum" condition for larvae survival by Cain's (1973) highly-controlled laboratory experiments with *Rangia cuneata*. Only the 15 day interval was evaluated, mostly for comparisons to the more commonly cited 2 - 10 ppt range. Figure 22 presents these results. This much more restrictive range of salinity does, as expected, re-occur less frequently than the 2 - 10 ppt range (of Figure 18). However the area of frequent occurrence, taken as a return period less than 5 years, still covers most of the Guadalupe Estuary and much of the Mission-Aransas Estuary including upper Aransas Bay and all of Copano Bay. This more restrictive salinity range for reproduction and recruitment does not align well spatially with the areas of apparently higher *Rangia cuneata* population, especially that in the upper Guadalupe Estuary.

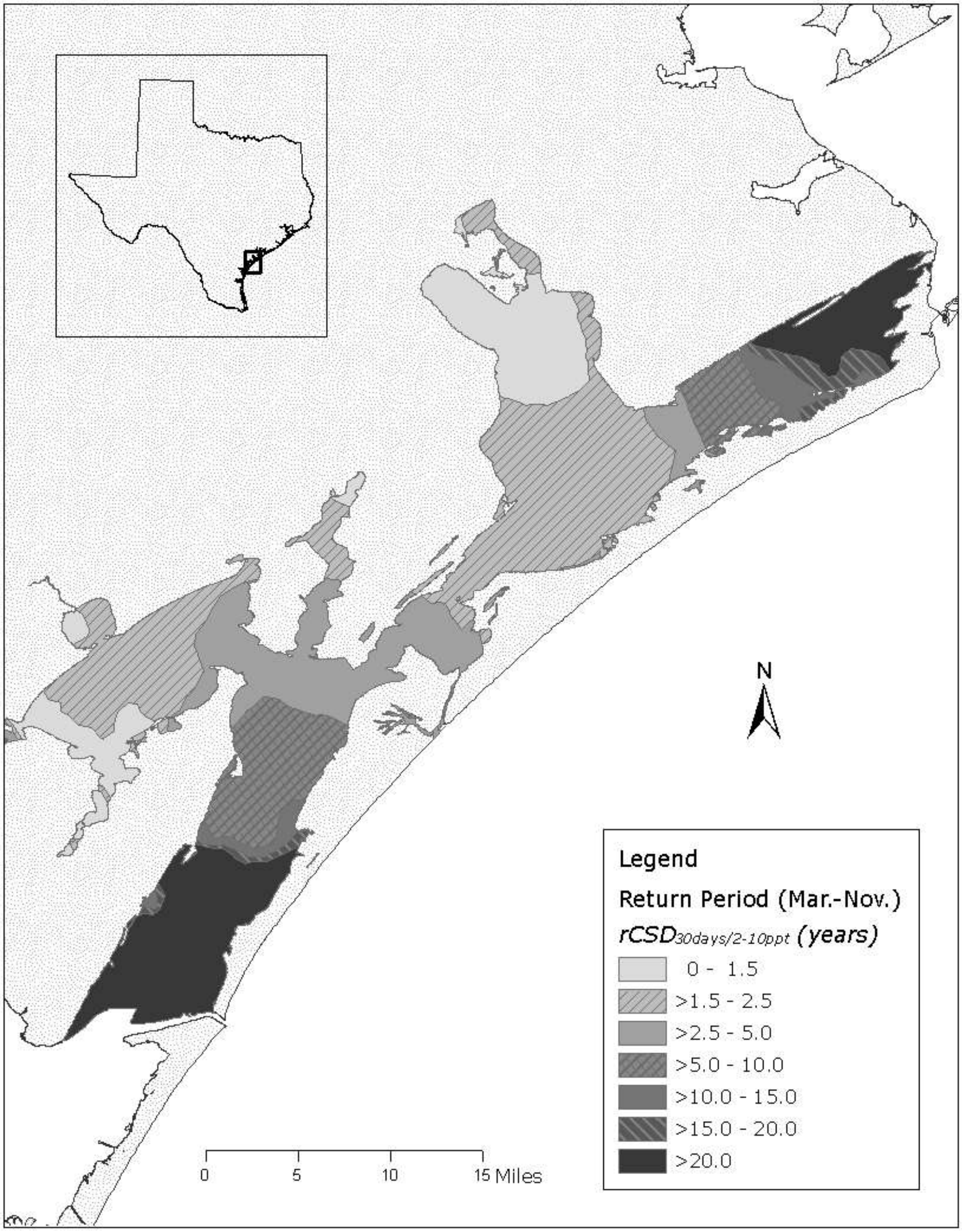

Figure 19. **Map view of the return period results for $CSD_{2\text{-}10}$ of 30 day duration, limited to the Mar.-Nov. period in years 1987-2009.**

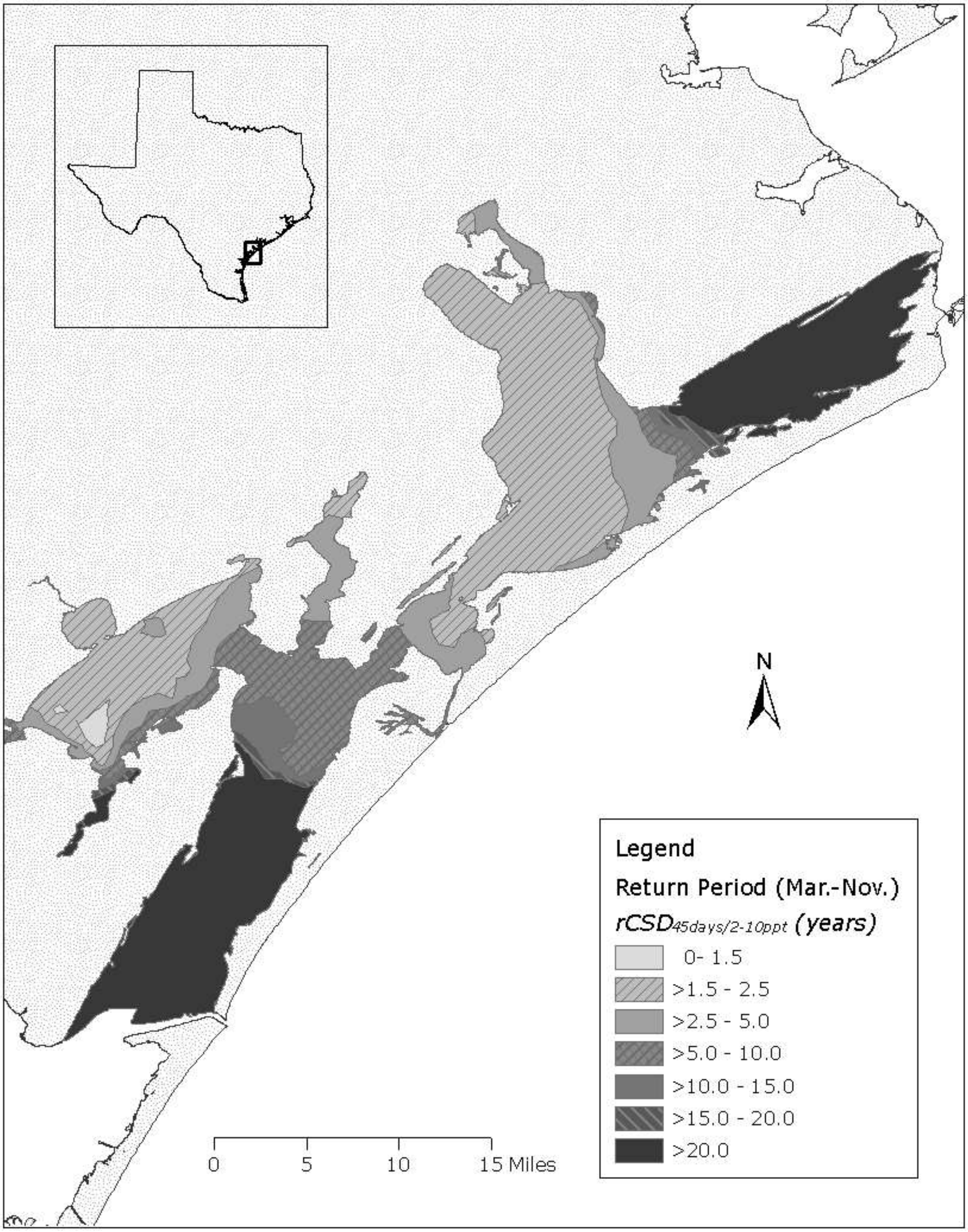

Figure 20. **Map view of the return period results for $CSD_{2\text{-}10}$ of 45 day duration, limited to the Mar.-Nov. period in years 1987-2009.**

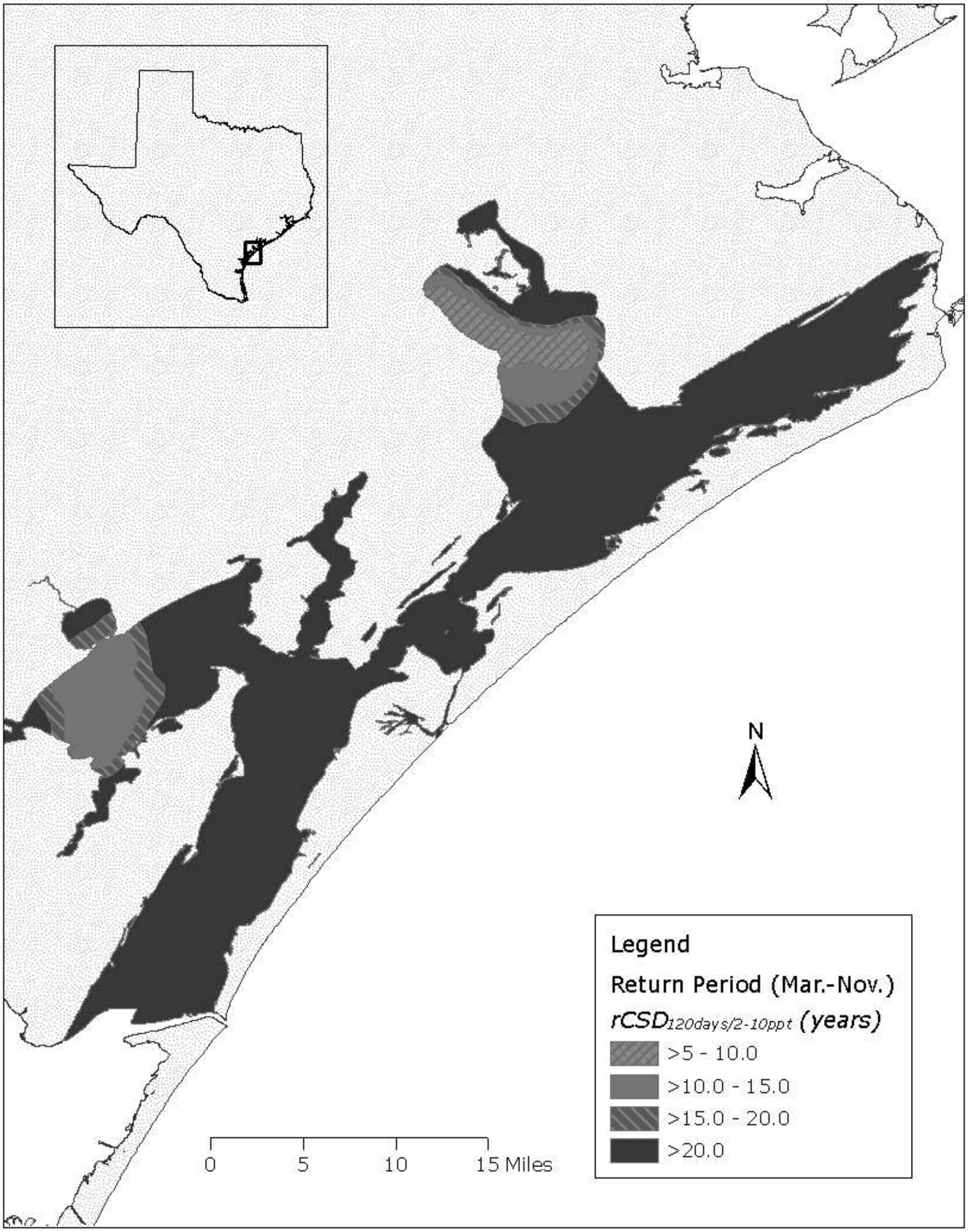

Figure 21. **Map view of the return period results for CSD_{2-10} of 120 day duration, limited to the Mar.-Nov. period in years 1987-2009.**

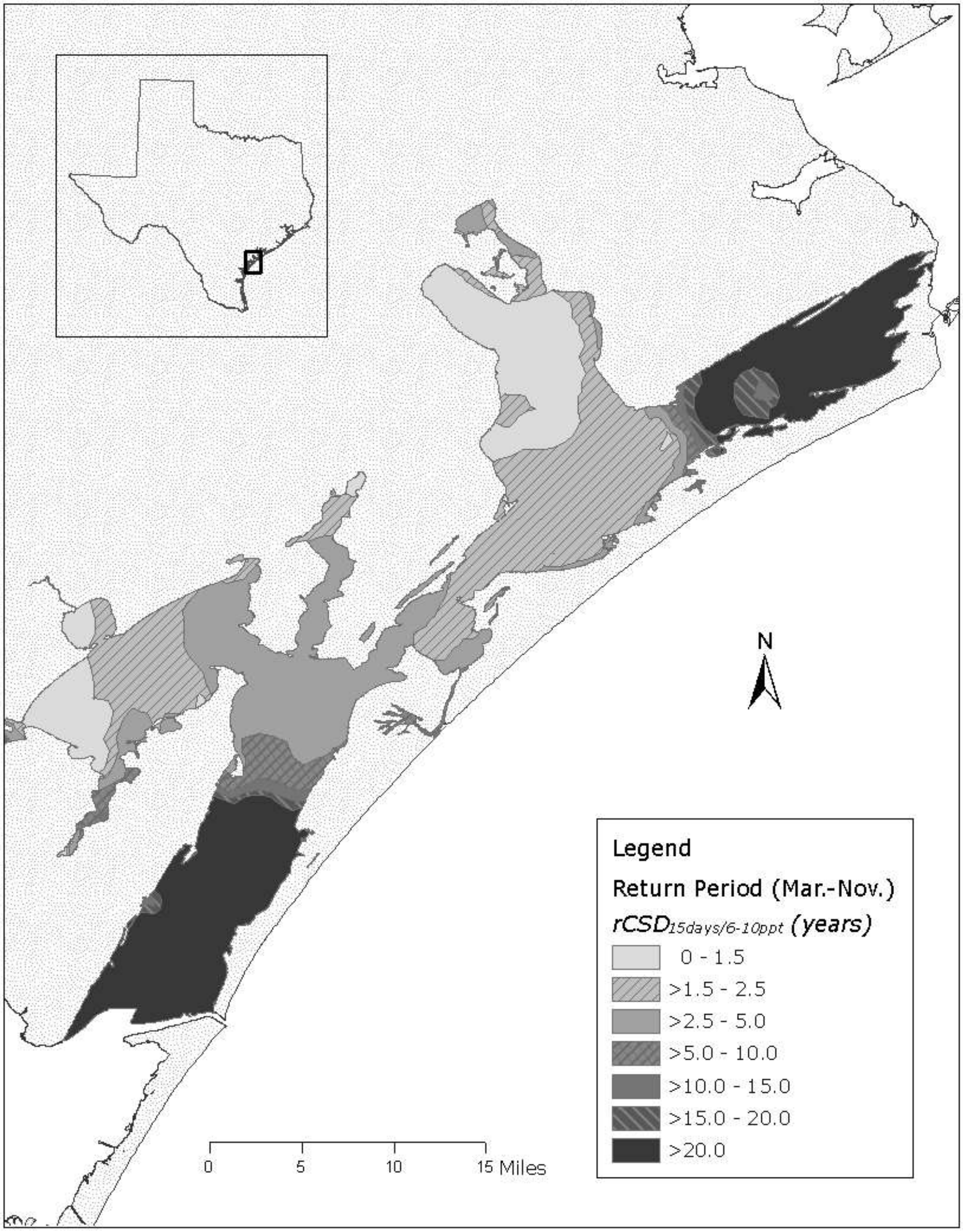

Figure 22. **Map view of the return period results for CSD_{6-10} of 15-day duration, limited to the Mar.-Nov. period in years 1987-2009.**

4.2 Spawning Pre-Condition Considerations

As presented above, the population distribution of *Rangia cuneata*, at least as approximated by the TPWD sampling data, does not appear to be limited due to the infrequent occurrence of a favorable salinity period for early larvae survival. Thus, additional efforts were taken to examine the possible influence of an abrupt salinity change as a spawning pre-condition. Cain's (1975) results from the James River in Virginia indicate that *rangia cuneata* clams required an abrupt increase or decrease in salinity to induce spawning. His results, as interpreted by others, would indicate that the clams in the upstream portions of the habitat required an increase of about 5ppt while clams in the downstream areas needed a decrease of 10 to 15 ppt to spawn (e.g. LaSalle and de la Cruz, 1985). Based on this author's interpretation of the original figures presented in Cain (1975) it would appear that salinity changes on the order of 5 - 10 ppt over an approximate one to two week period were effective for inducing spawning in the James River estuary.

An outline of the computations that were performed to examine the effect of the pre-condition on CSD events was introduced previously (Figure 15). In the actual search for potentially biologically important limits here, two series of test were performed. Each had a differing set of salinity change parameters used to define an "abrupt salinity change": a) a 5 ppt rise in salinity or a 5 ppt fall in salinity over a 7 day period, b) a 5 ppt rise in salinity or a 10 ppt fall in salinity over a period of up to 7 days in length. The approach was to ascertain if this pre-condition on CSD caused much change in the lengths and frequency of CSD events. Since it is an additional constraint, the length of any modified CSD occurrence (called CSD*), can only be equal to or less than the unconstrained value, and may disappear entirely if the pre-condition does not occur at all. Because a year-by-year comparison of the effects of the two sets of change parameters at several sites would be unwieldy, the evaluations here used a summary level. The effect of the pre-condition was evaluated by looking at the overall maximum annual sequence of CSD values without the pre-condition and with it in effect. It was beyond the scope of this current effort to also compute the return period with these modified CSD values.

Figure 23 presents the results for four specific points in the Guadalupe Estuary (as located on Figure 5) using the 5 ppt rise in salinity or a 5 ppt fall in salinity, with either occurring over up to a 7 day period [abbreviated 5R/5F/7day]. Clearly the additional pre-condition, that may be necessary to induce spawning in *Rangia cuneata*, has a very large effect overall. Specifically , points AA and CC, which are in areas of apparent high abundance of *Rangia cuneata* as shown in Figure 2 and 3 previously, do exhibit a good deal of reduction in CSD values, especially at AA. Point AA exhibits long periods of years in which $CSD^*_{2\text{-}10}$ values seldom surpass 30 days in length in a year. Point CC still has $CSD^*_{2\text{-}10}$ values on the order of 30-50 days fairly frequently. Point BB, further down the estuary in lower San Antonio Bay (see Figure 5) also exhibits a marked decline in the length of $CSD_{2\text{-}10}$ values if the spawning pre-condition is added. While the original $CSD_{2\text{-}10}$ occurred with lengths of approximately 30 days about 15 times, this is reduced to only about 7 occurrences for $CSD^*_{2\text{-}10}$. Point DD, far down the Guadalupe Estuary near the transition to Mesquite Bay (Figure 1) also exhibits a marked reduction in overall $CSD_{2\text{-}10}$ values with this spawning pre-condition.

Figure 24 presents similar results for Mesquite Bay and other points in the Mission-Aransas Estuary. The Mesquite Bay point, EE, had the greatest overall reduction in $CSD_{2\text{-}10}$ occurrence with this initial spawning pre-condition. Whereas, original $CSD_{2\text{-}10}$ values of approximate 30-60 day length occurred about 7 times in the period of record, this is reduced to only 1 event in 2001 that would appear to be of sufficient length to support reproduction and recruitment of *Rangia cuneata* upon consideration of $CSD^*_{2\text{-}10}$.

Point FF in upper Aransas Bay, was chosen for these evaluations because it is near the edge of the area of approximately 5-year re-occurrence for regular $CSD_{2\text{-}10}$ (see previous section), and thus marginally supportive of reproduction and recruitment based on that measure alone. Here with the addition of this spawning pre-condition, the occurrence of $CSD^*_{2\text{-}10}$ values drops, but not dramatically. Points HH and GG are in the interior of the Mission-Aransas Estuary, in Copano Bay. Both of these appear to barely support reproduction and recruitment, especially GG, even with the regular $CSD_{2\text{-}10}$. The occurrence and period lengths of $CSD^*_{2\text{-}10}$ do decline with the spawning pre-condition, but not dramatically. These two points appear to be marginal for *Rangia cuneata* reproduction and recruitment regardless of whether the pre-condition is in place or not.

A second more stringent level of spawning pre-condition was also evaluated with values more in line with what some interpret Cain's (1975) research to show: a necessary 5 ppt rise or a 10 ppt fall in salinity. Again the period length is up to 7 days for this salinity change to occur. In summary, as can be seen in Figures 22 and 26, these pre-conditions greatly reduce the occurrence of $CSD_{2\text{-}10}$ and often lead to long periods with no occurrence greater than a few days at several sites. In the Guadalupe Estuary only site AA presents a set of $CSD^*_{2\text{-}10}$ values of sufficient length (15-30 days) and of perhaps sufficient frequency to support reproduction and recruitment, although there was a very long period with little favorable salinity in the 1997-2004 period. All the sites in Mesquite Bay and the Mission-Aransas Estuary would only very sporadically support reproduction and recruitment with this more stringent spawning pre-condition applied. With the 5R/10F/7day spawning pre-condition in place, the occurrence of favorable salinity as measured by $CSD^*_{2\text{-}10}$ would not appear to support reproduction of *Rangia cuneata* in much of the estuary system.

Clearly there are a multitude of additional cases for the spawning pre-condition parameters that could be evaluated, but this limited set does indicate how important that this potential physiological requirement of *Rangia cuneata* may be in limiting its population.

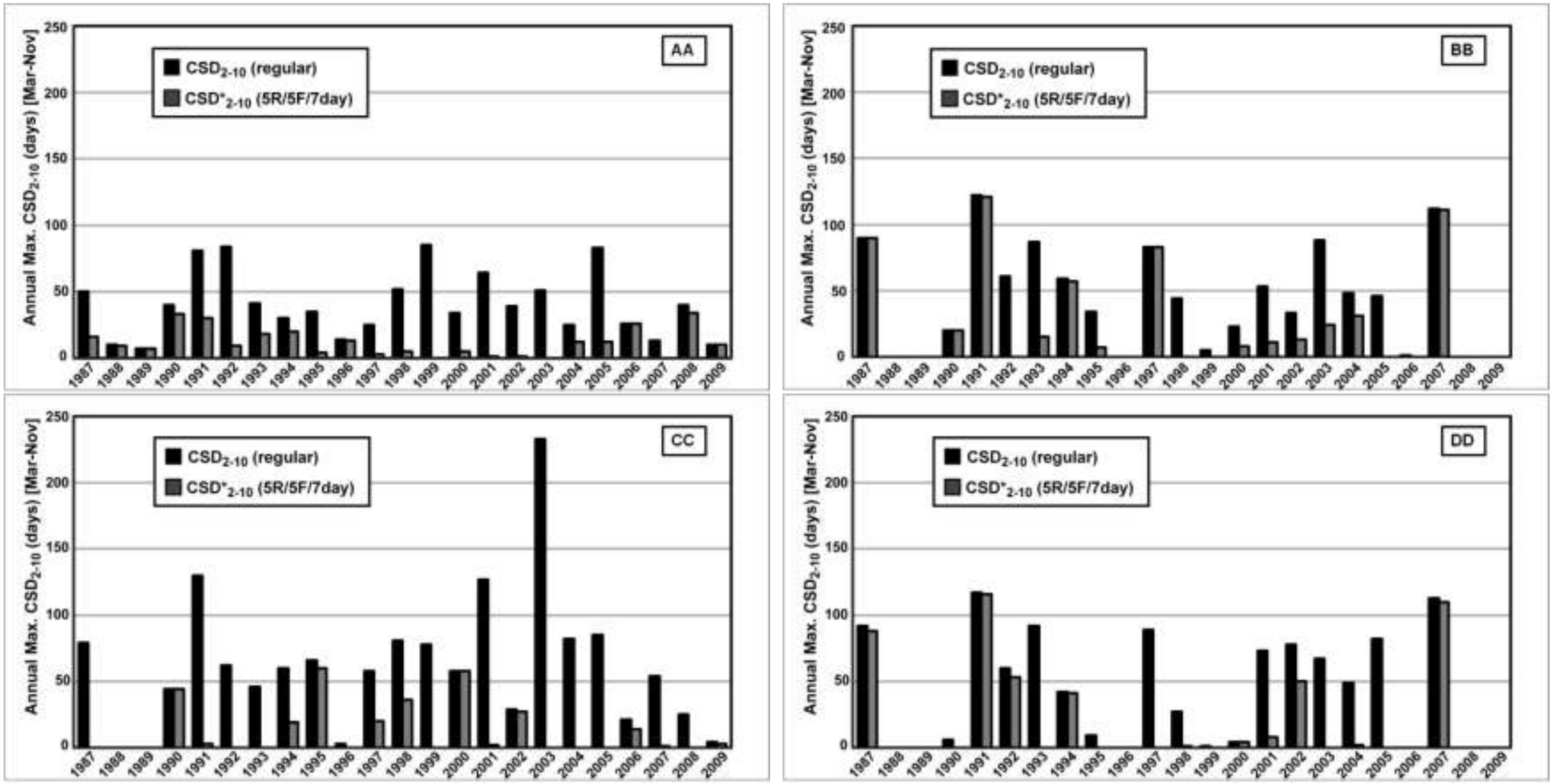

Figure 23. **Summary of the potential influence that a requirement of an abrupt salinity change may have on the occurrence of CSD_{2-10} throughout the Guadalupe Estuary system for the 1987-2009 period. Salinity change parameters: Rise 5 ppt, Fall 5 ppt, Time period=7 days. Locations of the points shown previously on Figure 5.**

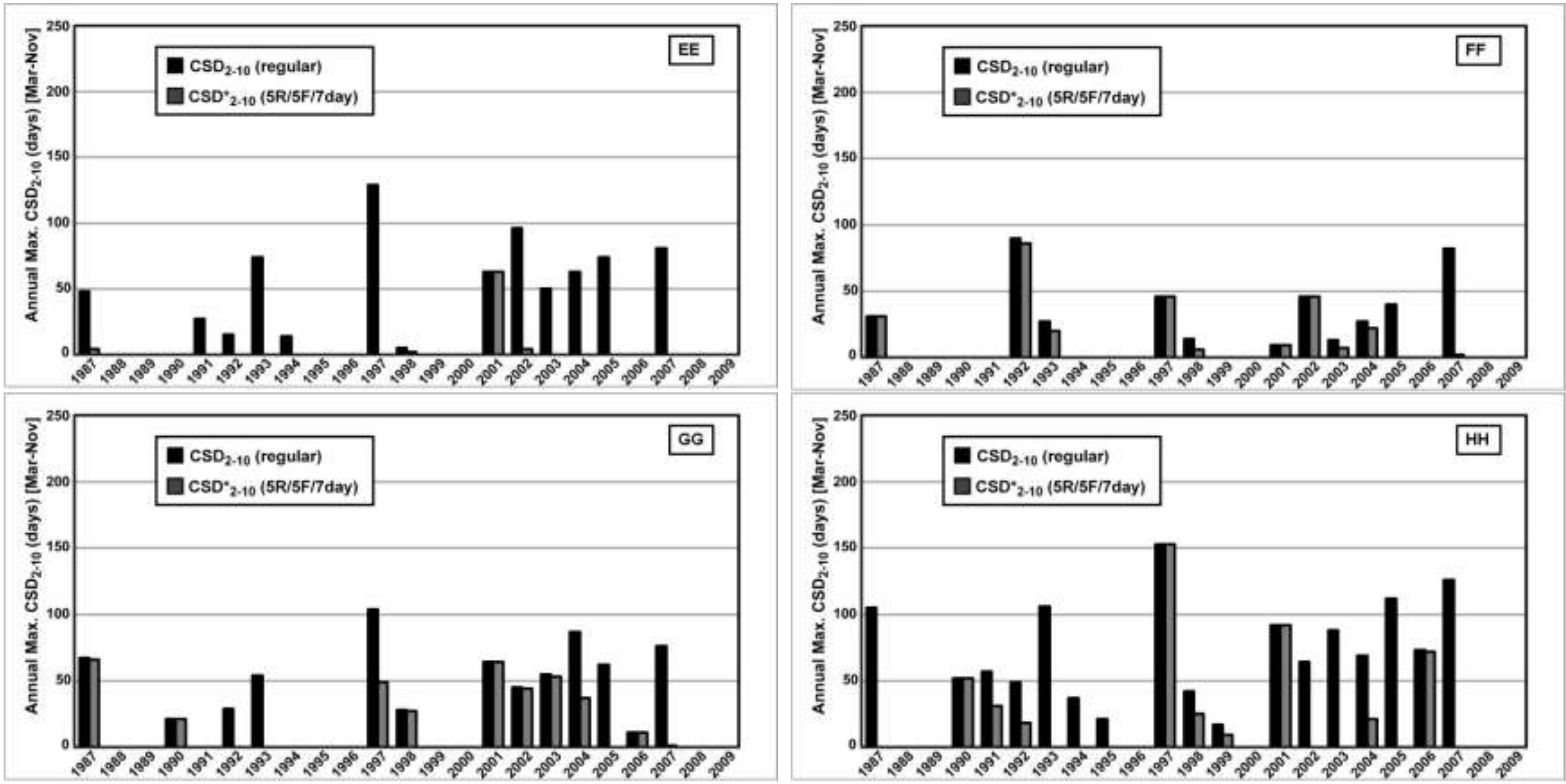

Figure 24. **Summary of the potential influence that a requirement of an abrupt salinity change may have on the occurrence of $CSD_{2\text{-}10}$ in the lower portion of the Guadalupe Estuary system (EE in Mesquite Bay) and throughout the Mission-Aransas Estuary for the entire 1987-2009 period. Salinity change parameters Rise 5 ppt, Fall 5 ppt, Time period=7 days. Locations of the points shown previously on Figure 5.**

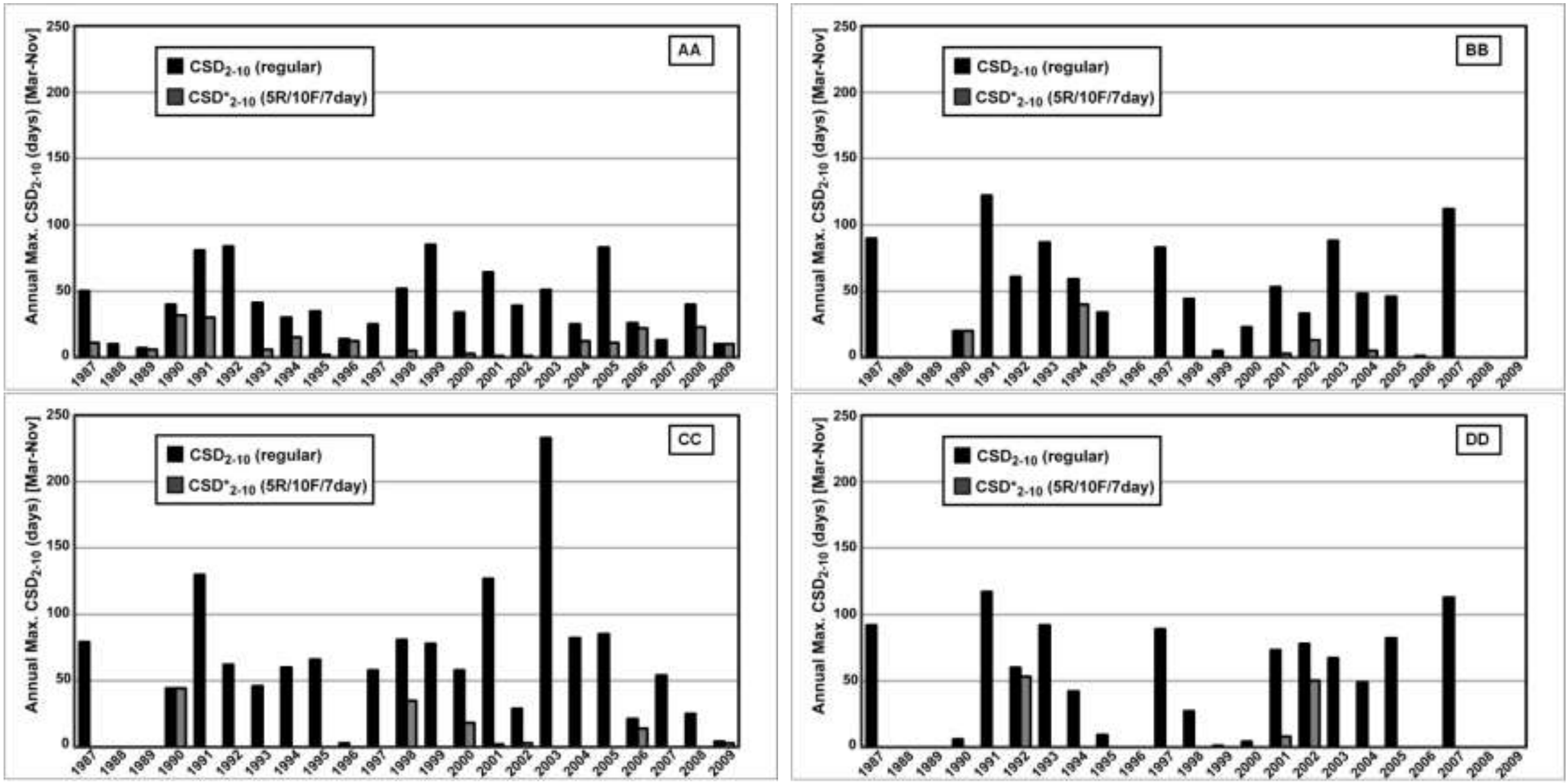

Figure 25. **Summary of the potential influence that a requirement of an abrupt salinity change may have on the occurrence of CSD_{2-10} throughout the Guadalupe Estuary systems for the entire 1987-2009 period. Salinity change parameters Rise 5 ppt, Fall 10 ppt, Time period=7 days. Locations of the points shown previously on Figure 5.**

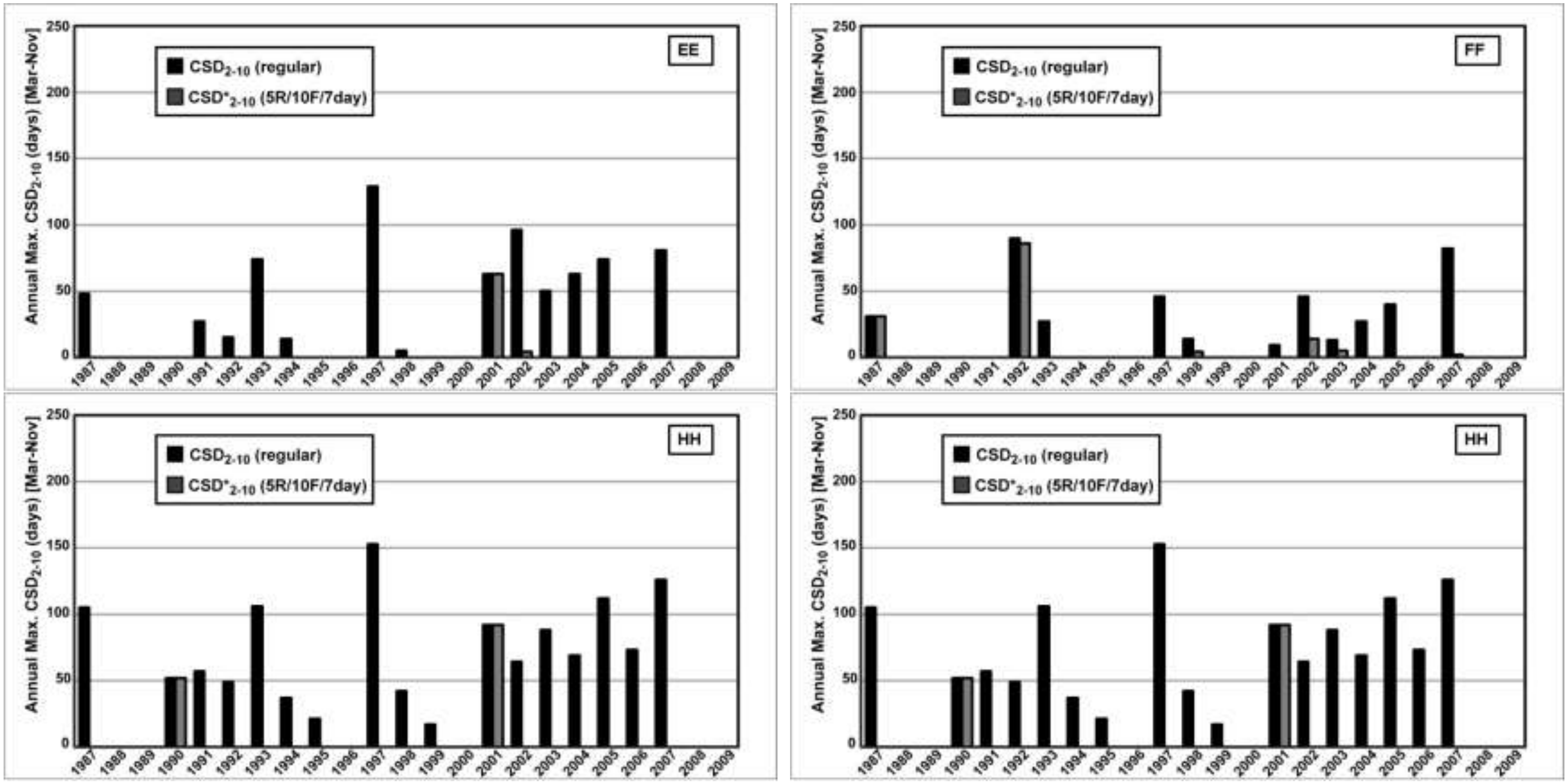

Figure 26. **Summary of the potential influence that a requirement of an abrupt salinity change may have on the occurrence of $CSD_{2\text{-}10}$ in the lower portion of the Guadalupe Estuary system (EE in Mesquite Bay) and throughout the Mission-Aransas Estuary for the entire 1987-2009 period. Salinity change parameters Rise 5 ppt, Fall 10 ppt, Time period=7 days. Locations of the points shown previously on Figure 5.**

4.3 Other Salinity Considerations

The focus of this study has been on the potential for salinity to exert the dominant limitation on *Rangia cuneata* population distribution via controls on reproduction and recruitment. This has long been postulated as the likely dominant control on the species' distribution (Hopkins and others, 1973, Cain, 1975). However, there is the possibility that other factors, including controls on other life stages, limit the population distribution. One potential limit, that does not appear to be addressed directly in the literature, is the possibility that extended high salinity episodes may have lethal effects on *Rangia cuneata* adults either directly or acting in combination with other environmental parameters. There are many general references to the fact that *Rangia cuneata* are seldom found in locations where salinity is above 15 - 18 ppt very often (e.g LaSalle and de la Cruz, 1985, Pattillo and others, 1995). Whether this is a direct limitation on *Rangia cuneata* or just a coincidental alignment of this salinity-bounded area with that of successful reproduction and recruitment appears to be unanswered.

As observed during first-hand field observations in January 2012,even areas typically having a high abundance of *Rangia cuneata* may experience occasional widespread mortality. On a field visit, with experienced personnel of the Texas Parks and Wildlife Department, only dead *Rangia cuneata* adults were observed in the upper portion of the Guadalupe Estuary, including areas typically heavily occupied with *Rangia cuneata* of many size classes (Norman Boyd, personal communication, January 31, 2012). This observed widespread mortality of *Rangia cuneata* in the Guadalupe Estuary appeared to have been very recent based on the bivalve shells still being buried intact with little discoloration (Norman Boyd, personal communication, January 31, 2012). Thus, the mortality does appear to be associated with the record-setting drought of 2011 though the precise mechanism is unclear.

Although it is very probable that low inflows and high evaporation rates of 2011, especially during the summer months, allowed very high salinity waters to intrude into these areas for extended durations, the observed widespread mortality of *Rangia cuneata* in the Guadalupe Estuary may or may not be attributable to this alone. Other research found that adult *Rangia cuneata* are osmoconformers at salinities greater than 10 ppt (Bedford and Anderson, 1972 as cited in LaSalle and de la Cruz, 1985) meaning that their internal ionic concentrations are similar to the surrounding waters. *Rangia cuneata* adults have been observed to withstand up to 30 ppt in laboratory settings (Pattillo and others, 1995), but there do not appear to have been explicit long-term field studies of high salinity exposure. As Pattillo and others (1995) point out, limitations on population distribution, if they can be related strictly to salinity at all, are likely due to an interacting mixture of effects from other variables such as temperature and food availability.

With the period data available for this study from the TxBLEND model (1987-2009), we can see that only the upper portions of the Guadalupe Estuary have typically not experienced exposure to high salinity waters in the >20 ppt range for extended periods. The map shown in Figure 27 (also in Appendix C) shows the occurrence of very high salinity waters within these estuary systems. As evident in this figure, the area of high Rangia cuneata abundance in the upper portions of the Guadalupe Estuary, only very rarely experiences (return period > 20 years) such high salinities for an extended duration. The conditions of 2011 likely were highly exceptional and may have led to high salinity in areas that Figure 27 would indicate only very rarely experience those conditions.

If there does exist an upper limit of salinity tolerance by *Rangia cuneata* adults, even if it must co-occur with other environmental stressors, this may limit the habitable area on the seaward side. This would be in opposition to many previous opinions (Hopkins and others, 1973; Cain, 1975) that the salinity-based limit on reproduction and recruitment is the control on the population distribution of *Rangia cuneata*.

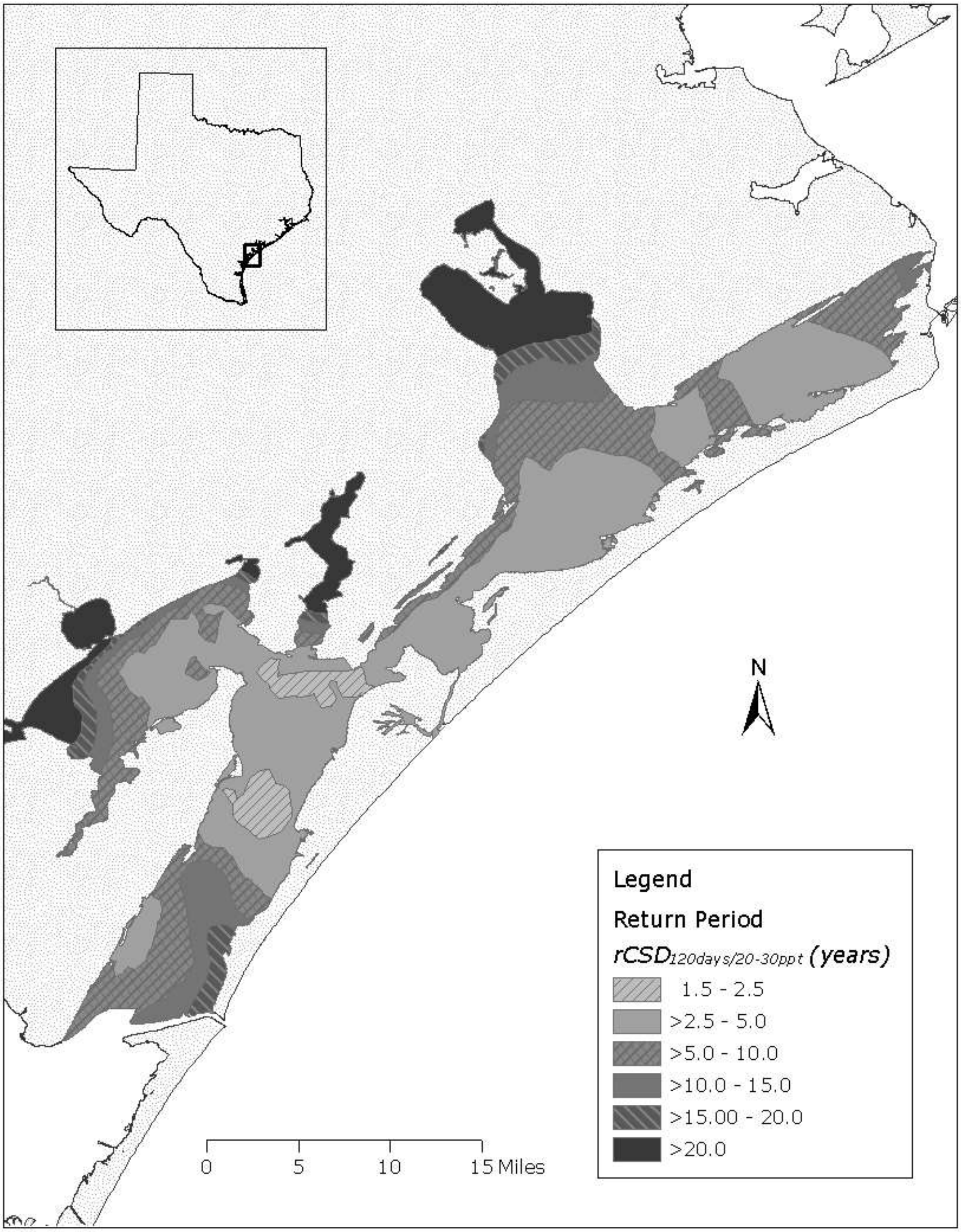

Figure 27. Map view of the return period results for $CSD_{20\text{-}30ppt}$ of 120 day duration for the whole year.

5 Conclusions and Recommendations

Given the evaluations of re-occurring salinity patterns undertaken in this study there are several observations and conclusions to be drawn. Most of these do bear the caveat discussed above that we only have approximate data on the actual distribution and abundance patterns of the *Rangia cuneata* population. Nonetheless, even with this approximate indication of the population we are able to make several observations:

● salinity in the range of 2 - 10 ppt continuously for durations of up to 15 days, a condition that would appear to be marginally favorable for *Rangia cuneata* reproduction and recruitment, occurs over a very large portion of the Guadalupe and Mission-Aransas Estuaries at least once every 5 years and much more frequently in much of the estuaries.

● salinity in the range of 2 - 10 ppt continuously for durations of up to 30 days, a condition that would appear to be very sufficient for *Rangia cuneata* reproduction and recruitment, occurs over a major portion of the Guadalupe and Mission-Aransas Estuaries at least once every 5 years.

● both of these re-occurring salinity patterns, either of which would appear supportive of *Rangia cuneata* reproduction and recruitment, are so widespread and of such frequent re-occurrence that they alone do not appear very explanatory in describing the limit to the apparent population distribution of the species.

● a long duration period of 120 days with salinity continuously in the range of 2 - 10 ppt re-occurs much less frequently than would appear supportive of *Rangia cuneata* reproduction and recruitment, although the spatial coverage of these areas do align reasonably well with observed concentrations of the species, especially in the upper Guadalupe Estuary.

● the occasional samples of *Rangia cuneata* found by the Texas Parks and Wildlife Department in areas of usually high salinity far removed from freshwater sources, at first appear to be relicts of very infrequent reproduction and recruitment events. However, this is not born out by the above.

● the need for an abrupt salinity change to initiate spawning, another potential salinity-based control on *Rangia cuneata* reproduction, as tested herein, would appear to be very restrictive and may have added explanatory power regarding the limits on *Rangia cuneata* population. This needs more investigation than was possible in this study. Such abrupt changes, if indeed controlling spawning, may indicate the need for pulses of freshwater inflow as opposed to constant inflows.

● other factors that may limit the population distribution of *Rangia cuneata* in areas further removed from freshwater sources, at least in the estuary systems examined, would appear to be related to predator-prey relations, competition, disease, or lack of a favorable substrate.

● the possibility that an upper limit of salinity tolerance by *Rangia cuneata* adults may exist, which is not clearly indicated by the literature on *Rangia*, is an important limitation on current knowledge. If it is a controlling influence, this would be in opposition to many previous opinions that the salinity-based limits on reproduction and recruitment are the dominant control on population distribution.

Several recommendations flow from the results of this study:

● the lack of a dedicated sampling program for *Rangia* of both species (*Rangia cuneata* and *Rangia flexuosa*), is very limiting, since the species have become so important for Texas estuary studies. A more thorough sampling program should be undertaken for these important species.

● As Cain (1975) and others have noted, the same species may exhibit differing physiological properties due to the exposure to differing environmental conditions over the long term. Thus, more precise analyses of the reproduction and recruitment requirements of *Rangia* in Texas are warranted. This should also include both observed species *Rangia cuneata* and *Rangia flexuosa* .

● more thorough information on the possible role of high salinity, and its interaction with other environmental variables, as a potential cause of adult mortality in *Rangia* is needed.

● the return period calculations herein would benefit greatly if the period of simulation for the TxBLEND model could be extended back in time. This is especially true for the analyses of less frequent events.

6 Acknowledgements

The author would like to extend thanks to several people who made this study possible. Obviously pivotal to this study was the provision of TxBLEND salinity model data by the TWDB staff. The efforts of Dr. Junji Matsumoto and Dr. Carla Guthrie were exceptionally notable in this regard. The GIS lab of the Texas Parks and Wildlife Department was instrumental to this study. Thanks to Kim Ludeke for expressing an early interest in this project. Thanks go especially to Dr. Nancy Heger who performed the contouring and map creation exercises herein. Thanks also to the field personnel of TPWD who routinely monitor the Guadalupe Estuary, especially Norman Boyd for several conversations about the Rangia cuneata samples that are available and a field tour to areas of usual high abundance of Rangia cuneata that are not sampled. Thanks to TPWD's Lynne Hamlin who also helped facilitate the transfer of the Rangia cuneata sampling data.

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Appendix A - Nodes Used for Pattern Searching

Seq. no.	Report label	GSMA-BBEST label	TxBLEND Node	Description BBEST	Verification node (1=yes)	QaQC node	Contouring (#=yes)
1		G1	2773	Guad., Rangia cuneata area - near river mouth	0	0	69
2	AA	G2	2612	Guad., Rangia cuneata area - near river mouth	0	0	61
3		G3	2570	Guad., Rangia cuneata area - off delta bend	0	0	57
4		G4	2687	Guad., Rangia cuneata area - in Hynes Bay	0	0	65
5		G5	2347	Guad., SE of Rangia cuneata area - nr. Seadrift	0	0	38
6		G6	2175	Guad., Oyster area - upper edge, east	1	0	n/a
7		G7	2058	Guad., Oyster area - mid. east	0	0	23
8		G8	2461	Guad., Oyster area - west edge	0	0	47
9	BB	G9	2113	Guad., Oyster area - nr. GIWW, center	0	0	25
10		G10	2393	Guad., Oyster area - nr. se. corner, nr. GBRA sonde	0	0	41
11	EE	M1	3241	Mesquite Bay	0	0	86
12		M2	3216	Mesquite Bay	0	0	85
13		M3	3169	Mesquite Bay	0	0	84
14	DD	M4	2739	Mesquite Bay	0	0	68
15		M5	3007	Mesquite Bay	0	0	81
16		M6	3344	Mesquite Bay	0	0	89
17		C1	4115	Copano Bay, Rangia cuneata area - nr. Aransas Riv. mouth	0	0	140
18		C2	3868	Copano Bay, Oyster area - central	0	0	120
19		C3	3748	Copano Bay, Oyster area - near 35 causeway [same as Cs3]	0	0	107
20		C4	4052	Copano Bay	0	0	136
21		Sc1	3590	St. Charles Bay	0	0	96
22		Sc2	3847	St. Charles Bay	0	0	117
23		A1	3665	Aransas, just S of Oyster area -	0	0	101
24		A2	3583	Aransas, Oyster area - central	0	0	95
25		A3	3522	Aransas, Oyster area - N. edge nr. GIWW	0	0	92
26		Gs1	2399	Guad., Oyster area - nr. upper edge	0	0	43
27		Gs2	2284	Guad., Oyster area - nr. center	0	0	34
28		Gs3	2228	Guad., Oyster area - nr. center	0	0	31
29		Gs4	1934	Guad., Oyster area - se. corner	0	0	19
30		Gs5	2395	Guad., Oyster area - nr. center	0	0	42
31		Gs6	2516	Guad., Oyster area - along west edge	0	0	52
32		Gs7	2514	Guad., Oyster area - along west edge	0	0	51
33		Gs8	2512	Guad., Oyster area - along west edge	0	0	50

Seq. no.	Report label	GSMA-BBEST label	TxBLEND Node	Description BBEST	Verification node (1=yes)	QaQC node	Contouring (#=yes)
34		Gs9	2279	Guad., Oyster area - nr. GIWW, sw.	1	0	n/a
35		Gs10	2453	Guad., Oyster area - sw. corner	0	0	46
36		Gs11	2770	Guad., Rangia cuneata area - nw. corner Hynes Bay	1	0	n/a
37		Gs12	2644	Guad., Rangia cuneata area - west edge Hynes Bay	0	0	63
38		Gs13	2565	Guad., Rangia cuneata area - sw. corner Hynes Bay	0	0	55
39	CC	Gs14	2567	Guad., Rangia cuneata area - se. corner Hynes Bay	0	0	56
40		Gs15	2608	Guad., Rangia cuneata area - se. delta/ Hynes Bay	0	0	60
41		Gs16	2525	Guad., Rangia cuneata area - nr. delta bend	0	0	53
42		Gs17	2527	Guad., Rangia cuneata area - delta bend	0	0	54
43		Gs18	2406	Guad., Rangia cuneata area - east arm	0	0	45
44		Gs19	2690	Guad., Rangia cuneata area - nr. river mouth	1	0	n/a
45		Gs20	2871	Guad., Rangia cuneata area - nr. river mouth	0	0	73
46		Cs1	3838	Copano Bay, Oyster area - NW	0	0	116
47		Cs2	3780	Copano Bay, Oyster area - NE corner	0	0	109
48		Cs3	3748	Copano Bay, Oyster area - near 35 causeway [same as C3]	0	1	n/a
49		Cs4	3870	Copano Bay, Oyster area - W edge	1	0	n/a
50	GG	Cs5	3807	Copano Bay, Oyster area - interior, E	0	0	113
51		Cs6	3899	Copano Bay, Rangia/Oys. area - off Mission Bay	0	0	123
52		Cs7	3867	Copano Bay, Rangia/Oys. area - off Mission Bay	0	0	119
53		Cs8	3865	Copano Bay, Oyster area - S corner	0	0	118
54		Cs9	3834	Copano Bay, Oyster area - S edge	0	0	115
55		Cs10	3805	Copano Bay, Oyster area - S edge, nearing causeway	0	0	112
56		Cs11	3930	Copano Bay, Rangia cuneata area - nr. Mission Bay entrance	0	0	125
57		Cs12	3957	Copano Bay, Rangia cuneata area - nr. Mission Bay entrance	0	0	130
58		Cs13	4012	Copano Bay, Rangia cuneata area - shore SE of Miss. Bay entrance	0	0	133
59		Cs14	3955	Copano Bay, Rangia cuneata area - SE of Miss. Bay entrance	0	0	129
60		Cs15	3925	Copano Bay, Rangia cuneata area - SE edge	0	0	124
61		Cs16	3981	Copano Bay, Rangia cuneata area - central	1	0	n/a
62		Cs17	4083	Copano Bay, Rangia cuneata area -	0	0	139

Seq. no.	Report label	GSMA-BBEST label	TxBLEND Node	Description BBEST	Verification node (1=yes)	QaQC node	Contouring (#=yes)
				nr. Aransas Riv. mouth			
63	HH	Cs18	4009	Copano Bay, Rangia cuneata area - nr. Aransas Riv. mouth	0	0	132
64		Cs19	3952	Copano Bay, Rangia cuneata area - nr. Aransas Riv. mouth	0	0	128
65		Cs20	4043	Copano Bay, Rangia cuneata area - nr. Aransas Riv. mouth	0	0	135
66		As1	3514	Aransas, Oyster area - NE corner	0	0	91
67		As2	3568	Aransas, Oyster area - N. edge nr. St. Charles	0	0	94
68		As3	3631	Aransas, Oyster area - Nw corner	0	0	99
69		As4	3696	Aransas, Oyster area - W edge, nr causeway	0	0	104
70	EE	As5	3627	Aransas, Oyster area - central W	0	0	98
71		As6	3560	Aransas, Oyster area - E edge	0	0	93
72		As7	3669	Aransas, Oyster area - SW edge	0	0	102
73		As8	3623	Aransas, Oyster area - S edge	1	0	n/a
74		As9	3618	Aransas, Oyster area - E edge	0	0	97
75		As10	3682	Aransas, Oyster area - SE corner	0	0	103
76			2938	#N/A	0	0	78
77			2893	#N/A	0	0	75
78			2913	#N/A	0	0	76
79			2804	#N/A	0	0	70
80			2838	#N/A	0	0	71
81			2726	#N/A	0	0	67
82			2235	#N/A	0	0	32
83			2118	#N/A	0	0	26
84			2061	#N/A	0	0	24
85			2050	#N/A	0	0	22
86			2345	#N/A	0	0	37
87			2007	#N/A	0	0	21
88			2120	#N/A	0	0	27
89			2166	#N/A	0	0	28
90			2402	#N/A	0	0	44
91			2286	#N/A	0	0	35
92			2169	#N/A	0	0	29
93			2240	#N/A	0	0	33
94			2294	#N/A	0	0	36
95			2350	#N/A	0	0	39
96			2356	#N/A	0	0	40
97			2476	#N/A	0	0	49
98			2576	#N/A	0	0	58
99			2580	#N/A	0	0	59
100			2653	#N/A	0	0	64
101			2621	#N/A	0	0	62
102			2848	#N/A	0	0	72

Seq. no.	Report label	GSMA-BBEST label	TxBLEND Node	Description BBEST	Verifica-tion node (1=yes)	QaQC node	Contour-ing (#=yes)
103			2967	#N/A	0	0	79
104			3048	#N/A	1	0	n/a
105			3087	#N/A	0	0	82
106			3157	#N/A	0	0	83
107			2695	#N/A	0	0	66
108			2777	#N/A	1	0	n/a
109			2873	#N/A	0	0	74
110			2919	#N/A	0	0	77
111			2980	#N/A	0	0	80
112			1876	#N/A	0	0	17
113			1996	#N/A	0	0	20
114			1431	#N/A	0	0	14
115			1227	#N/A	0	0	12
116			1989	#N/A	1	0	n/a
117			1800	#N/A	0	0	15
118			1425	#N/A	0	0	13
119			1225	#N/A	1	0	n/a
120			1928	#N/A	0	0	18
121			1803	#N/A	0	0	16
122			1224	#N/A	0	0	11
123			2284	#N/A	0	1	n/a
124			2464	#N/A	0	0	48
125			2180	#N/A	0	0	30
126			559	#N/A	0	0	1
127			694	#N/A	0	0	3
128			616	#N/A	1	0	n/a
129			654	#N/A	0	0	2
130			795	#N/A	0	0	6
131			768	#N/A	0	0	5
132			765	#N/A	0	0	4
133			872	#N/A	0	0	7
134			927	#N/A	0	0	8
135			1079	#N/A	0	0	10
136			1038	#N/A	0	0	9
137			2695	#N/A	0	1	n/a
138			3007	#N/A	0	1	n/a
139		M4	2739	Mesquite Bay	0	1	n/a
140			3655	#N/A	0	0	100
141			3936	#N/A	0	0	126
142			3323	#N/A	0	0	88
143			3295	#N/A	0	0	87
144			3475	#N/A	0	0	90
145			3550	#N/A	1	0	n/a
146			3742	#N/A	0	0	106
147			3713	#N/A	0	0	105

Seq. no.	Report label	GSMA-BBEST label	TxBLEND Node	Description BBEST	Verification node (1=yes)	QaQC node	Contouring (#=yes)
148			3759	#N/A	0	0	108
149			3797	#N/A	0	0	111
150			3822	#N/A	1	0	n/a
151			3880	#N/A	0	0	121
152			3891	#N/A	0	0	122
153			3942	#N/A	0	0	127
154			3968	#N/A	0	0	131
155			4066	#N/A	0	0	137
156			4070	#N/A	0	0	138
157			4152	#N/A	0	0	142
158			4148	#N/A	0	0	141
159			4231	#N/A	0	0	143
160			4210	#N/A	1	0	n/a
161			4243	#N/A	0	0	144
162			4289	#N/A	0	0	145
163			4391	#N/A	0	0	146
164			4454	#N/A	0	0	147
165			4039	#N/A	0	0	134
166			3782	#N/A	0	0	110
167			3814	#N/A	0	0	114
168			4052	#N/A	0	1	n/a

Appendix B - Developing Maps of Contoured CSD and rCSD data.

Geostatistical Methodology

The salinity-based variables used in this study, either consecutive salinity day durations (CSD) or return period statistics thereof (rCSD), were examined for patterns in both the Guadalupe Estuary and Mission-Aransas Estuary. The existence of patterns was assessed via interpolation / contouring exercises of the underlying variables derived at 147 nodes throughout the Guadalupe Estuary and Mission-Aransas Estuaries. Each contouring map was derived through interpolation using the Geostatistical Analyst extension of ArcGIS 9.3.1 (Environmental Systems Research Institute, Redlands CA). Interpolation is a geostatistical method that uses values from known location points to assess values and gradation patterns of unknown locations. To select a suitable interpolation method for this study, a test data set of San Antonio Bay salinity durations was used to assess the efficacy of the following interpolation methods: Inverse Distance Weighted (IDW), local and global polynomials, radial basis functions (RBF) or spline, and kriging. Those models that produced lower root mean square errors (RMSE) and mean error values and produced interpolation maps that visually fit salinity patterns likely for the area were deemed as more accurate. For all these parameters, kriging using a spherical model, four neighbors (k), and an ellipse with four diagonal sectors produced the best results and so was used for all further analyses and the creation of salinity duration contour maps.

To assess whether the interpolation model adequately predicted salinity duration patterns throughout the bay system, a set of 15 known points, referred to as validation nodes, were set aside and were not used in the creation of the interpolation contours. Once a map was created, these points and their known salinity duration values were overlaid to assess the validity of the predicted salinity duration patterns. Maps were deemed adequate if 12 or more points fit the predicted pattern. Only two of the maps didn’t fit this criterion with the original set of kriging parameters. In those cases, k was modified as needed (decreased to 3 or increased to 7) and this improved the efficacy of the predictive models better than any other model adjustments attempted. Validation assessment was re-done and both maps predicted 12 or 15 validation node accurately. An example map depicting validation efforts are shown in the following figure.

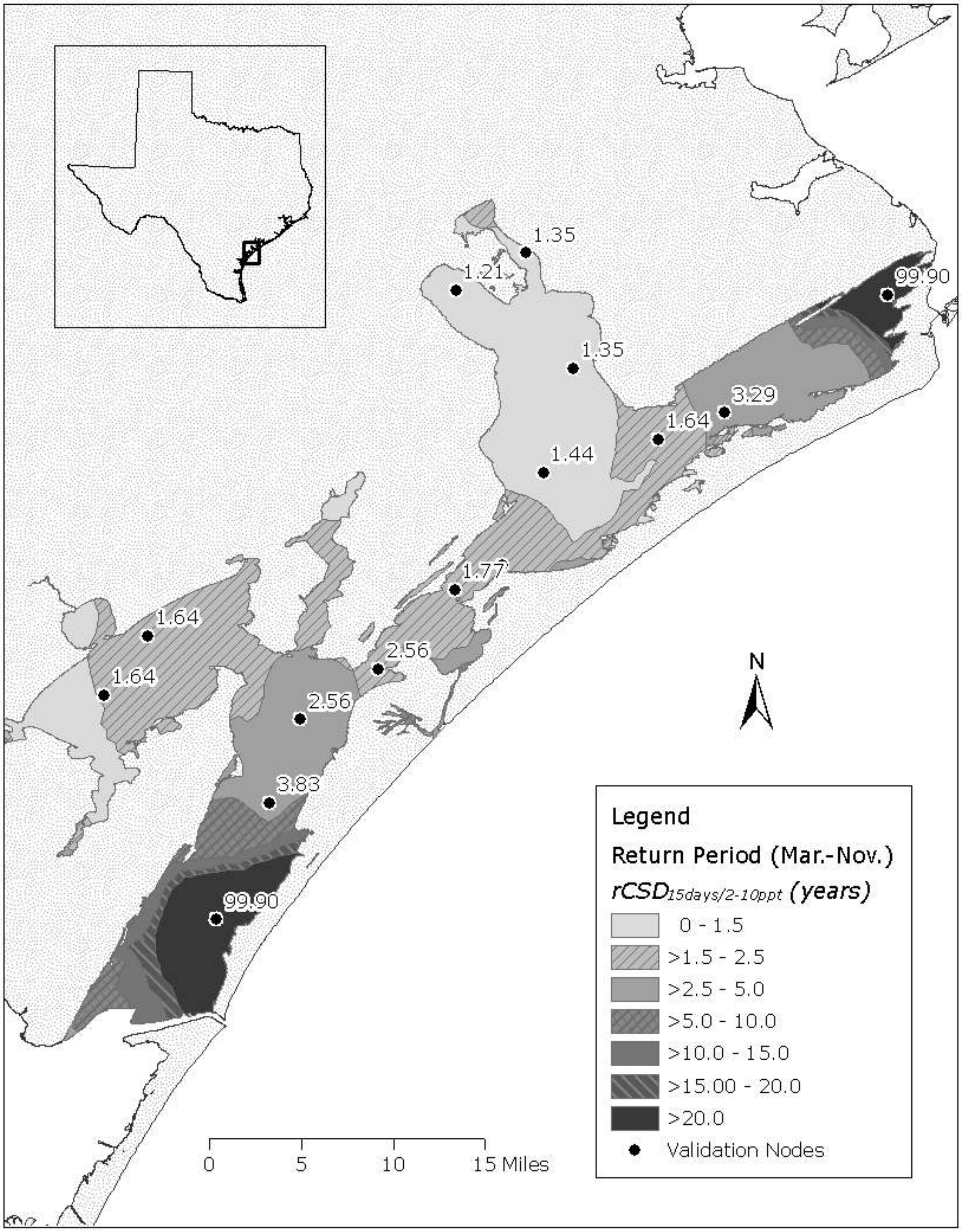

Figure B-1. **An example of the validation exercise performed for each map created. The example is the creation of the map view of the return period results for consecutive days of salinity in the 2 - 10 ppt range (CSD_{2-10}) of 15 day duration within the seasonal limits of Mar-Nov.**

Appendix C - Typical Re-occurring Salinity Patterns in the Guadalupe and Mission-Aransas Estuaries.

Because of the potential general utility of portraying re-occurring salinity patterns, but not specifically related to the reproduction of *Rangia*, a series of maps depicting the return period (frequency of re-occurrence) for several even increment salinity ranges (e.g. 0 - 10 ppt) and durations (e.g. 15 days) were developed in this study.

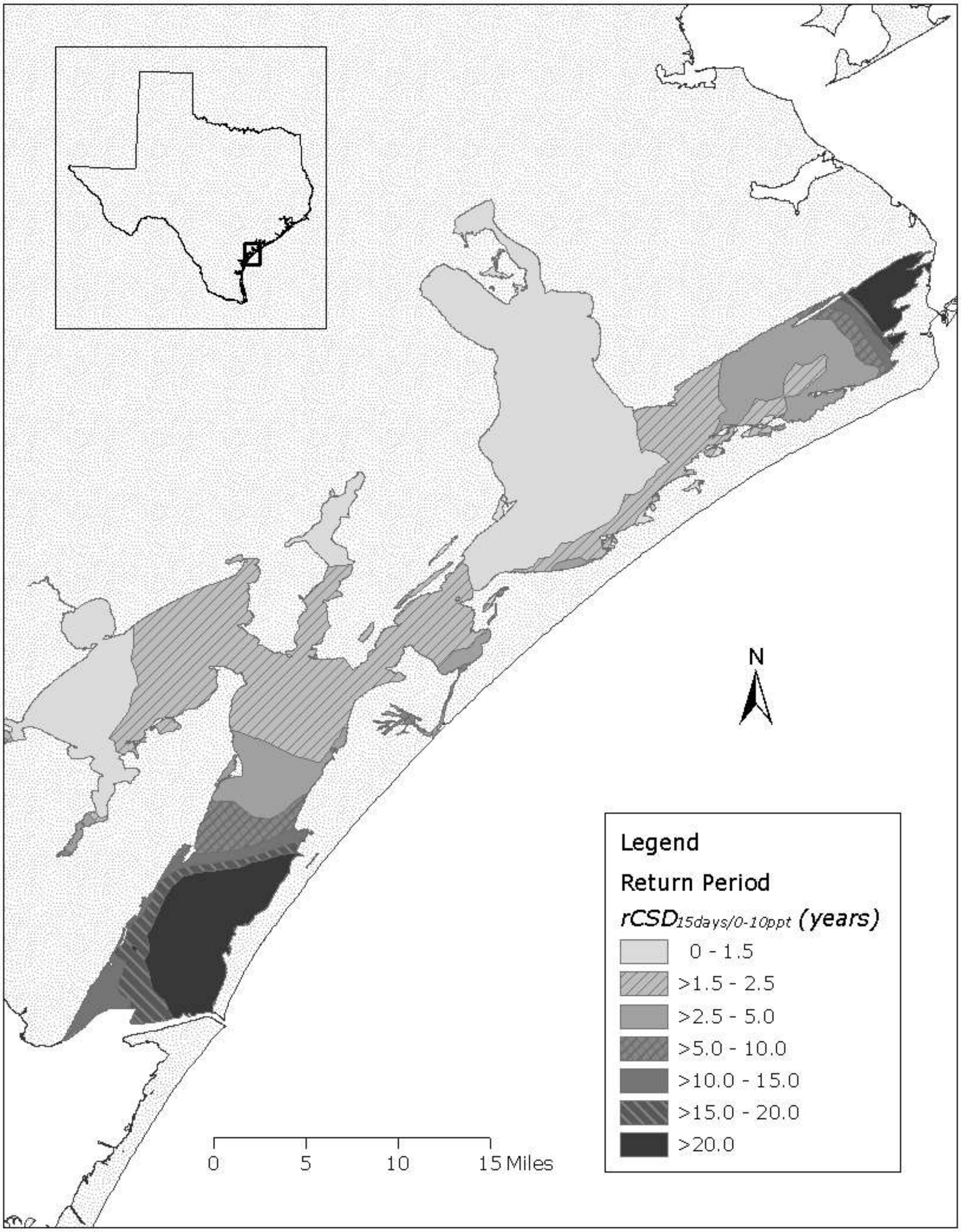

Figure C-1. **Map view of the return period results for consecutive days of salinity in the 0 - 10 ppt range (CSD_{0-10}) of 15 day duration throughout the Guadalupe and Mission-Aransas Estuary systems for entire 1987-2009 period.**

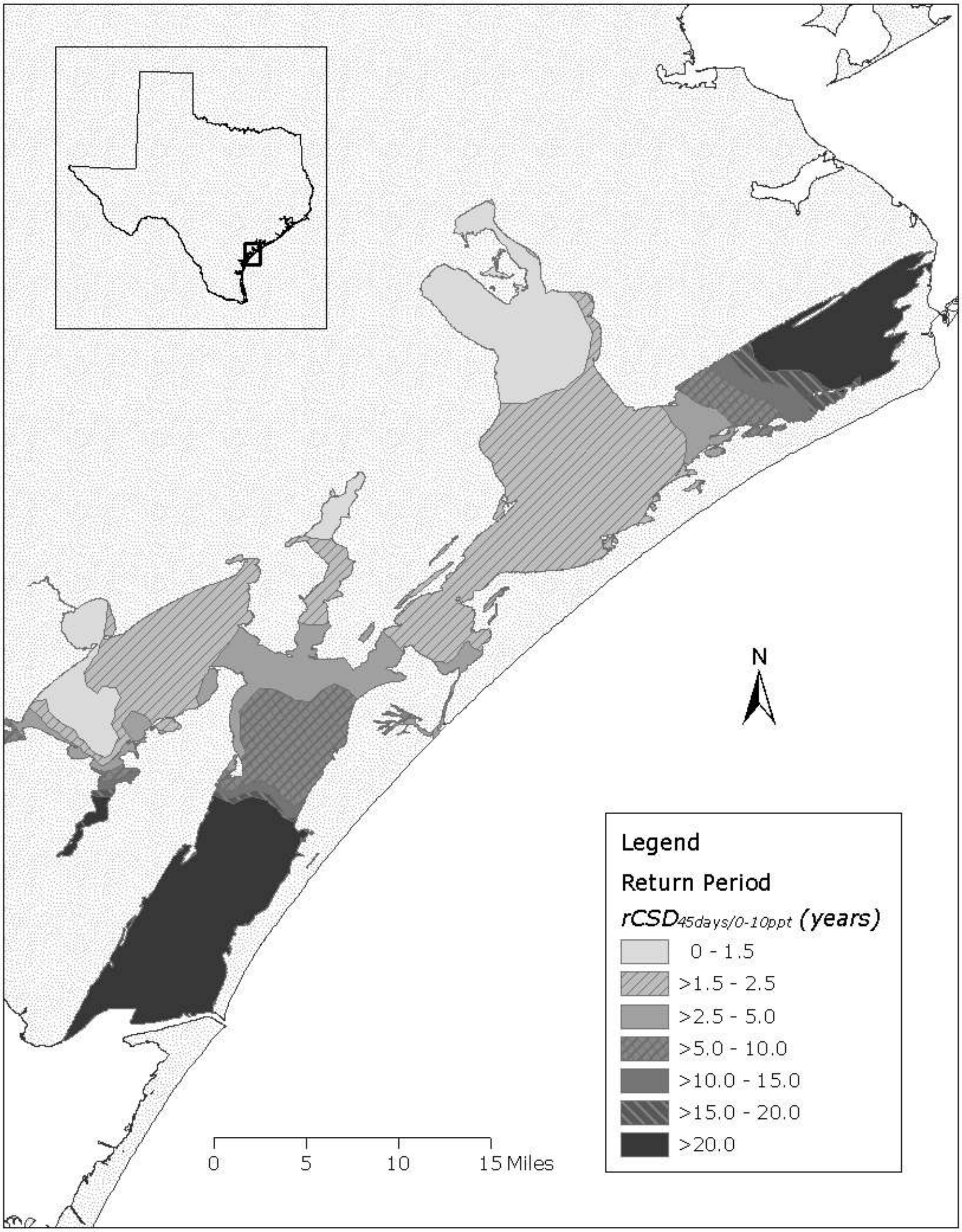

Figure C-2. **Map view of the return period results for consecutive days of salinity in the 0 - 10 ppt range (CSD_{0-10}) of 45 day duration throughout the Guadalupe and Mission-Aransas Estuary systems for entire 1987-2009 period.**

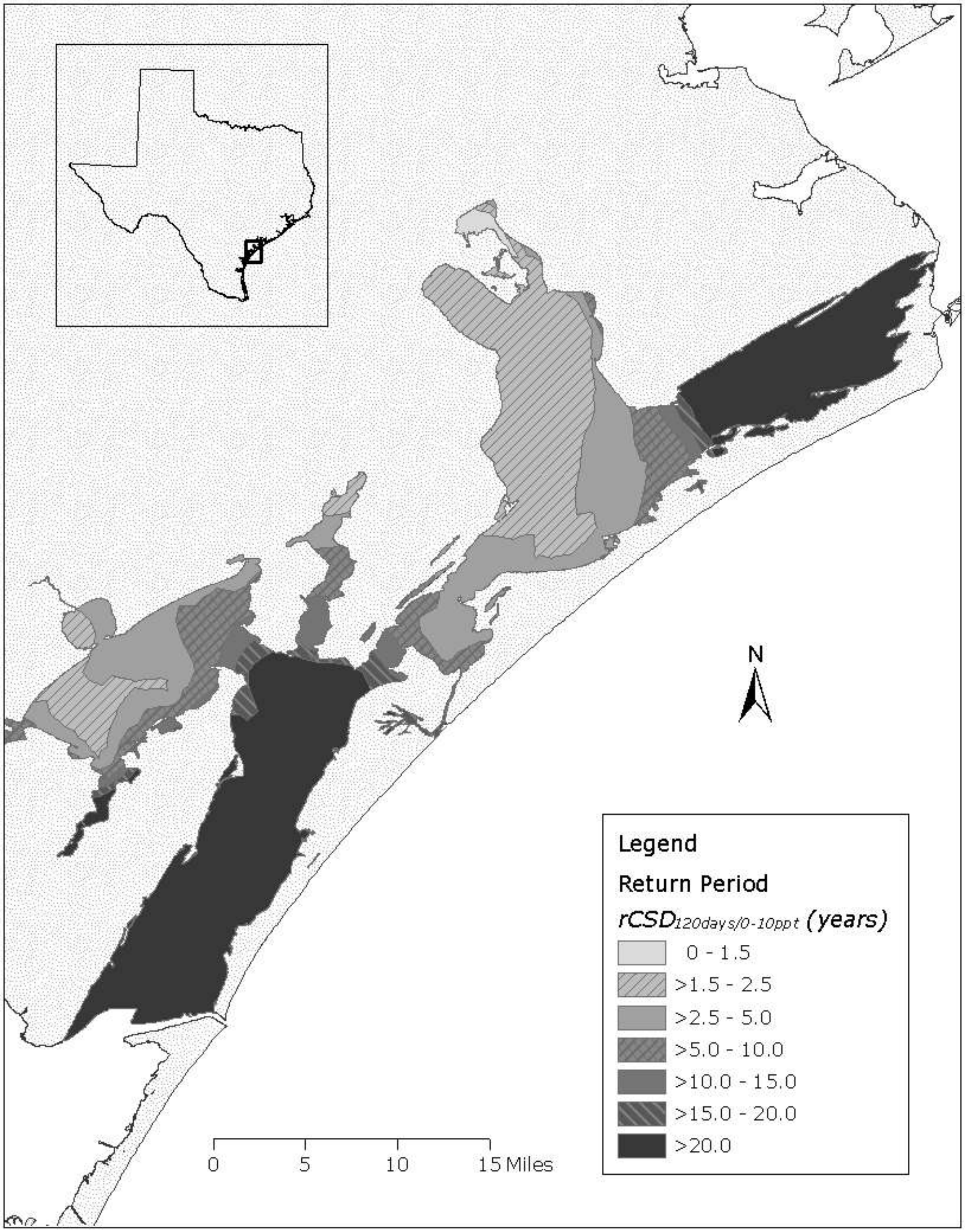

Figure C-3. **Map view of the return period results for consecutive days of salinity in the 0 - 10 ppt range (CSD_{0-10}) of 120 day duration throughout the Guadalupe and Mission-Aransas Estuary systems for entire 1987-2009 period.**

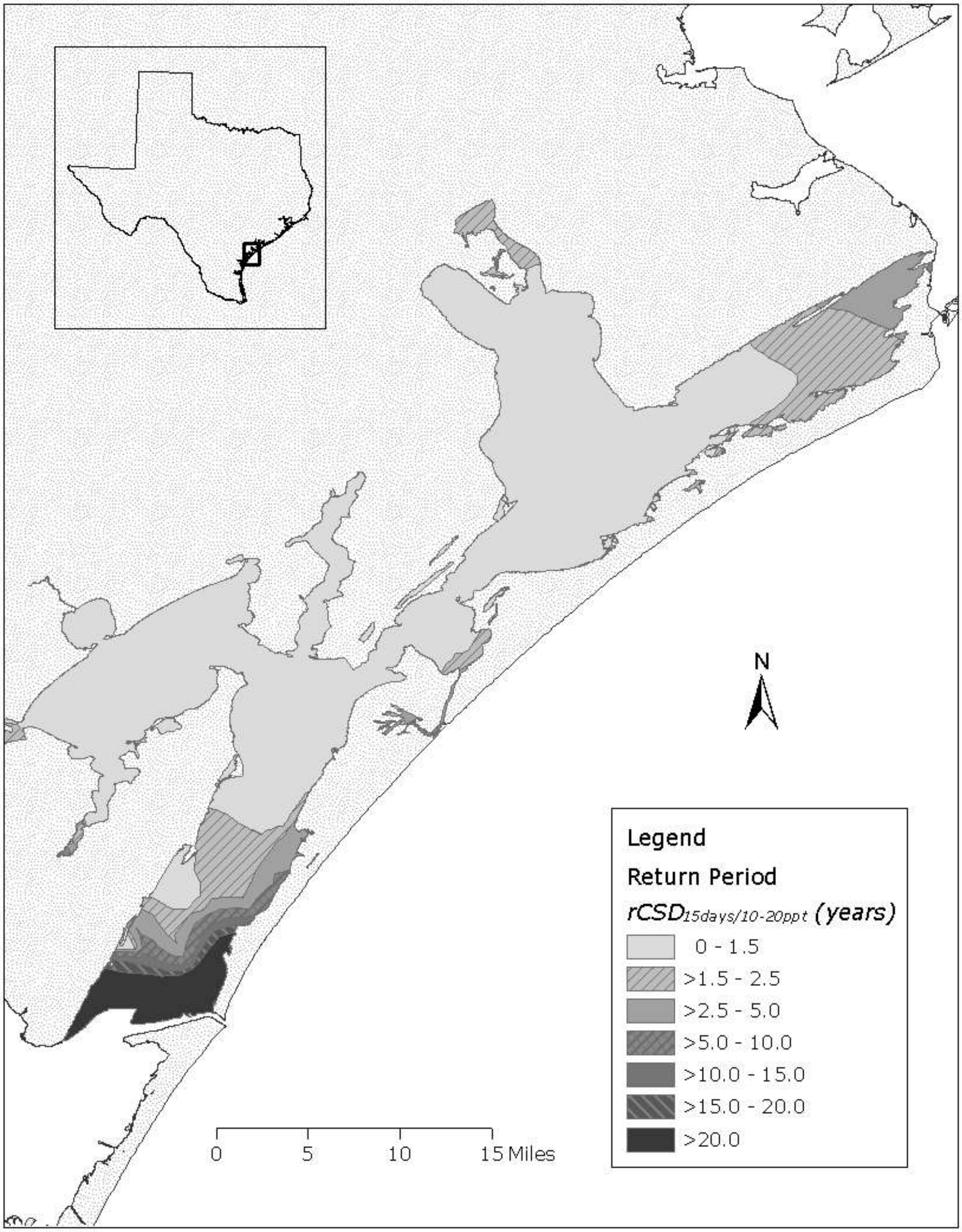

Figure C-4. **Map view of the return period results for consecutive days of salinity in the 10 - 20 ppt range (CSD_{10-20}) of 15 day duration throughout the Guadalupe and Mission-Aransas Estuary systems for entire 1987-2009 period.**

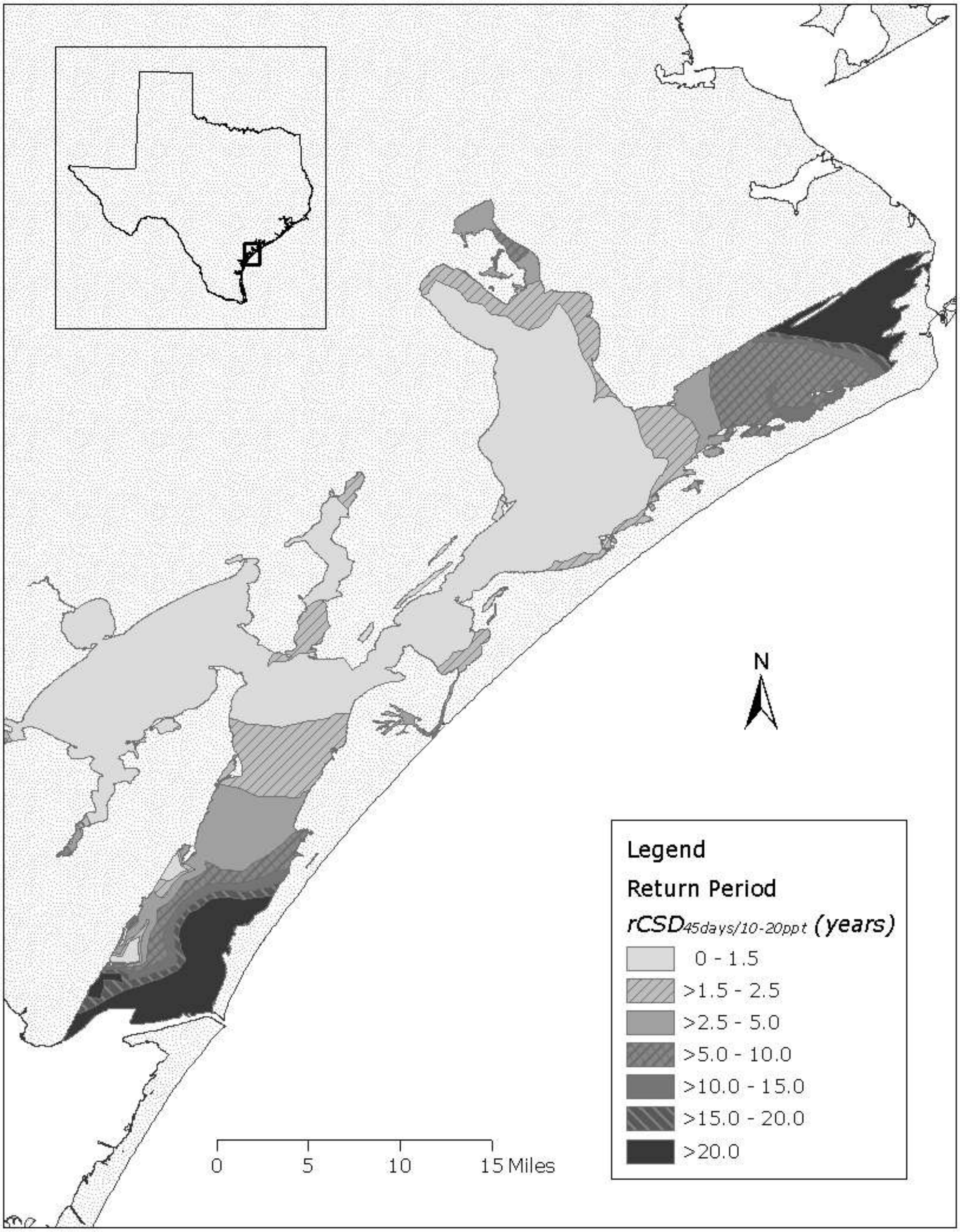

Figure C-5. **Map view of the return period results for consecutive days of salinity in the 10 - 20 ppt range (CSD_{10-20}) of 45 day duration throughout the Guadalupe and Mission-Aransas Estuary systems for entire 1987-2009 period.**

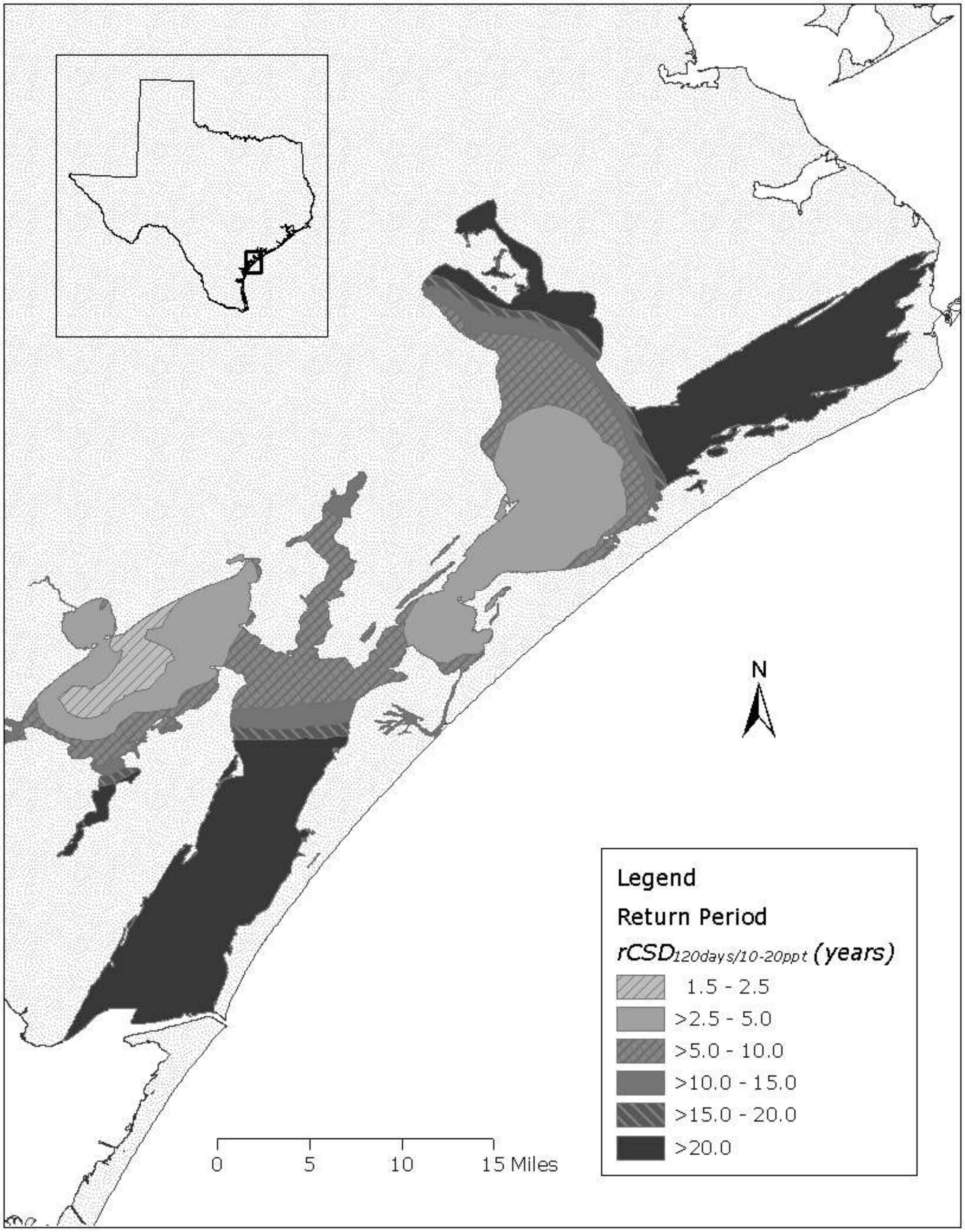

Figure C-6. **Map view of the return period results for consecutive days of salinity in the 10 - 20 ppt range (CSD_{10-20}) of 120 day duration throughout the Guadalupe and Mission-Aransas Estuary systems for entire 1987-2009 period.**

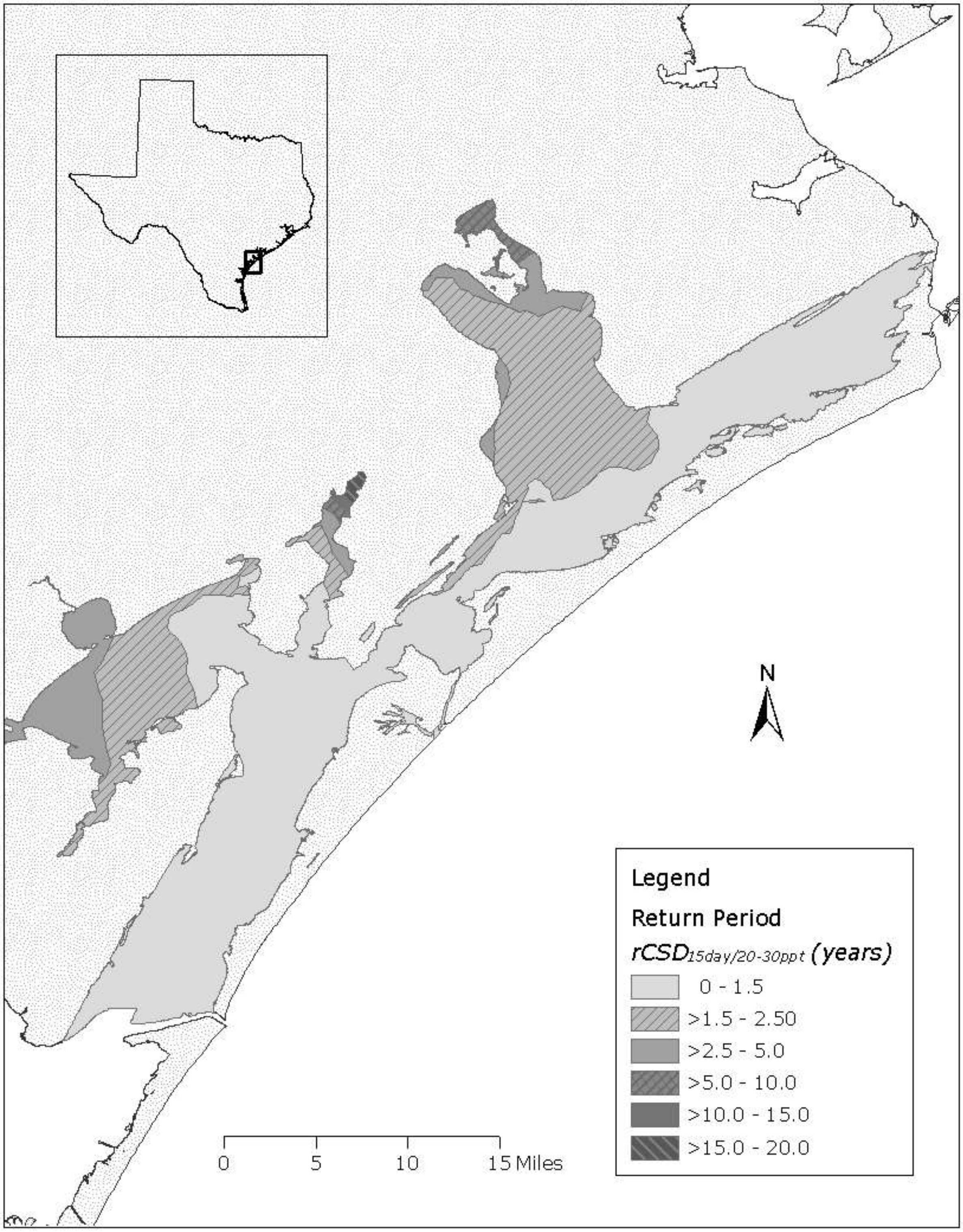

Figure C-7. **Map view of the return period results for consecutive days of salinity in the 20 - 30 ppt range (CSD_{20-30}) of 15 day duration throughout the Guadalupe and Mission-Aransas Estuary systems for entire 1987-2009 period.**

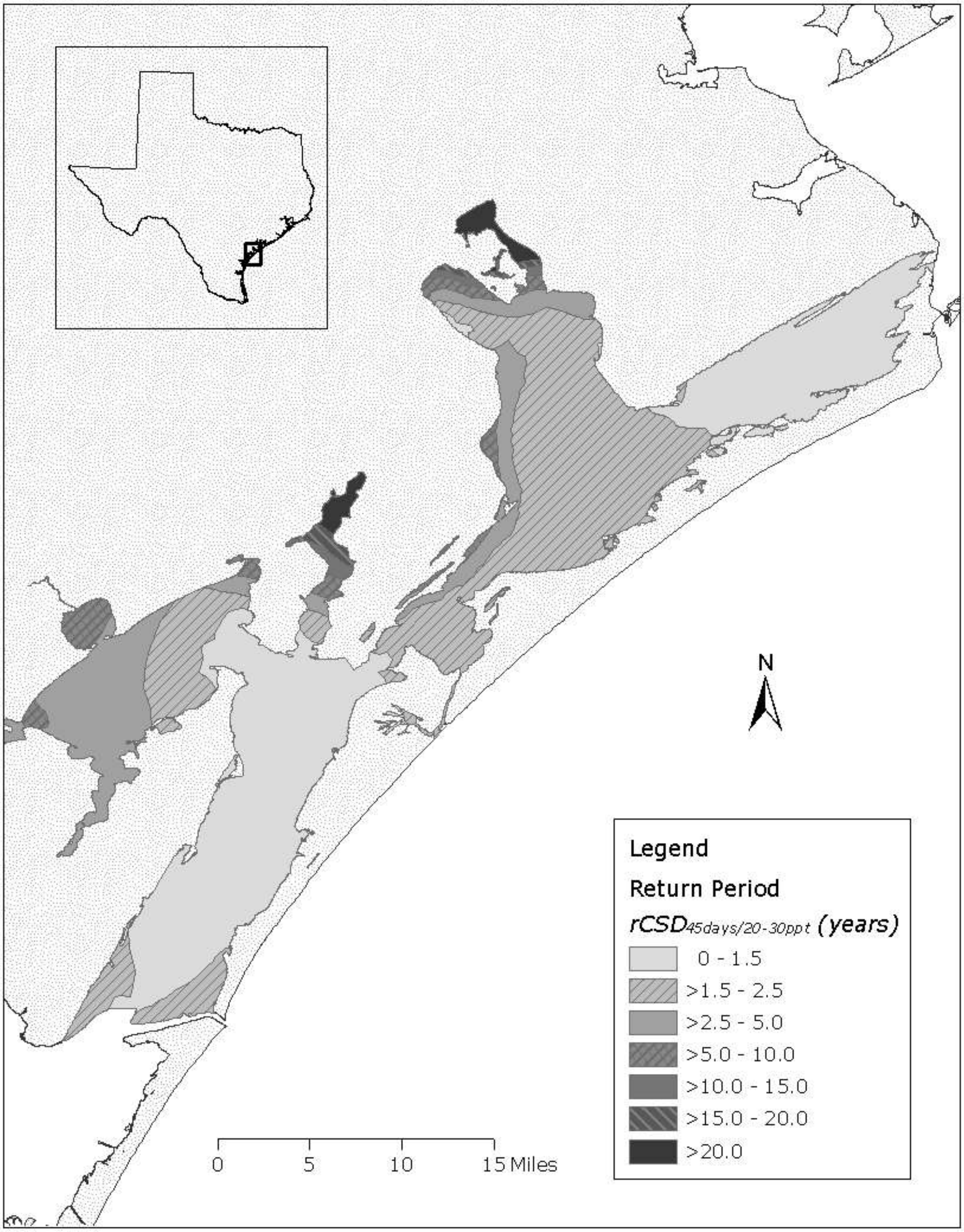

Figure C-8. **Map view of the return period results for consecutive days of salinity in the 20 - 30 ppt range (CSD_{20-30}) of 45 day duration throughout the Guadalupe and Mission-Aransas Estuary systems for entire 1987-2009 period.**

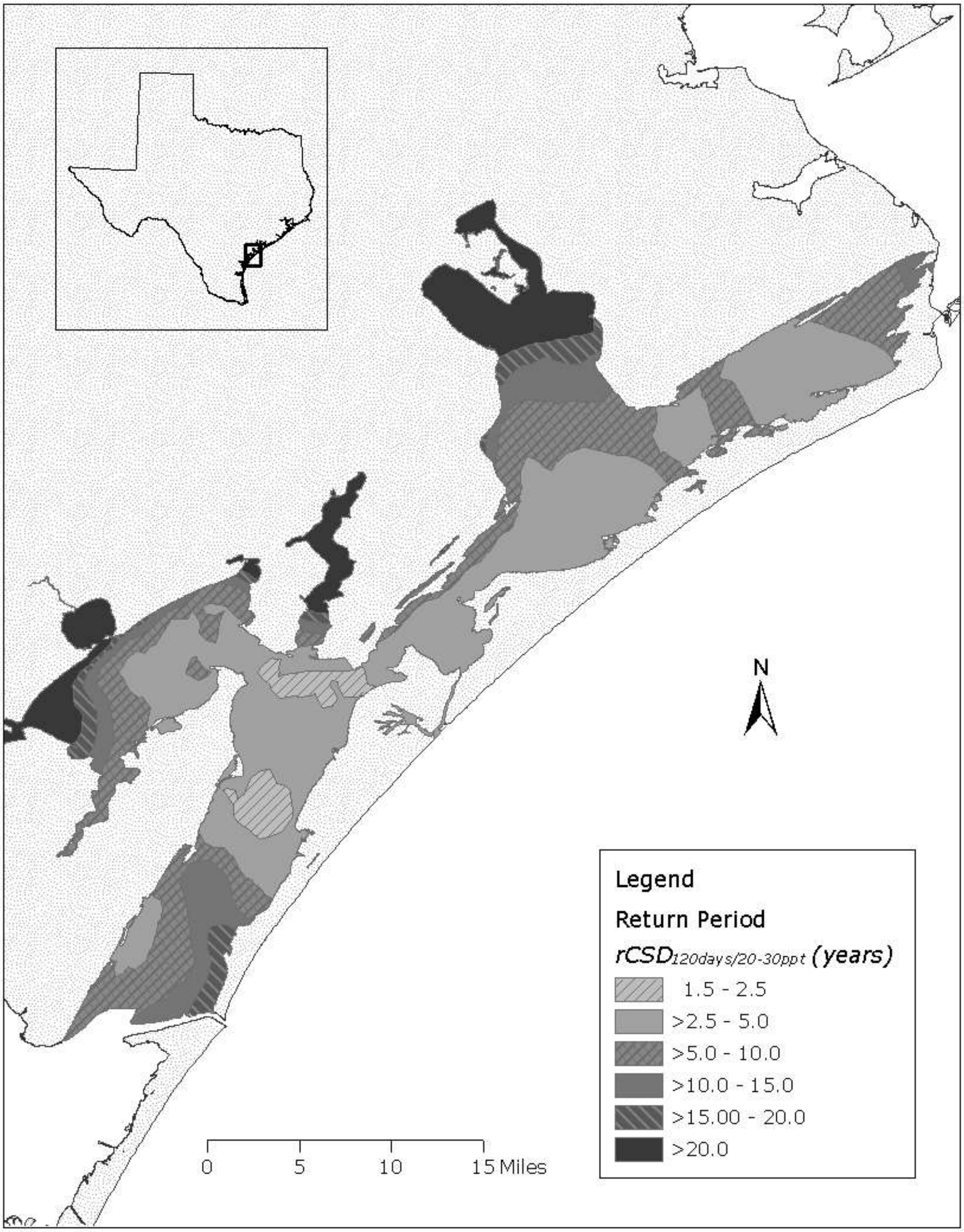

Figure C-9. **Map view of the return period results for consecutive days of salinity in the 20 - 30 ppt range (CSD_{20-30}) of 120 day duration throughout the Guadalupe and Mission-Aransas Estuary systems for entire 1987-2009 period.**

Appendix D - Scope of Work

Bay Salinity Patterns and Limits to the Extent and Persistence of *Rangia cuneata* Clams

Norman Johns, Ph.D.
National Wildlife Federation, South Central Regional Office
44 East Avenue Suite 200
Austin, Texas 78701

Introduction

The proposed $29,069 Research and Planning Fund contract is for the purpose of investigating the potential explicit spatial linkages between the frequency and duration of low-salinity zones and the distribution of the important native, brackish water clam species, *Rangia cuneata*, in Texas estuaries.

Rangia cuneata is an ecologically important species, because it filters detritus and phytoplankton from the water and serves as an important food source for fish, crustaceans, and water fowl. Texas Parks and Wildlife Department data show that *Rangia cuneata* are more abundant in upper estuary zones, where salinity typically is less than 15 ppt. According to scientific literature, *Rangia cuneata* has strict salinity requirements during the reproductive cycle, which often are triggered by freshwater inflow events, where rapid decreases in salinity can trigger spawning events (Hopkins *et al.* 1973). However, in order for larvae to settle and mature, salinities must be sustained at low levels (2 - 10 ppt) for approximately twenty days immediately after a spawning event (Cain 1975). While the factors which limit *Rangia cuneata* distribution in Texas estuaries are unknown, as distance from the source of freshwater inflow (*i.e.*, river mouth) increases, *Rangia cuneata* abundance tends to decrease. Therefore, it is probable that *Rangia cuneata* populations are limited by the lack of reoccurring favorable salinity conditions as distance increases from the mouth of rivers or as the volume of freshwater inflow declines.

This study will thoroughly document the frequency and duration of reoccurring salinity patterns, which may limit *Rangia cuneata* distributions in Texas estuaries. The goal is to achieve a better understanding of long-term patterns of salinity and the potential ecological impacts of altering historic patterns of freshwater inflows to the estuaries. *Rangia cuneata* is an ideal test species for this methodology and has become one of the primary indicator species for establishing estuarine inflow regimes for Texas estuaries, as it is has been or is being used by four Bay and Basin Expert Science Teams as part of the Senate Bill 3 process for environmental flows.

Purpose

This research study will examine explicit spatial linkages between the frequency and duration of salinity zones and the distribution of *Rangia*, specifically *Rangia cuneata*, by determining the salinity magnitude and time of exposure factors that appear to limit the extent and persistence of *Rangia cuneata* within a Texas estuary. In so doing, this study will more thoroughly document key reoccuring salinity patterns within the bays and will provide a better understanding of the potential impact of altering historic patterns of freshwater inflows to the estuaries.

Method

This study will utilize *Rangia cuneata* data collected by the Texas Parks & Wildlife Department and hydrodynamic model output (*i.e.*, simulated salinities) generated by the TWDB's TxBLEND salinity transport and circulation model to compare the distribution of *Rangia cuneata* with respect to the frequency of occurrence and duration of key salinity zones within Texas bays, given historic freshwater inflow patterns. *Rangia cuneata* occur in several of the major bays along the Texas coast; however, analyses will be applied to the Guadalupe Estuary, though, time permitting, additional bays may be selected by mutual agreement between the contractor and TWDB.

The approach will use daily salinity output from the TxBLEND model in order to describe salinity patterning, including the integration of salinity magnitude, duration of occurrence, and periodicity of reoccurrence (*e.g.,* the area at or below 10 ppt for 20 days, re-occurring at least once per five years), within the estuary. By finding key reoccurring salinity-duration patterns, the project will differentiate between a *core area* of permanent *Rangia cuneata* inhabitation and more transitory areas with only occasional reoccurrence of appropriate salinity conditions.

Model simulations, provided by TWDB, will be based on the historical record of freshwater inflows and other meteorological conditions for the Guadalupe Estuary for the period 1987 - 2009. Analysis of salinity-duration frequencies will include evaluation of simulated salinity in 2 ppt intervals, ranging from 0 – 34 ppt. Duration of salinity will be evaluated for at least the 10-day, 20-day, and 30-day intervals, while frequencies of reoccurrence will consider at least the one-year, two-year, five-year, 10-year, and 15-year intervals[1] (Figure 1).

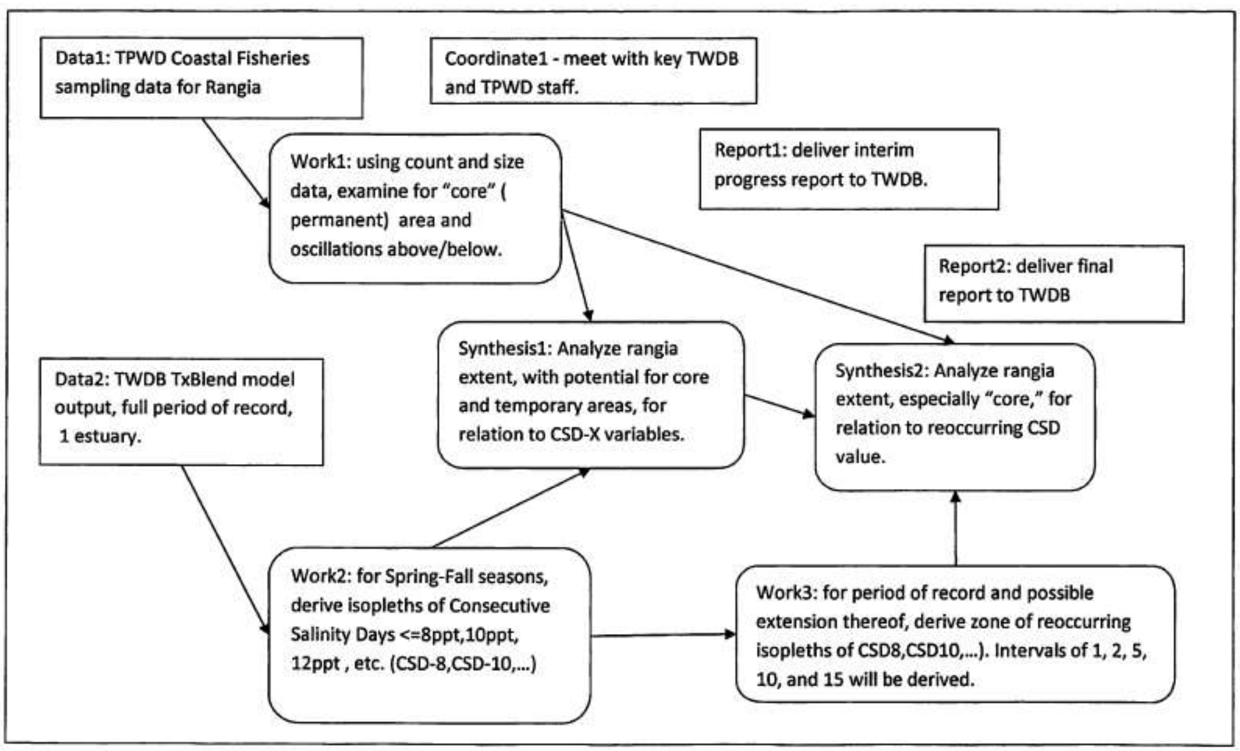

Figure 1. Principal work elements for project.

[1] because of the short 23year period of record of the TxBlend model, the longer 10-year and 15-year reoccurrence interval data will be much more uncertain. Contractor will explore, subject to consultation with TWDB, methods of extending the period via salinity-inflow regression techniques.

Deliverables

1) Quarterly Progress reports, no more than 30 days following each State fiscal quarter: 1 September - 30 November, 1 December - 28 February, 1 March - 31 May, and 1 June - 31 August.

2) Draft Final Report due 60 days prior to the end of the contact. The Draft Final Report will summarize study findings and will include maps and graphics demonstrating salinity-duration frequencies and *Rangia cuneata* distribution for the Guadalupe Estuary or other estuaries as analyzed. The Final report will include introduction, methods, results, and discussion sections. The Final report will be accompanied by a transmittal letter.

3) Final Report with revisions as requested by TWDB within 30 days of receiving comments.

References

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

Hopkins, S.H., J.W. Anderson, and K. Horvath. 1973. *The Brackish Water Clam* Rangia cuneata *as Indicator of Ecological Effects of Salinity Changes in Coastal Waters*. Contract report H-73-1. Submitted to the U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi. Prepared by Department of Biology, Texas A&M University, College Station, Texas. 250pp.

EXHIBIT B

Task and Expense Category Budget

Task	Description	Amount
1	*Bay Salinity Patterns and Limits to the Extent and Persistence of* Rangia cuneata *Clams*	$29,069
Total		**$29,069**

Expense Category	Total Amount
A. Salaries & Wages[1]	$18,063
B. Fringe[2]	4877
C. Travel	0
D. Other costs[3]	129
E. Subcontract Services	6000
TOTAL	$29,069

[1]Covers salary of principal investigator, Dr. Norman Johns;
[2]Fringe and benefit multiplier for National Wildlife Federation is currently at 27%;
[3]Includes anticipated cost for report production & transmittal, coordination expenses for subcontract
[4]Subcontract expenses are for GIS services from as yet to be determined party.

Appendix E - TWDB Comments on Draft Report

Texas Water Development Board
P.O. Box 13231, 1700 N. Congress Ave.
Austin, TX 78711-3231, www.twdb.texas.gov
Phone (512) 463-7847, Fax (512) 475-2053

October 10, 2012

Norman D. Johns, Ph.D.
National Wildlife Federation
44 East Avenue, Suite 200
Austin, Texas 78701

Re: Research Contract between the Texas Water Development Board (TWDB) and the National Wildlife Federation (NWF); TWDB Contract No. 1148311236, Draft Report Comments for Examining Bay Salinity Patterns and Limits to *Rangia* Populations in Texas Estuaries

Dear Dr. Johns: Norman!

Staff members of the TWDB have completed a review of the draft report prepared under the above-referenced contract. ATTACHMENT I provides the comments resulting from this review. As stated in the TWDB contract, the NWF will consider incorporating draft report comments from the Executive Administrator as well as other reviewers into the final report. In addition, the NWF will include a copy of the Executive Administrator's draft report comments in the Final Report.

The TWDB looks forward to receiving one (1) electronic copy of the entire Final Report in Portable Document Format (PDF) and six (6) bound double-sided copies. **Please further note, that in compliance with Texas Administrative Code Chapters 206 and 213 (related to Accessibility and Usability of State Web Sites), the digital copy of the final report must comply with the requirements and standards specified in statute. For more information, visit http://www.sos.state.tx.us/tac/index.shtml.** If you have any questions on accessibility, please contact David Carter with the Contract Administration Division at (512) 936-6079 or David.Carter@twdb.texas.gov

The NWF shall also submit one (1) electronic copy of any computer programs or models, and, if applicable, an operations manual developed under the terms of this Contract.

If you have any questions concerning the contract, please contact Dr. Carla Guthrie, the TWDB's designated Contract Manager for this project at (512) 463-4179.

Sincerely,

Robert E. Mace, Ph.D., P.G.
Deputy Executive Administrator
Water Science and Conservation

Enclosures
c: Carla Guthrie, Ph.D., TWDB

Attachment 1
Examining Bay Salinity Patterns and Limits to Rangia Populations in Texas Estuaries
P.I. Norman Johns
Contract #1148311236
TWDB comments to Final Report

REQUIRED CHANGES

General Draft Final Report Comments:

The study scope of work to examine spatial linkages between the frequency and duration of salinity zones and the distribution of *Rangia* in the Guadalupe and Mission-Aransas Estuaries was successfully completed. The Principal Investigator also included additional efforts that went beyond the scope of work to examine whether the primary salinity pattern search (based on favorable salinity conditions that support reproduction and recruitment) also met a spawning pre-condition and the potential influence on the consecutive days of favorable salinity conditions. This report is excellent in its analysis and presentation. The procedures and data interpretations were nice explained.

Please check the document for grammar, spelling, and typographical errors. Please also ensure that *Rangia* is capitalized and italicized throughout the document, when referring to the genus (as opposed to any references using the common name).

Specific Draft Final Report comments:

1. Please look for typos or grammatical omission throughout the document, such as:
   On page 7 near the end of page, "*de la Cruz (1985) point our*" should be "*point out*"

   On page 10 in the Figure 5 title, "*will be referred to withing*" should be "within"

   On page 30 in the midle of page, "*comparison of the effects fo*" should be "*effects for*".

2. Section 2.2, page 9, 1st ¶: Please correct the statement "*TxBLEND....simulates the salinity at each with a time step on the order of 30 minutes to an hour*" to read "*...simulates the salinity at each with a time step of three minutes with one hour output.*"

3. Section 2.2, page 9, 3rd ¶, last sentence: Figure 6 shows changes in salinity at site BB, but while the report text states that site BB has a lesser level of salinity depression (as compared to AA or other sites), the figure does not seem to suggest this is the case. Please verify and correct the statement if necessary.

4. Section 3.1, page 25, 1st ¶, last sentence: Please correct the use of "the latter" and "the former".

5. Section 3.2, page 30, 1st ¶, first sentence: Here is suggested wording for the first sentence, " *...based on regular consecutive salinity days did not yield results that would support the observed population distribution of Rangia.*" This is in contrast to the current wording of "*...would appear to limit the apparent population...*".

6. Section 4, page 38, 8th bullet point: Please consider rephrasing the statement to replace the wording "*official samples*" with "*the lack of a dedicated sampling program...*"

7. Section 4, page 39, 1st bullet point: Please consider rephrasing the last two sentences to say "... *reproduction and recruitment requirements of Rangia in Texas are warranted. This should also include both observed species, R. cuneata and R. flexuosa.*"

8. Section 4, page 39, 3rd bullet point: It may or may not be possible to the period of simulation of TxBLEND. Therefore, please consider changing the wording from "*model were extended*" to "*model could be extended.*" In addition, is the recommendation to extend the model to an earlier time period or to extend it forward to a more recent time than was available for this study?

9. Section 5, Acknowledgements, page 40: Please consider acknowledging TWDB staff, in particular Dr. Junji Matsumoto for assistance in running the TxBLEND model.

10. Section 6 References, page 40: Please ensure that all citations mentioned in the report are listed in the References section. Please also ensure that all references are complete (i.e. Chow *et al.* does not have a date listed).

11. Section 6, References, page 41: Please cite the three referenced TWDB citations as follows (or at least modify the references to include authorships and dates):

    Guthrie, C.G., J. Matsumoto, and Q. Lu. 2010. *TxBLEND Model Calibration and Validation for the Guadalupe and Mission-Aransas Estuaries. July 2010.* Texas Water Development Board, Austin, Texas. 46 pp.

    Guthrie, C.G., J. Matsumoto, and Q. Lu. 2010. *TxBLEND Model Validation for the Upper Guadalupe Estuary Using Recently Updated Inflow Data. November 2010.* Texas Water Development Board, Austin, Texas. 25 pp.

    Guthrie, C.G., and Q. Lu. 2010. *Coastal Hydrology for the Guadalupe Estuary: Updated Hydrology with Emphasis on Diversion and Return Flow Data for 2000-2009. November 2010.* Texas Water Development Board, Austin, Texas. 28 pp.

Figures and Tables Comments:

1. Figure 5, page 10: Please explain the difference between the points, yellow circles, and red crosses shown in the figure.

2. Table 1, page 21: Please ensure that formatting allows the table to be displayed on one page.

SUGGESTED CHANGES

Specific Draft Final Report Comments:

1. Please consider adding an Executive Summary.

2. Section 2.2, page 9, 2nd ¶: Please consider providing justification why 162 TxBLEND nodes were selected for pattern searching. Were you limited by some factor, or motivated by maintaining consistency with BBEST analysis?

3. Throughout, please consider using the designation *TxBLEND* as opposed to *TxBlend*. Dr. Matsumoto is the developer and author of TxBLEND and prefers this designation for the model.

Figures and Tables Comments:

1. Figures 20-23, Section 3.2, page 32-35: Although it is noted that this effort went beyond the scope of the study, were map views created to display the maximum annual sequence of CSD values with the spawning pre-condition included? If so, consider placing those maps in another appendix.