Habitat Suitability Index Modeling and GIS Technology to Support Habitat Management: Pensacola Bay, Florida Case Study

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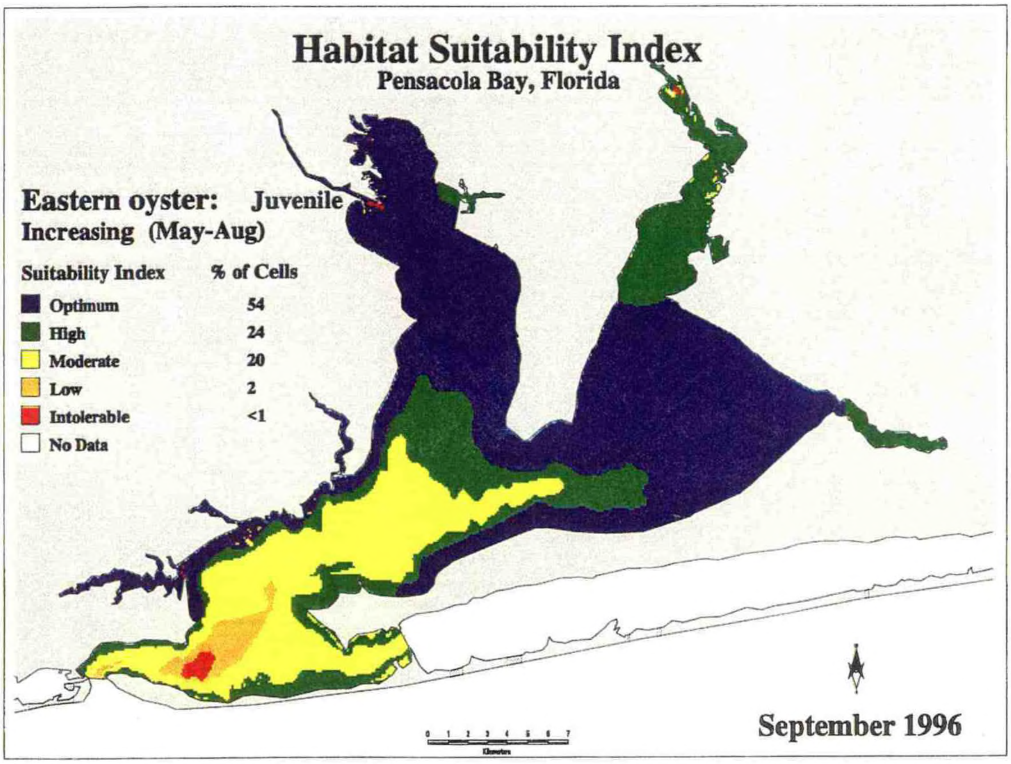

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ABSTRACT

This report presents results of an approach to examine the potential changes in selected fishery habitats as affected by alterations in freshwater inflow. Although the focus is one of freshwater inflow as it primarily affects salinity, the analysis is conducted in the context of the other necessary habitat parameters. Thus, the analysis is based upon habitat suitability as determined by the combination of salinity (ppt), water temperature (C), dissolved oxygen content (mg/l), substrate type, bathymetry (m), and the presence or absence of submerged aquatic vegetation and emergent wetland macrophytes, as they vary in both time and space. Eastern oyster (*Crassostrea virginica*), white shrimp (*Penaeus setiferus*), and spotted seatrout (*Cynoscion nebulosus*) were selected to study via habitat suitability index (HSI) modeling. Models were developed for Pensacola Bay, Florida; however, the model was designed to be applied across a wide range of estuaries in the central Gulf of Mexico. The models resulted in a numerical index of habitat suitability ranging from 0.0 - 1.0. GIS technology was explicitly incorporated to produce a "seascape" view of the relative suitability of locations in geographic space through time. Species suitability index values (SIs) were generated through an extensive data and literature search for documented tolerances to, and affinities along, each environmental and biological gradient included in the model. Adult oyster habitat suitability exhibited a dramatic decline across most of the bay complex during the summer/fall transition. Intrusion of high-salinity waters into the upper reaches of East Bay and Escambia Bay resulted in an 87% decrease in the optimum HSI class, and was displaced by a threefold increase in the moderately HSI class. Scenarios depicting potential effects of habitat change can easily be modeled and observed using HSI modeling in conjunction with GIS technology.

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INTRODUCTION

In cooperation with the Freshwater Inflow Committee of the U.S. Environmental Protection Agency's Gulf of Mexico Program (GOMP), NOAA's Strategic Environmental Assessments (SEA) Division convened a workshop from March 14-16, 1995 to identify estuaries to examine important relationships among freshwater inflow alteration and estuarine habitat. As a result, eastern oyster (*Crassostrea virginica*), white shrimp (*Penaeus setiferus*), and spotted seatrout (*Cynoscion nebulosus*) were selected as test species for habitat suitability index (HSI) modeling based on their elevated sensitivity to acute and/or persistent salinity fluxes as compared to other estuarine and estuarine-dependent species common to Gulf estuaries. In addition, these species support significant commercial and recreational fisheries in these estuaries (Christensen 1996). Test models were developed for Pensacola Bay, Florida; however, the model was designed to be applied generically across a wide range of estuaries in the central Gulf of Mexico.

A requisite of the model was that it be based upon existing information to ensure that it could be readily applied as a strategic planning tool, and where data permits, as a tactical tool to address site-specific questions. The purpose of this report is to present the results of an approach to examine potential changes in selected fishery habitats as effected by alterations in freshwater inflow. Although the focus is one of freshwater inflow as it primarily affects salinity, the analysis is conducted in the context of the other necessary habitat parameters. Thus, the analysis is based upon habitat suitability as determined by the combination of relevant physical, biological, and chemical factors as they vary in both time and space.

Pensacola Bay was chosen as a pilot area for this project because it represented an estuary that workshop participants rated as medium to high based upon sensitivity to changes in freshwater inflow. In addition, the availability of existing information represented the typical condition that would be encountered Gulfwide, and would therefore address the question of transferability. Although the project focus was one of freshwater inflow as it affects salinity and salinity-sensitive species, the modeling framework was designed to test the sensitivity of any or all other habitat parameters for these or other designated estuarine and near-coastal species. This model is, therefore, a tool that can be used to examine a range of possible Gulf-wide habitat issues.

METHODS

Approach

The underlying modeling approach was introduced by the U.S. Fish and Wildlife Service's (USFWS) Habitat Evaluations Procedures Program, whereby models resulted in a numerical index of habitat suitability ranging from 0.0 - 1.0. Models were based on the assumption that a positive relationship exists between the index and a habitat's carrying capacity for a given species (Schamberger 1982). Our models exhibited a significant departure from USFWS methods by incorporating a spatial component to produce a view of the relative suitability of locations in geographic space through time. The intent was to develop a simple spatial model using GIS technology that offers estuarine resource managers a habitat assessment capability that can be applied to a wide range of estuarine species.

Geographic Setting

The Pensacola Bay estuary is a drowned river valley and lagoonal system covering approximately 370 km^2 (NOAA 1989). It includes Pensacola, Escambia, East, and Blackwater Bays, as well as Santa Rosa Sound, although the latter was not included in this analysis (Figure 1). The estuary is separated from the Gulf of Mexico by Santa Rosa Island, and direct tidal exchange is limited to the Pensacola Inlet. Limited exchange occurs with the Perdido Bay system through Big Lagoon, and with the Choctawhatchee system via Santa Rosa Sound (Orlando et al. 1993).

The Escambia River discharges to Escambia Bay, and is the primary source of freshwater into the system. The Yellow and Blackwater Rivers are major contributors of freshwater to East and Blackwater Bays, respectively. Together, these rivers discharge approximately one-half the flow of the Escambia River. Circulation in Escambia Bay is dominated by a counterclockwise flow throughout the year, resulting from the movement of

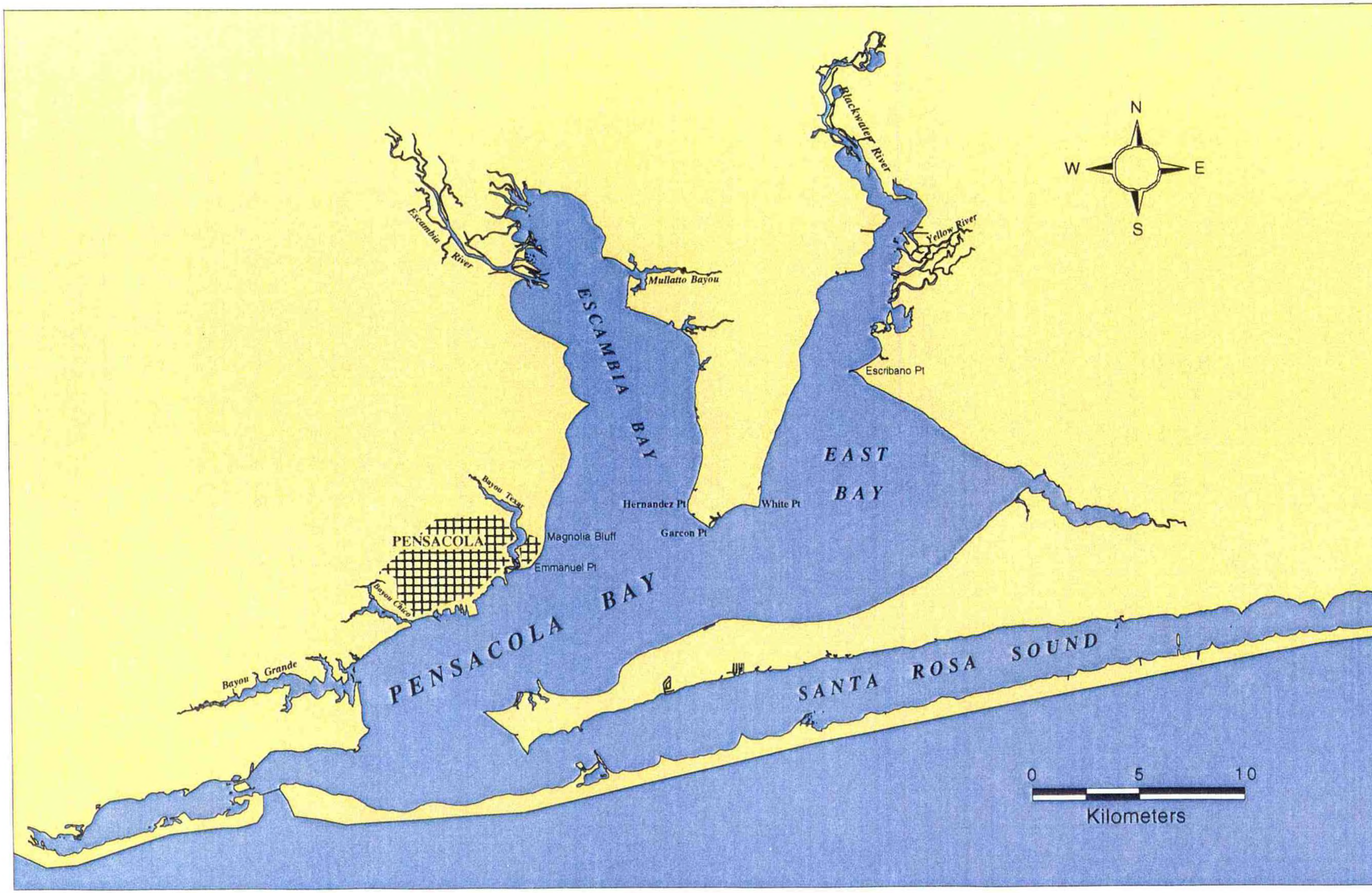


Figure 1. *Case study area map: Pensacola Bay, Florida.*

freshwater along the western shoreline and saline bottom water intrusion along the eastern shoreline (Wolfe et al. 1988).

Model Development

The first step in developing the seascape HSI models was to initiate a comprehensive data and literature search. This was coupled with an expert review process to select an appropriate set of environmental and biological variables to include in the model. A steering committee comprised of fisheries biologists, commercial fishermen, chemical oceanographers, hydrographers, and living resource managers was assembled to provide recommendations. The consensus was that salinity, water temperature, dissolved oxygen content, bathymetry, substrate type, and the presence or absence of submerged aquatic vegetation (SAV) and emergent wetland macrophytes (EV) were sufficient to model habitat suitability, and to infer potential distributions of estuarine species in most Gulf estuaries.

A species occurrence matrix (presence/absence) to generate suitability index (SI) values was developed in one-unit increments for each environmental parameter — salinity (ppt), water temperature (°C), dissolved oxygen content (mg/l), depth (m), presence of submerged aquatic vegetation (i.e., *Halodule wrightii*), and presence of emergent wetland vegetation (i.e., *Spartina alterniflora*). These matrices enabled identification of critical values above and/or below which species were never present (Figure 2). Although interactions commonly occur between environmental variables, this model assumes their independence from one another. Biological covariates (i.e., oyster drill densities and salinity) were considered in the development of SI values for each species, and adjusted accordingly. Individual SIs also were derived under the assumption that all other parameters were held constant at, or near, their species-specific optimum. Under these assumptions, complete absence indicated zero suitability, and SI coefficients were set to zero.

Next, species suitability index values were generated through an extensive literature search for documented tolerances to, and affinities along, each environmental and biological gradient included in the model. HSI models previously developed for American oyster, white shrimp, and spotted seatrout by the USFWS were used as a "baseline" reference, when applicable, to ensure that the SI values were comparable to those developed using empirical data. Several modifications were made to the USFWS models based upon the authors' working knowledge of species-habitat associations. Information on species life history requirements was compiled and subsequently used to categorically rank habitat suitability (Figure 2). Resulting categories were transformed into SI values ranging from 0.0 (unsuitable) to 1.0 (optimum). Assigning SIs involved considerable expert knowledge and judgment; hence, values may require adjustments based on biogeographic differences.

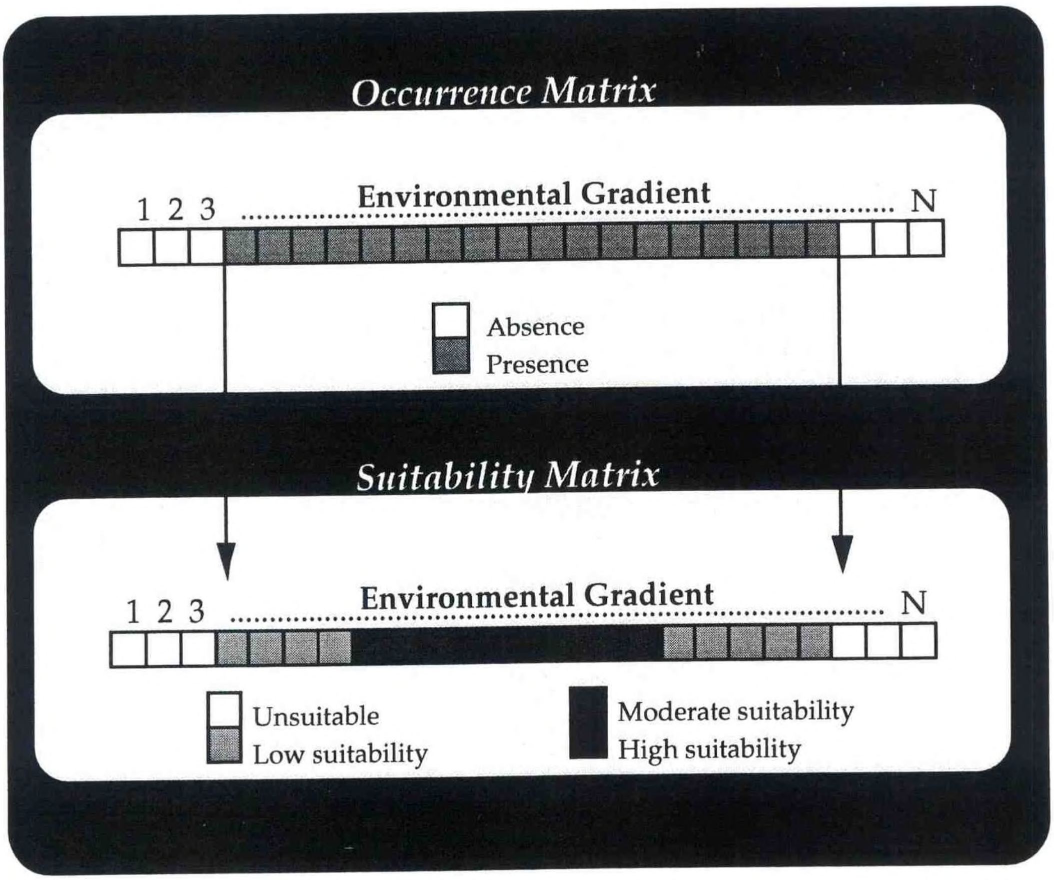


Figure 2. Conceptual model of methods used to generate HSI coefficients.

SI increments varied across environmental parameters, and were based on the number of habitat association categories that the authors could identify with sufficient reliability. This approach is termed a "word model" by USFWS (USFWS 1981). An elaboration of this model would be to statistically define the species-habitat associations via ordination procedures, regressions, or multinomial response curves, resulting in a "mechanistic model" (Monaco et al. in press).

Due to the lack of appropriate density data for submerged aquatic and emergent wetland vegetation, SI values were assigned based on the presence or absence of these habitats. In the example conceptual model shown in Figure 2, SI values would have been assigned to a discrete value within the following ranges: Unsuitable = 0.00, Low suitability = 0.01-0.33, Medium suitability = 0.34-0.66, High suitability > 0.67-0.99, and Optimum suitability = 1.0. Exact values assigned within these ranges were based on findings in the literature coupled with expert judgment.

NOAA's Estuarine Living Marine Resources (ELMR) Program has spent several years assembling a comprehensive inventory of the relative abundance and distribution of important finfish and macroinvertebrates in Gulf estuaries (Nelson et al. 1992, Patillo et al. in prep), with considerable effort spent documenting ontogenetic shifts in habitat associations (Christensen 1996). These data enabled the authors to model habitat suitability for several life stages. Only adult and juvenile life stages were modeled in this study; however, habitat suitability values also were developed for spawning adults, larvae, and eggs. Adults and juveniles were selected for this study because life history information was considerably more reliable than for the earlier life history stages.

Because the relationship between environmental and biological gradients and species distributions is impractical and inappropriate to quantify without a robust data set documenting relative abundance across the complete range of each environmental parameter, variables were not weighted in the conventional manner. Variables were placed in two categories, critical and non-critical, based on their potential effect on species distributions. A "critical variable" was defined as one exhibiting the potential to exclude a population if physiological tolerances are exceeded. Salinity, temperature, dissolved oxygen, and bathymetry were considered as potentially critical parameters for species modeled in this study. Critical variable SI values ranged from 0.0-1.0. Thus, if any of these were scored as 0.0 for a particular species, the resulting HSI model would predict complete species exclusion.

A "non-critical variable" was defined as one that has an effect on species distributions; however, it alone will never completely exclude a population from utilizing a particular habitat. Substrate type, and the presence or absence of SAV and EV were considered non-critical for the three target species. Non-critical variable SI values ranged from >0.2-1.0. By scaling SIs in this manner, the authors were able to “weight” the variables without utilizing statistical techniques to quantify the relationships.

Once suitability index values were developed, the Arc/Info 7.03 GRID© module* was utilized to conduct the HSI Modeling procedures. The grid-based system was used because it offers a multitude of advantages suitable for spatial analysis. The grid-based system utilizes a Cartesian matrix consisting of rows and columns of discrete uniform cells, each of which stores a numeric code that is assigned according to the feature being represented (SI values). The use of numeric values greatly facilitates the speed of processing. Grid cells also store a unique location identifier, a feature not inherent to other spatial model data structures (i.e., vector models). The module combines a grid-cell spatial model with a relational attribute model. The hierarchical tile-block structure of the module compresses data using run-length encoding that supports expeditious and random retrieval of the stored data. Several advantages of the GRID module making it ideal for use in the HSI model was that it supports both continuous and discrete data, as well as the concept of no data. Furthermore, the tables storing data for each input grid allows full relational database model querying (ESRI 1991).

Variable distributions (vectors) in Pensacola Bay were first contoured using Map-Info©, and subsequently imported into Arc/Info and transformed to a grid map. Point data used to generate contours were acquired from the Florida Department of Natural Resources and the Environmental Protection Agency's EMAP Program (FLDNR 1991, USEPA 1996). Each of the grids utilized in the model store one habitat variable. Since each grid was created with the same coordinate system, cells among grids were aligned in geographic space which facilitated inter-grid processing. The cell size also was identical across all grids. A cell size of 1,000 m^2 was selected as the most appropriate size based on the number and distribution of original data points used to create the habitat variable grid maps. At this resolution, each environmental grid map in Pensacola Bay consisted of approximately 37,000 cells. GRID supports cartographic spatial analysis using a high-level computational language. Thus, geoprocessing between grids utilizes a simple and efficient map-algebra calculation of numeric cell values. The HSI model made use of the GRID Arithmetic computational operator to calculate a geometric mean between the input grids using the following equation:

$$HSI = [\prod_{i=1}^{n} (v_i)]^{\wedge}(1/n);$$ *where* v_i *= environmental variable, and n=number of variables in model.*

Optimum HSI values (1.0) are only achieved if all environmental variable SIs are at optimum. Likewise, if any one variable SI is unsuitable (0.0) at a particular location, the HSI model will indicate unsuitable habitat regardless of the SI value for all other variables at that time. A conceptual model exhibiting the integration of SI values and grid maps to produce HSI models is shown in Figure 3.

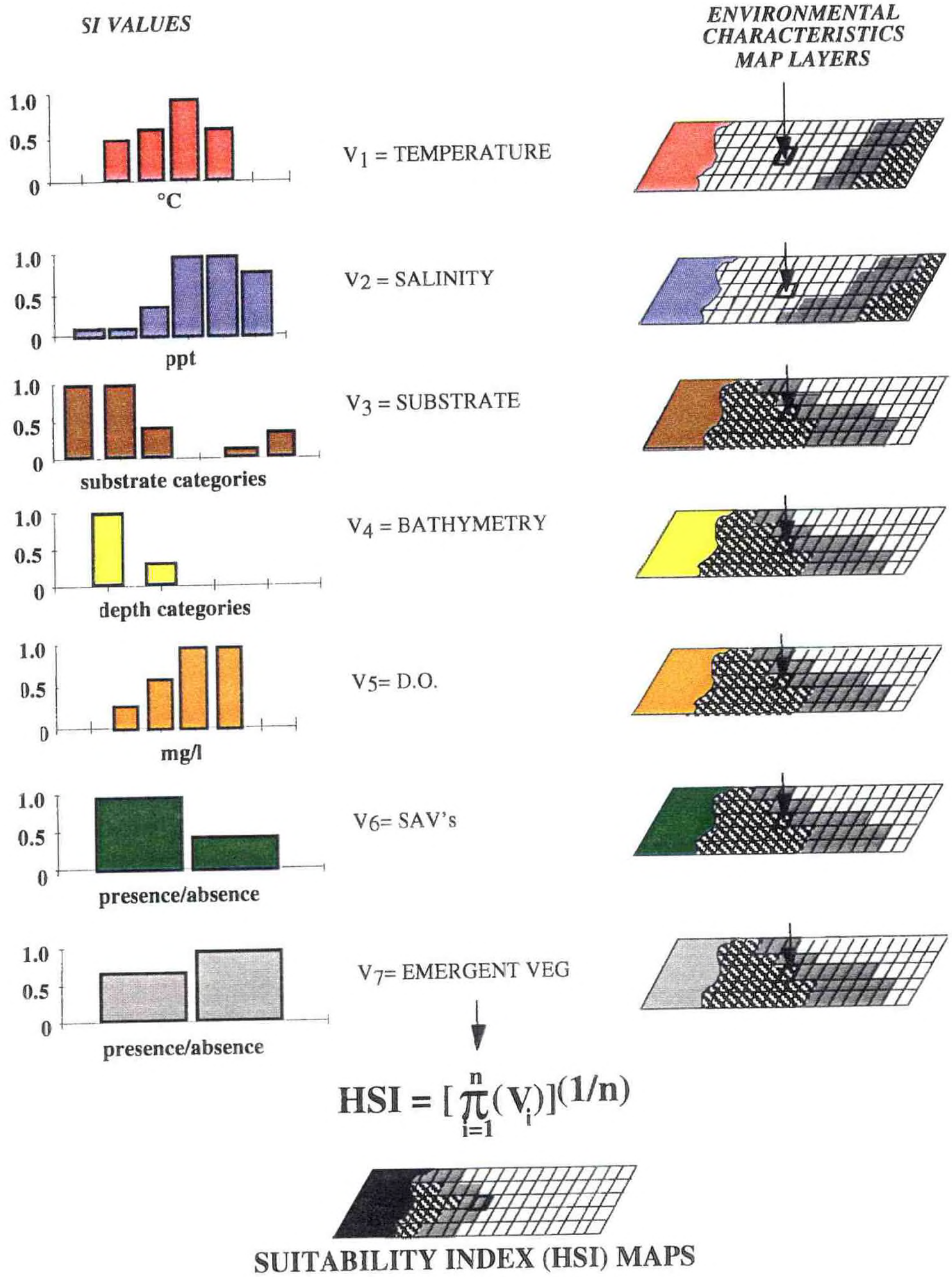


Figure 3. Grid-based habitat suitability index modeling with Arc/Info©.

The development of contour maps and the Arc/Info tabular infrastructure to enable grid-based modeling is a substantial task; hence, each environmental grid was categorized. Salinity was mapped in 5 ppt increments (Orlando et al. 1993), water temperature in 2° C isotherms (SAB 1986), and DO in 1 mg/l increments (SEA unpublished data). Substrate was categorized using a modified Shepard's classification scheme (Shepard 1954), and was classified as either sand, silt, or clay. Submergent aquatic vegetation and emergent wetland macrophytes were categorized as present or absent for modeling purposes. The bathymetric grid was contoured in 1.82 m (6 foot) isobaths (NOAA 1994). The distribution of SAVs and EVs in Pensacola bay was recorded using low altitude fly-overs and mapped by the USFWS in 1986 (USFWS 1986). These maps were used to create the SAV and EV grid maps. Although the USFWS classified EV's into several categories based on tidal flooding periodicity and duration, only those macrophytes classified as "regularly flooded" and "irregularly exposed" were incorporated in the models. These classes of emergent vegetation best represent the "edge habitat" that is most critical to estuarine fishes and macroinvertebrates.

Models were run during four time periods to address seasonal fluctuations in species distributions. Representative periods for the Pensacola Bay HSI model were determined by characterizing salinity conditions in the estuary. Seasonal depth-averaged salinity was modeled from a subset of field salinity data collected between 1970 and 1994 (Orlando et al. 1993). Salinity analysis for the Pensacola Bay system focused on two three-month periods (high and low salinity time periods), and two transitional salinity time periods. These periods represent the typical high, transitional, and low-salinity conditions experienced under average and present-day seasonal freshwater inflow conditions.

Three months were selected as the appropriate averaging period because seasonal variation in freshwater inflow produces an important change in estuary-wide salinity patterns. In addition, three months were considered to be the minimum period necessary to observe the response of salinity to freshwater inflow and other physical phenomena operating at and within the seasonal time scale. Isohalines were developed to represent the typical range of salinity conditions experienced under average seasonal freshwater inflow conditions. The isohalines that define the salinity zones shift seasonally due to environmental factors such as freshwater inflow, tides, evaporation, and wind (Orlando et al. 1993). The time periods modeled were: 1) High salinity (September-November), 2) Low salinity (February-April), 3) Increasing salinity (May-August), and 4) Decreasing salinity (December-January). Depth-averaged water temperature also was contoured for the same salinity defined seasons to ensure temporal uniformity in the models.

The series of steps used to generate the input grids are shown in Figure 4. Initially, point coverages were created in Map/Info 4.0 for each of the environmental variables using location and value attributes. Vectors were then mapped from these point covers using the Inverse Distance Weighting (IWD) method. These contour coverages were then exported into Arc/Info using the ArcLink software which retains the topology and attributes between software systems. Arc/Info grids were created for each of the environmental variables during each salinity-defined time period using these polygon coverages. Resulting maps were generated to provide a spatial assessment of the relative suitability of the combination of habitats contained in each of the 37,000+ grid cells across Pensacola Bay.

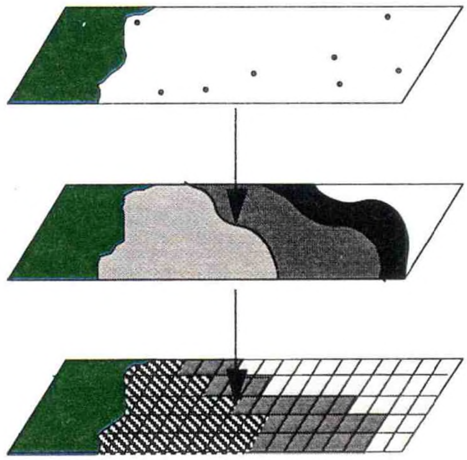


Figure 4. *Grid map development procedure.*

Two hypothetical salinity scenarios also were modeled to investigate the potential impacts of anthropogenic modifications. To simulate increased freshwater inflow into Pensacola Bay, salinity values for the low-salinity time period were decreased by 5 ppt throughout the bay. Isohaline locations were kept static to facilitate ease of comparison with model results using empirically derived salinity distributions. Likewise, bay-wide salinities for the high-salinity time period were increased by 5 ppt to simulate a freshwater diversion away from the system.

Model Validation

A frequency analysis of oyster presence mapped from existing oyster reef plots by habitat suitability class was performed to verify the oyster model (Mark Berrigan (FLDEP) - pers. comm, Little and Quick 1976). Due to the lack of fisheries-independent field data, a team of fisheries biologists, commercial fishermen, and physical oceanographers convened in Pensacola in June 1996, and again in September, to qualitatively verify the model for white shrimp and spotted seatrout. To gain further understanding of the relative effect of each variable on species distributions, a Pearson product-moment correlation coefficient matrix was calculated using SAS 3.0© (SAS 1996) to reflect the relationships between the verification data and environmental variable distributions.

*Proprietary software products of Environmental Systems Research Institute (ESRI).

RESULTS AND DISCUSSION

Environmental Variables

Salinity

Depth-averaged isohaline distributions for the low-salinity time period (February-April) indicated the presence of two large water masses ranging from 5-10 parts per thousand (ppt) in both upper Escambia and East Bays. These hydrological features resulted from peak annual freshwater inflow from the Escambia (mean flow = 760 m^3/s) and Blackwater Rivers (mean flow = 110 m^3/s), respectively (Orlando et al. 1993). Together, these water masses covered approximately 25% of the surface area for the entire Pensacola Bay complex (Figure 5). The 10-15 ppt isohaline covered approximately 39% of Pensacola Bay. The southern range of this water mass extended westward from the terminus of Bayou Grande in the east across much of East Bay. On average, the remainder of the Pensacola Bay complex ranged from 15-25 ppt from February through April, with approximately 23% ranging from 15-20, and 13% from 20-25.

As the volume of freshwater inflow abated during the increasing-salinity time period (May-August), the relative proportion of the 5-10 ppt salinity zone decreased by 65% compared to the antecedent salinity season, covering only 8.7% of the total system surface area (Table 1). The proportion of the 10-15 ppt salinity zone exhibited only a minor reduction (-11%); however, its location shifted markedly to the north in Escambia Bay, and to a lesser extent in East Bay (Figure 6). The greatest increase in surface area was observed in the 15-20 ppt salinity zone, rising from 22.6% to 41.1% of the total surface area

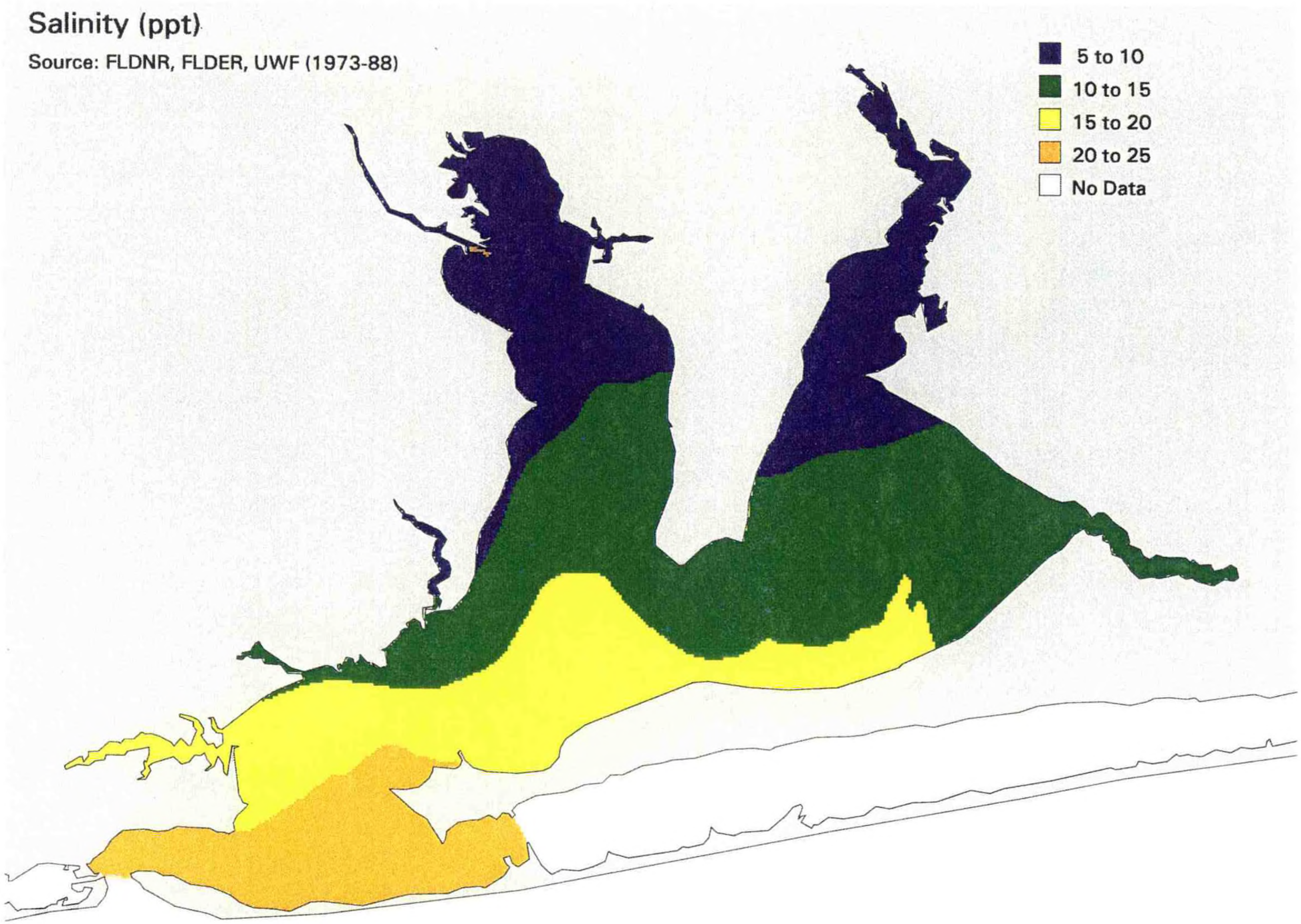


Figure 5. *Isohaline distributions during the low salinity time period (Feb-Apr).*

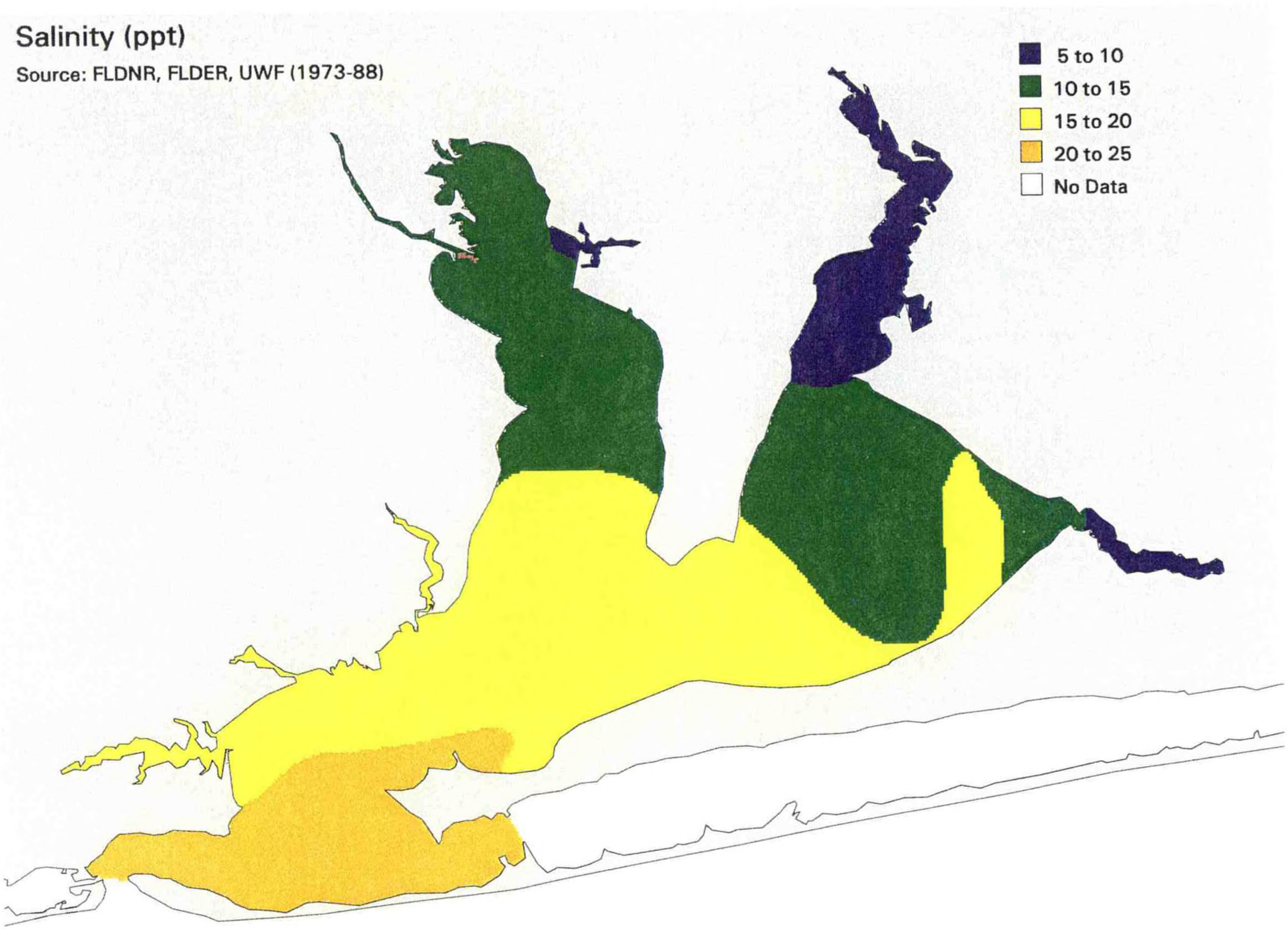


Figure 6. *Isohaline distributions during the increasing salinity time period (May-Aug).*

coverage. The northward extension of this salinity zone observed in southern East Bay is indicative of a baroclinic gyre resulting from inflow from the Blackwater River to the north and the East River to the east. The proportion of the 20-25 ppt zone increased only slightly in comparison to the previous salinity season.

The high salinity time period (September-November) was characterized by a dramatic shift in isohaline distributions (Figure 7). The 5-10 ppt salinity zone was completely eliminated by the intrusion of high salinity bottom waters via the Escambia Bay channel (Orlando et al. 1993). During this period, average freshwater inflow was approximately three times lower than during the low-salinity time period. Salinities ranging from 10-15 ppt were reduced by 80% from the antecedent salinity time period, and the 15-20 ppt salinity zone decreased by 19%. The most conspicuous change during the high-salinity time period was that the 20-25 ppt zone increased by 284%, and covered the majority of the Pensacola Bay complex (59.8%).

The volume of freshwater delivered to Pensacola Bay increased during winter months (December-January), resulting in a significant southward shift of the 10-15 and 15-20 ppt isohalines (Figure 8). This shift eliminated the 20-25 ppt salinity zone altogether. On average, 99% of the bay consisted of a 10-15 ppt zone (56.6%), and a 15-20 ppt zone (42.4%).

Water Temperature

Annual depth-averaged water temperatures ranged from 10° C during the December-January time period to a maximum of 30° C during May through August (Figures 9-12). Water temperatures varied only slightly across Pensacola Bay during the low-salinity time period (February-April). Ninety-two percent of Pensacola Bay ranged between 18 and 22° C, while approximately 7% ranged from 16-18° C. Water temperatures in Mulatto Bayou

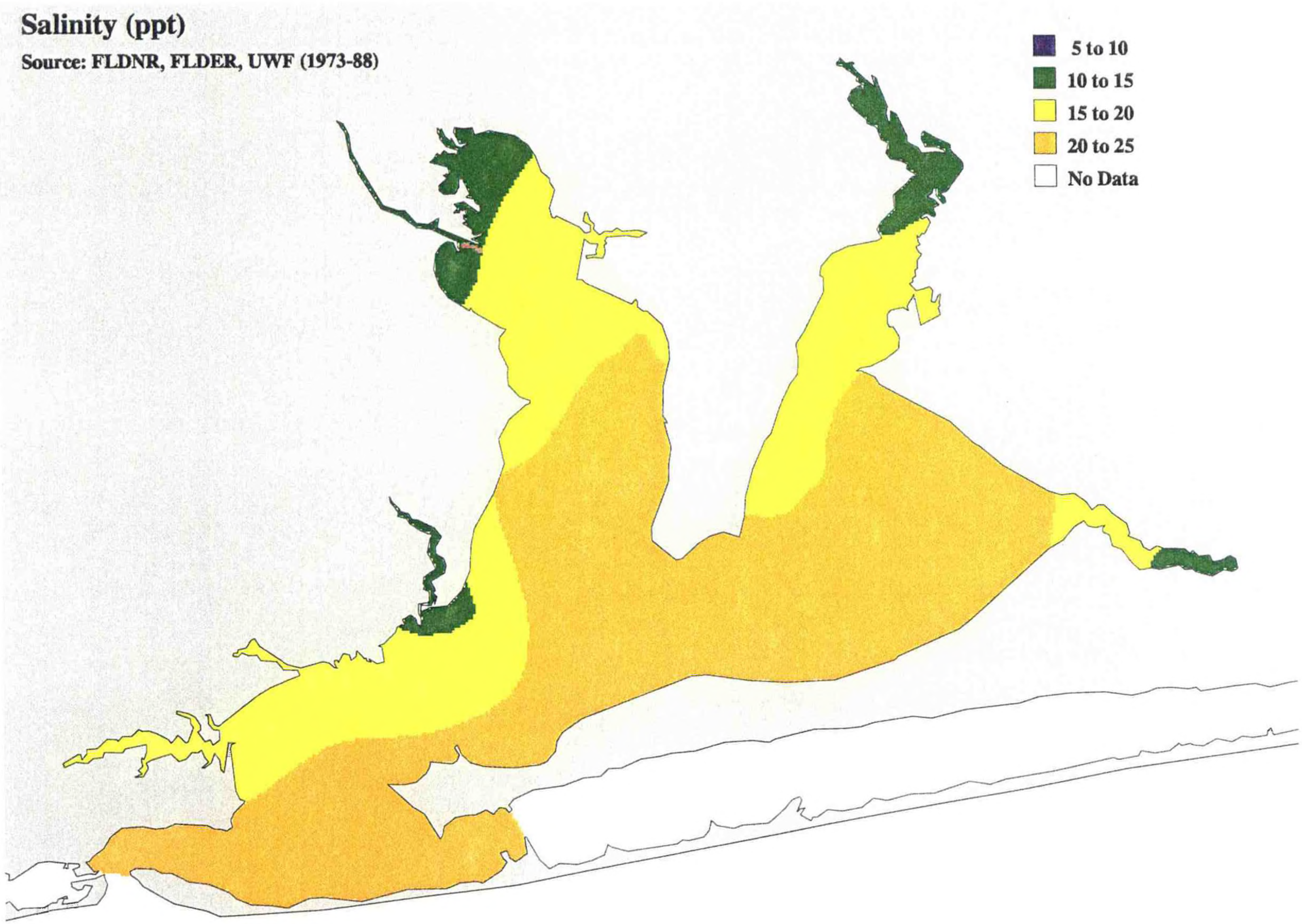


Figure 7. *Isohaline distributions during the high salinity time period (Sep-Nov).*

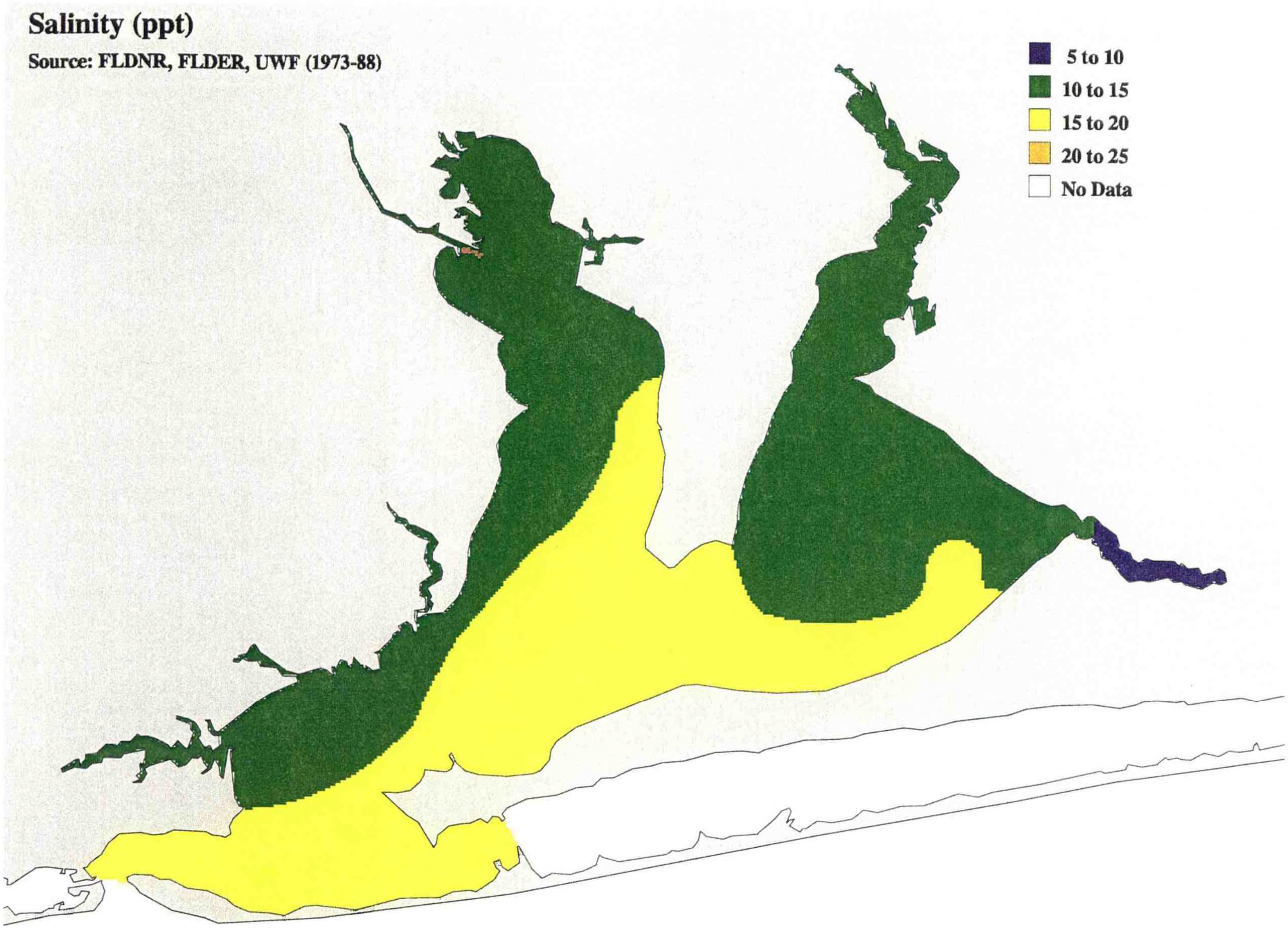


Figure 8. *Isohaline distribuitions during the decreasing salinity time period (Dec-Jan).*

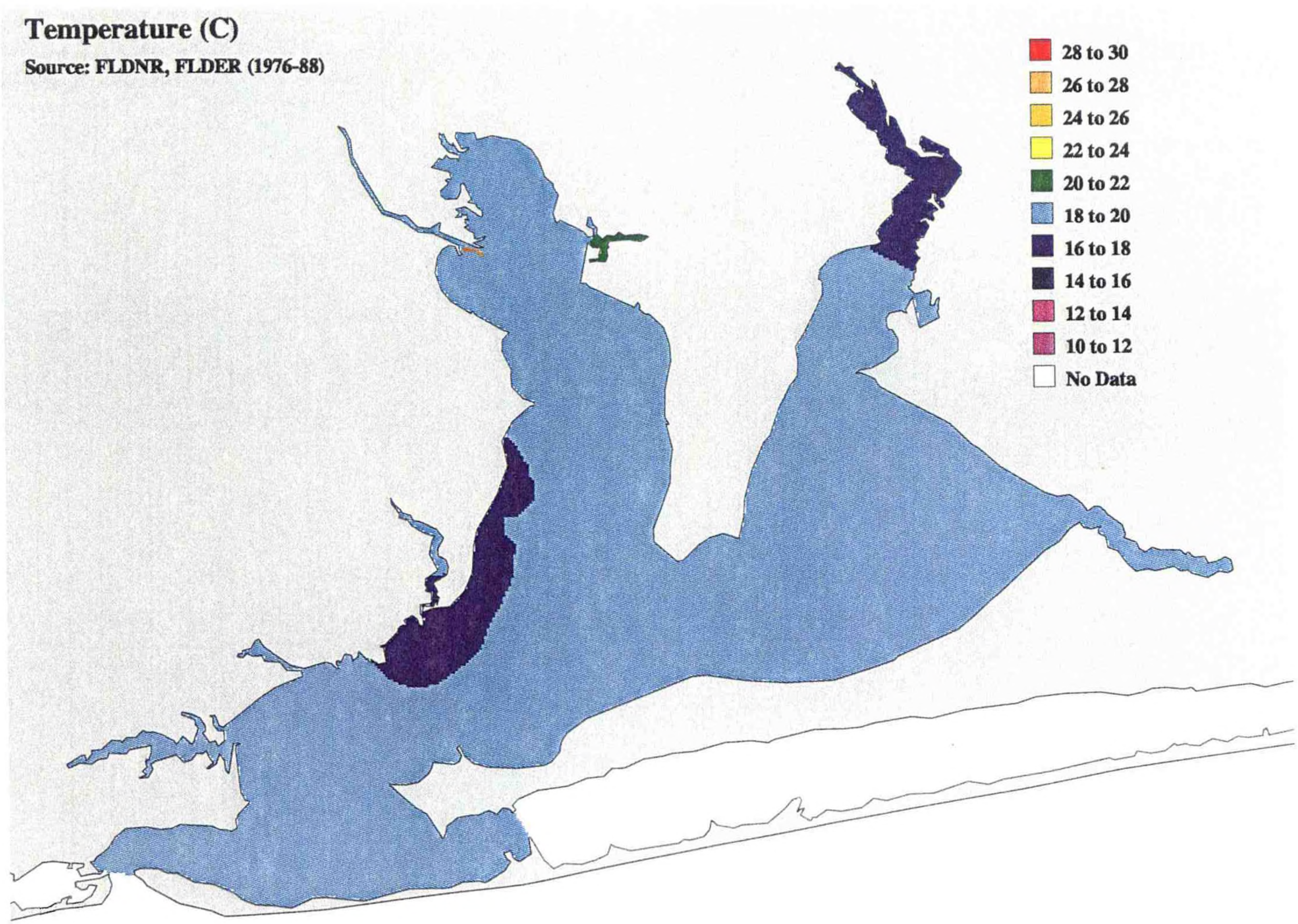


Figure 9. *Isotherm distributions during the low salinity time period (Feb-Apr).*

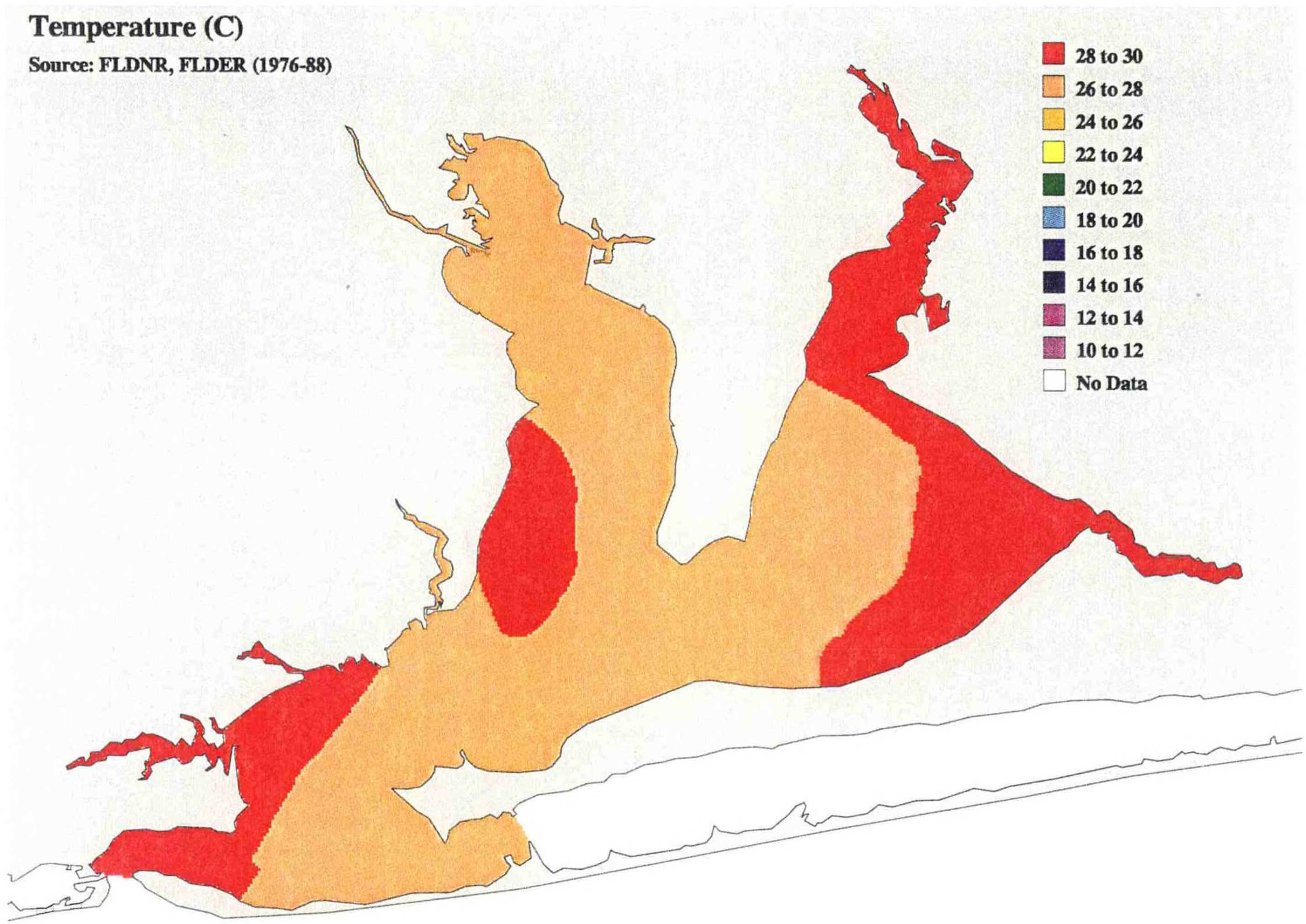


Figure 10. *Isotherm distributions during the increasing salinity time period (May-Aug).*

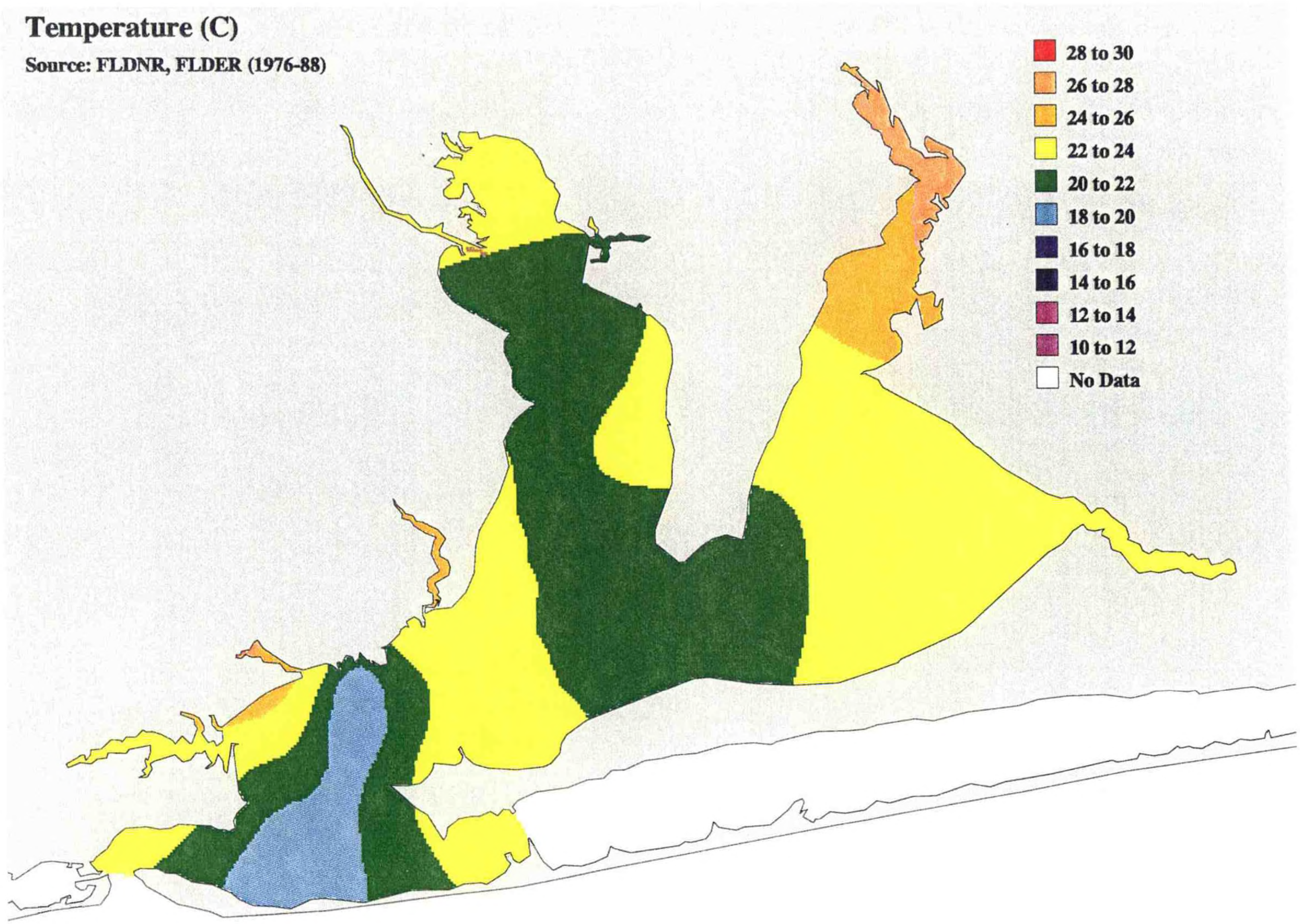


Figure 11. *Isotherm distributions during the high salinity time period (Sep-Nov).*

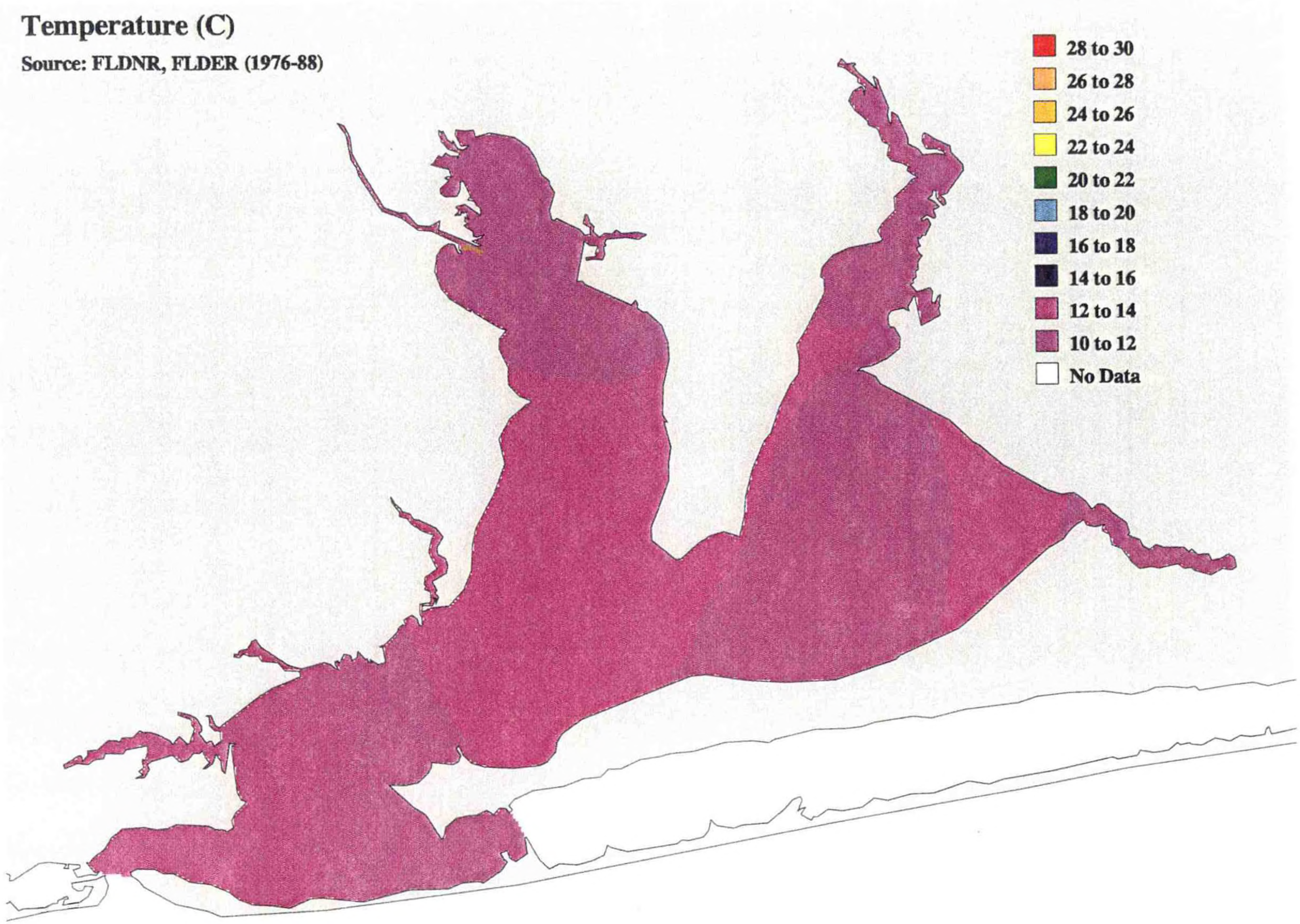


Figure 12. *Isotherm distributions during the decreasing salinity time period (Dec-Jan).*

ranged from 20-22° C; however, this temperature interval contributed less than 0.5% of the total surface area of the bay system during this time period.

Mean water temperatures increased considerably to a range of 26-30° C during the late spring (May) through August. Approximately two-thirds of the bay ranged from 26-28° C, with the remainder ranging from 28-30° C. The high-salinity time period was characterized by a complex isotherm distribution pattern, resulting in a conspicuous temperature gradient across the bay. Cool offshore waters ranging from 18-20° C entered the bay through the Pensacola Inlet, while temperatures in extreme northern Blackwater Bay averaged 26° C (Figure 11). The onset of prevailing north winds during December and January reduced average water temperatures significantly and uniformly across the bay. Approximately 65% of Pensacola Bay ranged from 10-12° C, while the remainder ranged from 12-14° C.

Substrate

The distribution of substrate sampling points was highly variable (patchy); therefore, to minimize the effects of sampling bias, substrates were categorized into three broad classes based on particle size. These categories — sand, silt, and clay — represent vertices of Shepard's grain size classification scheme (Shepard 1954). Moreover, few studies have been investigated the relationship between estuarine species distribution patterns and substrate particle size at fine scales. Thus, this broad substrate classification was the most appropriate and reliable for modeling purposes. Pensacola Bay sediment distributions exhibited classical patterns, with fine particle depositions in the basins and river deltas, while coarse sediment fractions were associated with shorelines and beaches (Figure 13). The sand fraction covered approximately 43% of the bay, while the silt and clay fractions covered 20% and 37%, respectively.

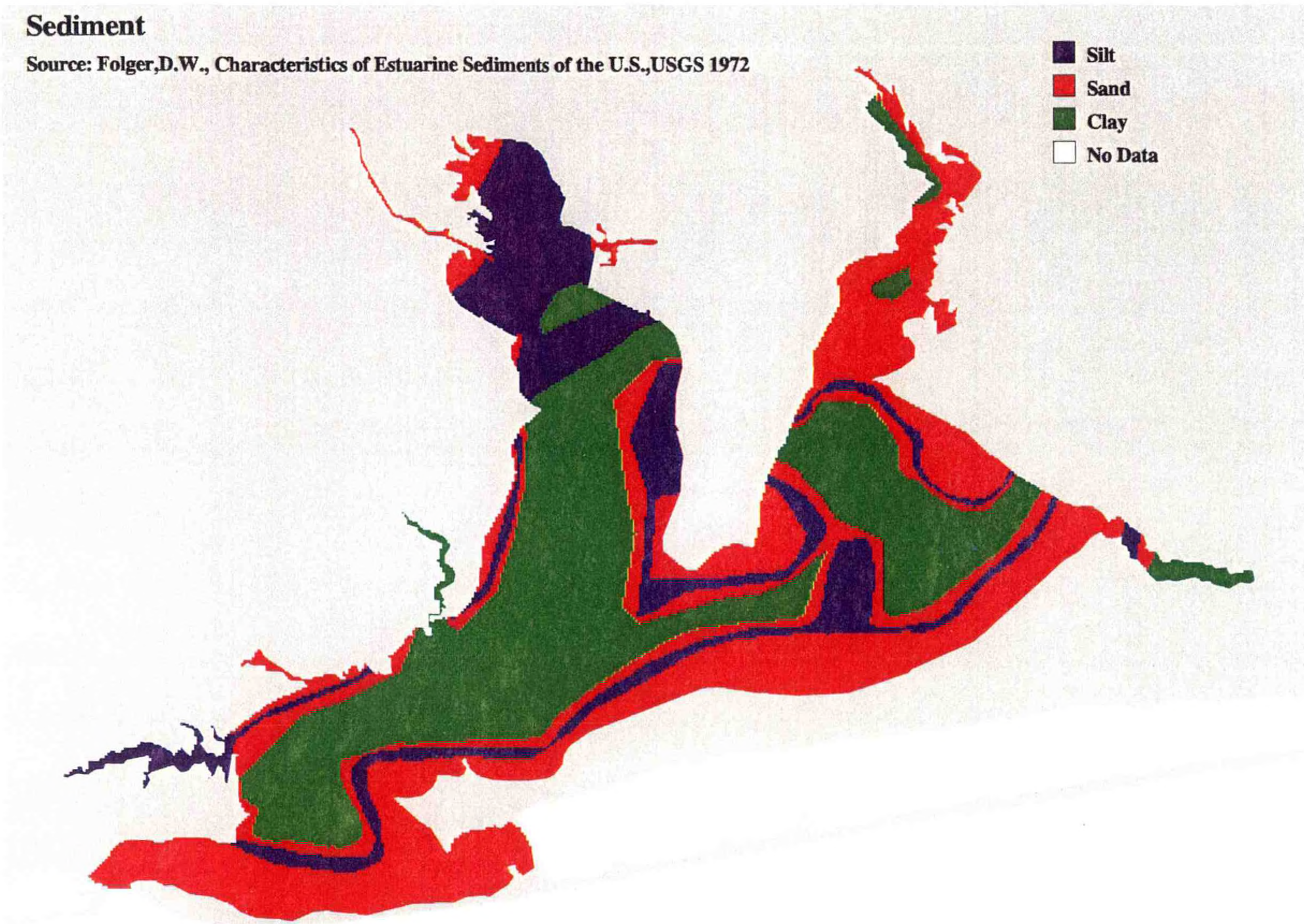


Figure 13. *Pensacola Bay substrate distribution map.*

Bathymetry

Depth was separated into 1.8 meter depth intervals to enable expeditious modeling with bathymetry (Figure 14). Escambia, East, and Blackwater Bays are shallow, and range from 0-4 m throughout most of their extent. Pensacola Bay exhibited greater variation, with depths ranging from 0-15 m. Approximately 80% of the entire bay complex ranged from 0-6 m, while 11% ranged from 6-8 m. The remainder of the Pensacola Bay system is greater than 8 meters in depth.

Submerged Aquatic Vegetation & Emergent Wetland Macrophytes

Both submerged aquatic vegetation (SAV) (e.g., *Halodule wrightii*) and emergent wetland vegetation (EV) (e.g., *Spartina alterniflora*) were included in the models. Because all EV types identified by U.S. Fish and Wildlife Service's National Wetland Inventory (NWI) were not appropriate for estuarine fish and macroinvertebrate habitat modeling, only "regularly flooded emergent vegetation" and "irregularly exposed emergent vegetation" were addressed (Figure 15) (USFWS 1985). These EV classes consisted mainly of *Spartina alterniflora* in East and Pensacola Bays. Species composition in the upper reaches of Escambia and Blackwater Bays were more characteristic of persistent tidal freshwater environments (i.e., *Scirpus spp.* and *Typha latifolia*). Individual EV classes and species were not considered independently in the model; hence, both types were given the same suitability index value. This also held true for submerged aquatic vegetation. Approximately 1.7% of the Pensacola Bay complex included in the model was covered by emergent wetland macrophytes. Only 0.01% of the study area contained submerged aquatic vegetation. Extensive SAV meadows present in Santa Rosa Sound would have increased the percentage of coverage considerably; however, due to the lack of reliable hydrologic data, this area was not considered in this analysis.

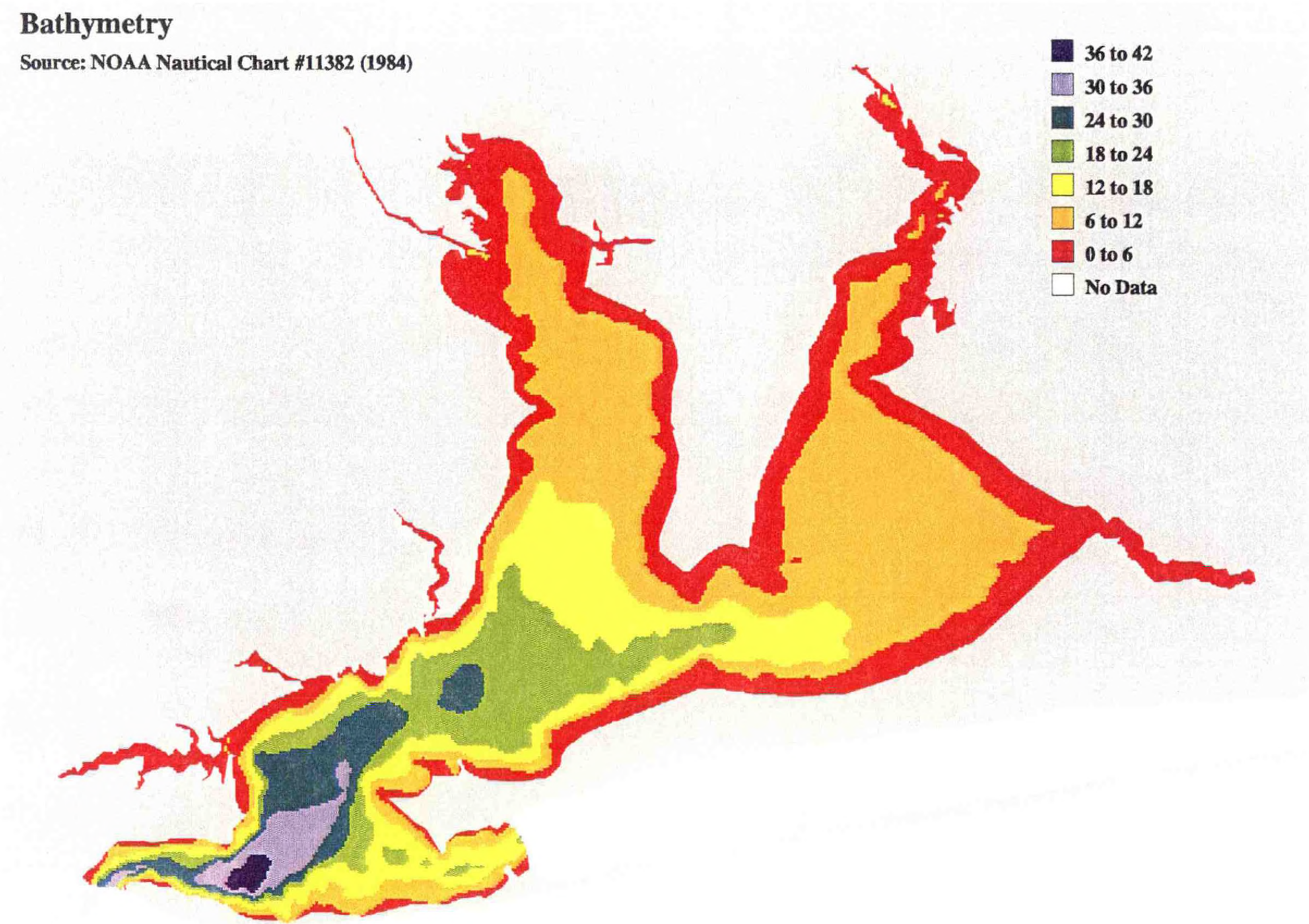


Figure 14. *Pensacola Bay bathymetric map (NOAA 1984).*

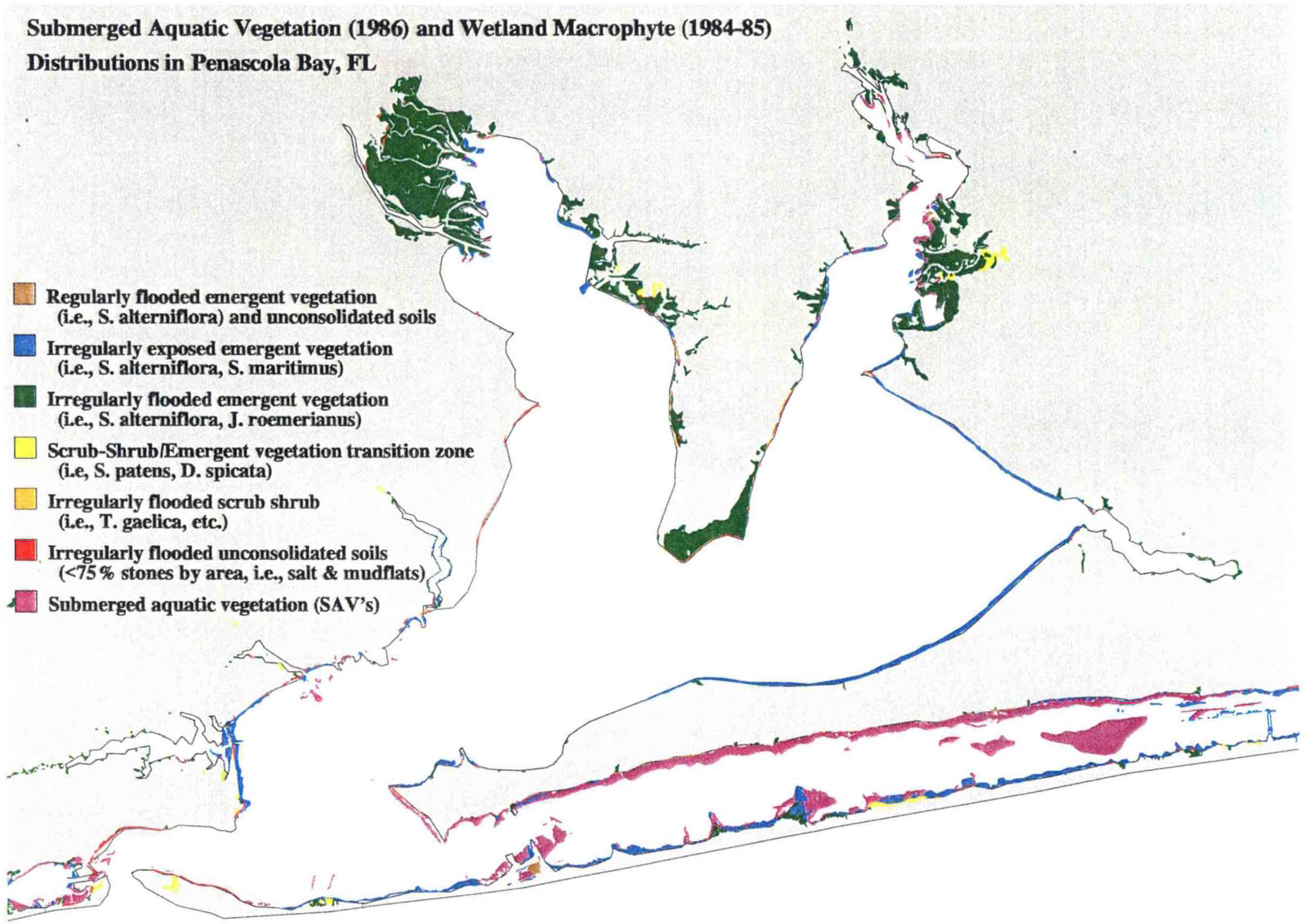


Figure 15. *Pensacola Bay SAV and emergent wetland macrophyte distribution map (USFWS 1986).*

Dissolved Oxygen

Dissolved oxygen content also was contoured for the Pensacola Bay complex during each of the four salinity defined time periods; however, it never reached levels that would have adversely affected the species modeled in this study. Because DO had no effect on model results, it was eliminated from the modeling procedure.

Table 1. *Percent of area per environmental class. Water temperature and salinity are separated into seasonal distributions.*

DEPTH-AVERAGED WATER TEMPERATURE (C)				
Range	*Dec-Jan*	*Feb-Apr*	*May-Aug*	*Sep-Nov*
10-12	64.01	0.00	0.00	0.00
12-14	35.99	0.00	0.00	0.00
14-16	0.00	0.00	0.00	0.00
16-18	0.00	7.30	0.00	0.00
18-20	0.00	92.49	0.00	6.73
20-22	0.00	0.21	0.00	37.91
22-24	0.00	0.00	0.00	48.34
24-26	0.00	0.00	0.00	4.92
26-28	0.00	0.00	64.96	2.10
28-30	0.00	0.00	35.04	0.00

DEPTH-AVERAGED SALINITY (ppt)				
Range	*Dec-Jan*	*Feb-Apr*	*May-Aug*	*Sep-Nov*
5-10	1.02	25.34	8.69	0.00
10-15	56.54	39.02	34.68	7.21
15-20	42.43	22.59	41.05	32.96
20-25	0.00	13.05	15.58	59.83

BATHYMETRY (m)	
Interval	% Area
0	0.09
0-2	32.23
2-4	35.10
4-6	14.44
6-8	10.91
8-10	4.70
10-12	2.15
12-14	0.38

SUBSTRATE	
Type	*% Area*
Silt	19.86
Clay	42.60
Sand	37.55

VEGETATION	
Type	*% Area*
SAVs [1]	0.01
EVs [2]	1.67

1 SAVs = Submerged Aquatic Vegetation

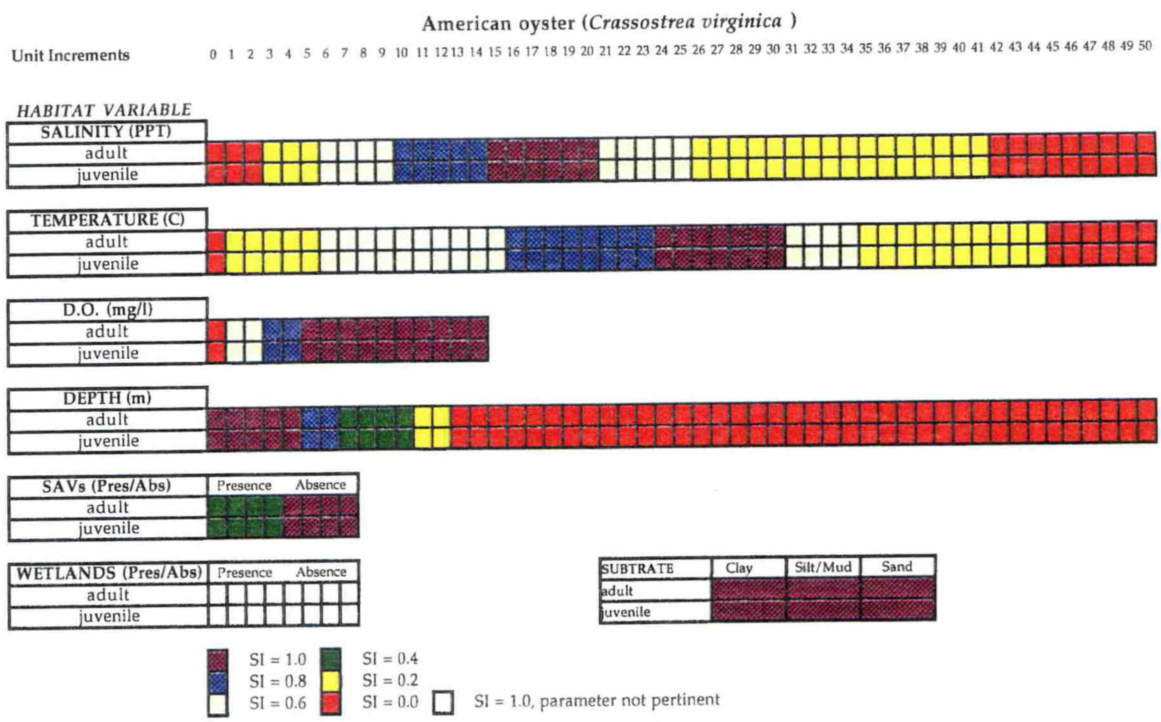
2 EVs = Emergent Wetland Macrophytes

Habitat Suitability Models

American oyster (Crassostrea virginica)

Table 2 depicts the suitability index values assigned for each parameter included in the American oyster adult model. The following references were used in developing these values: Berigan et al. (1991); Cake (1983); Gauthier (1989); Little and Quick (1976); Loosanoff (1965); Lowery (1995); Patillo et al. (*in press*); Stanley and Sellers (1986); Butler (1954); Eleutrius (1977). Although suitability models were run for both adult and juvenile life stages, only results for adult oysters are discussed in this section. Because of the life history strategy employed by oysters (sessile, gregarious), one cannot discern significant differences in habitat associations between the two life stages; hence, all suitability index values assigned for each variable were identical for both stages.

Table 2. *Suitability index (SI) values for American oyster (Crassostrea virginica).*



Approximately 74% of the available habitat was predicted to be highly suitable for adult oysters during the low-salinity time period (February-April) (Figure 16). All of East, Blackwater, and Escambia Bays fell into this category. Maximum values for salinity in these portions of the bay ranged from 10-20 ppt, and water depths rarely exceeded 4 m (12'). Much of Pensacola Bay proper (24%) fell within the medium suitability range. This is due to elevated salinities, which may cause osmoregulatory stress when high salinities persist for a protracted period of time (Butler 1954, Eleutrius 1977). Salinities greater than 20 ppt also provide optimum salinity habitat for the oyster drill (*Thais haemastoma*), a common predator of American oysters in Gulf estuaries. Elevated salinities also increase the likelihood of dermo (*Perkinsus marinus*) infection, thereby reducing HSI values. Approximately 2% of the bay provided low suitability, and less than 1% was considered unsuitable. The low and unsuitable HSIs resulted from water depths exceeding 10 m (30'), coupled with persistent salinities ranging from 20-25 ppt. The inverse correlation between oyster HSI values and depth was incorporated to account for potential decreased food availability in deeper portions of the bay. The stratification of Pensacola Bay during this time period may inhibit the quantity and quality of food available in deeper portions of the bay. Furthermore, primary productivity, and subsequent food availability, may be further reduced due to attenuated light penetration at these depths in turbid Gulf estuaries.

The cluster of medium suitability cells bounded by areas of high suitability near the terminus of Bayou Chico resulted from the presence of submerged aquatic vegetation beds. The relationships between seagrasses and oyster populations is not well documented, yet most studies indicate that the two rarely coexist at microscales (Everett et al. 1995, Dr. Peter Sheridan - NMFS Galveston, Pers. Comm). It seems intuitive that the presence of extensive oyster reefs would inhibit establishment of seagrass communities; however, the transpose effect of seagrasses on oysters is less transparent. Elevated predator densities within seagrass beds may result in extensive spat mortality, thereby preventing the establishment of

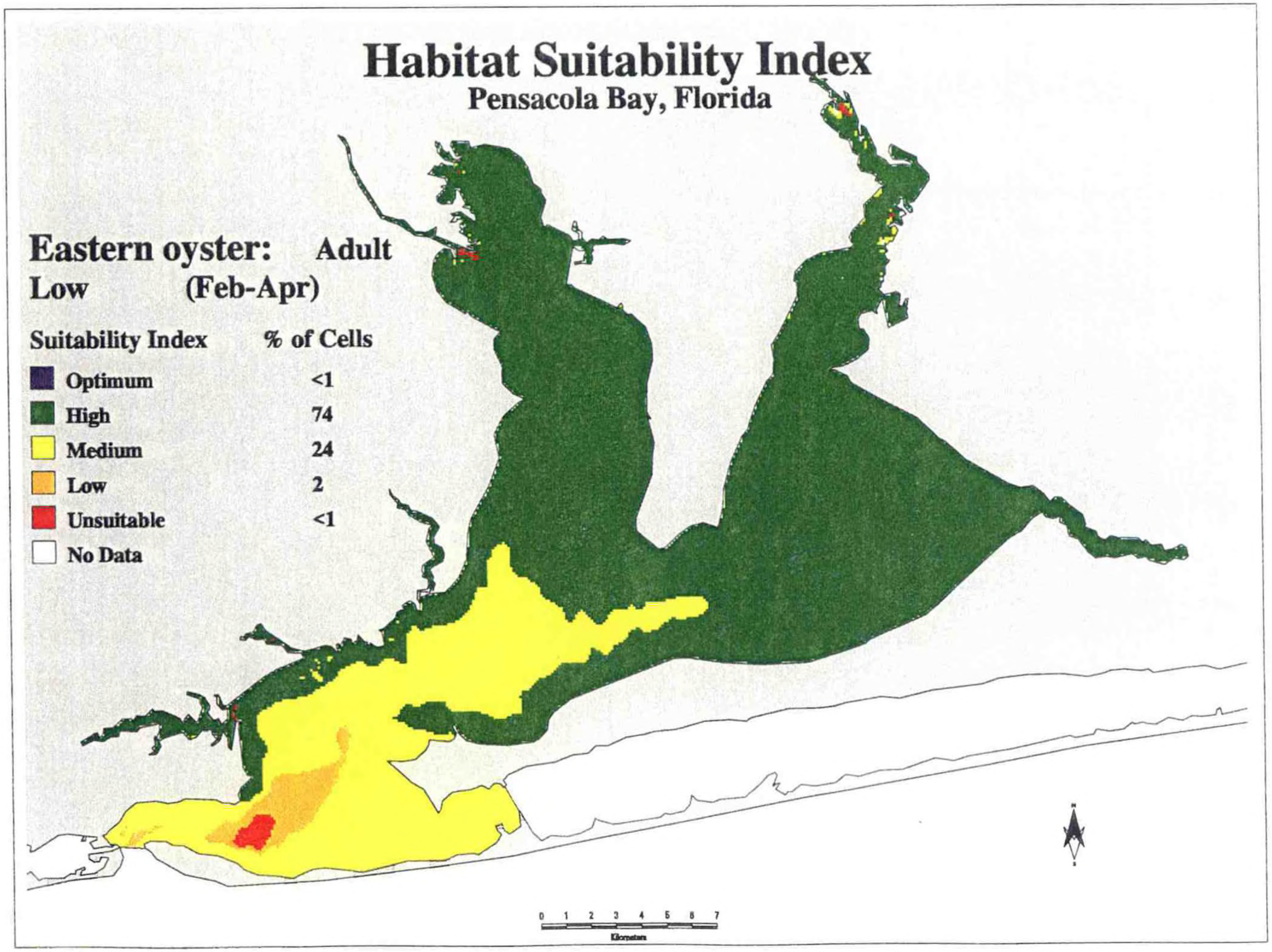


Figure 16. *HSI Model results for American oyster adults during the low salinity time period (Feb-Apr).*

reefs in preexisting SAV beds. It also is conceivable that this phenomenon is an artifact of preemptive resource competition for suitable substrates (Pianka 1988).

As freshwater inflow abated during late spring through summer, habitat suitability in much of the Pensacola Bay complex increased in areas where maximum water depths do not exceed 4 m, with the exception of Blackwater Bay, where salinities remained below optimum levels (Figure 17). This change primarily resulted from increased water temperatures. Ranges increased from 16-22° C during the antecedent months to 26-30° C during the increasing salinity time period. Although oysters are tolerant of a wide range of water temperatures, it is widely believed that temperatures of 20° C are necessary to induce a spawning event in Gulf populations, and temperatures ≥ 25° C are needed to induce mass spawning (Stauber 1950, Hoffsetter 1977, Cake 1983). Somatic growth during this time period may cease altogether, however, a great deal energy is acquired by Gulf oysters, most of which is allocated to gametogenic processes (Berrigan et al. 1991). This energy shunt was used as an indicator of optimum temperatures in developing the adult oyster model.

Adult oyster habitat suitability exhibited a dramatic decline across most of the bay complex during the high-salinity time period (September-November), with 67% of the entire system dropping to the medium suitability category (Figure 18). Only upper Blackwater Bay, Bayou Chico, and Bayou Texar remained at optimum, comprising 7% of the total system surface area. This decrease in suitability resulted from the intrusion of salinities ranging from 20-25 ppt into the upper reaches of the bay.

Habitat suitability for adult oysters returned to a state nearly identical to that of the low-salinity time period between December and January (Figure 19). Although salinities for much of the bay were optimal during this time period, water temperatures were sub-optimal, ranging from 12-14° C. The overall distribution of HSI classes across the

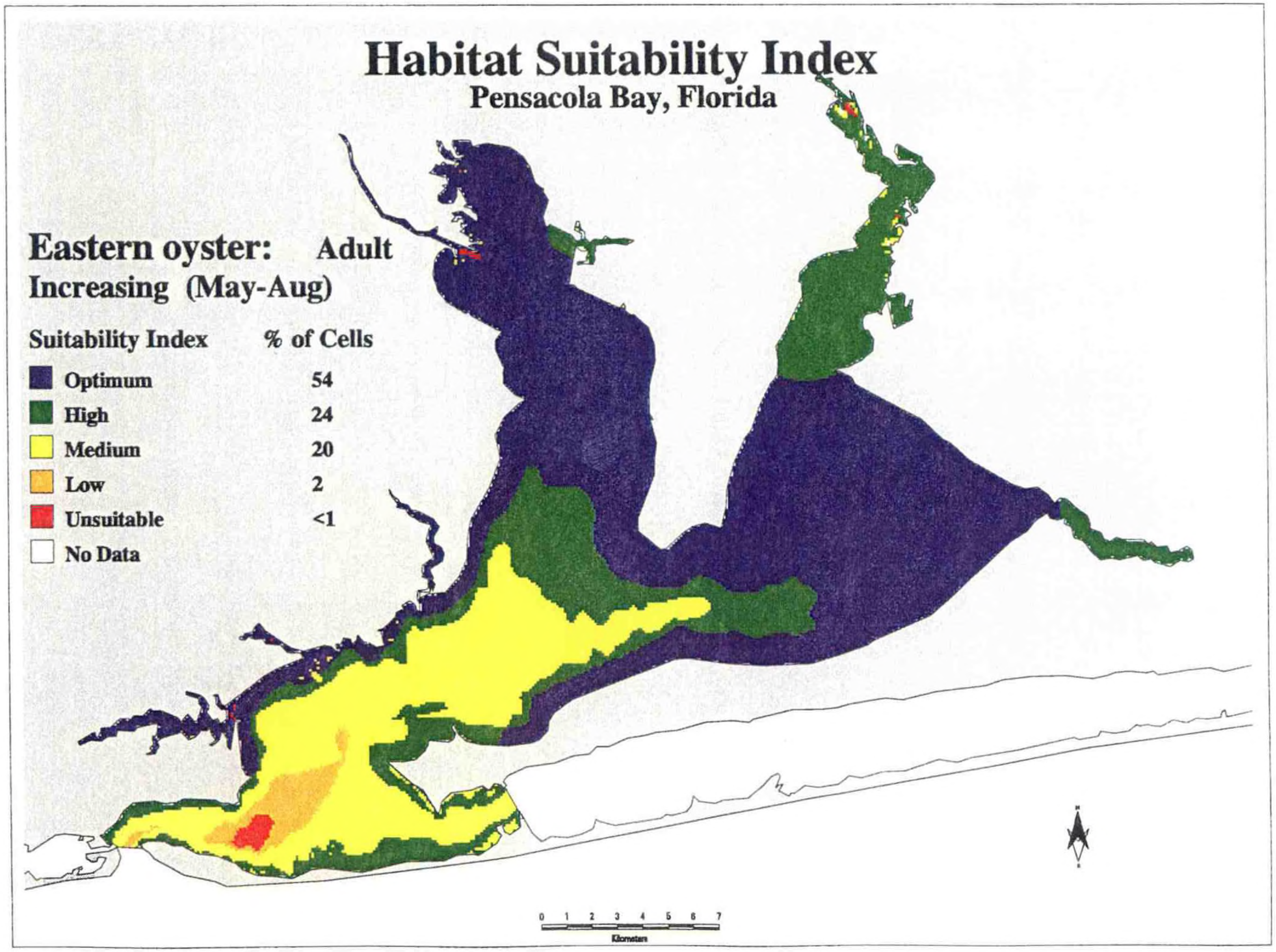


Figure 17: *HSI Model results for American oyster adults during the increasing salinity time period (May-Aug).*

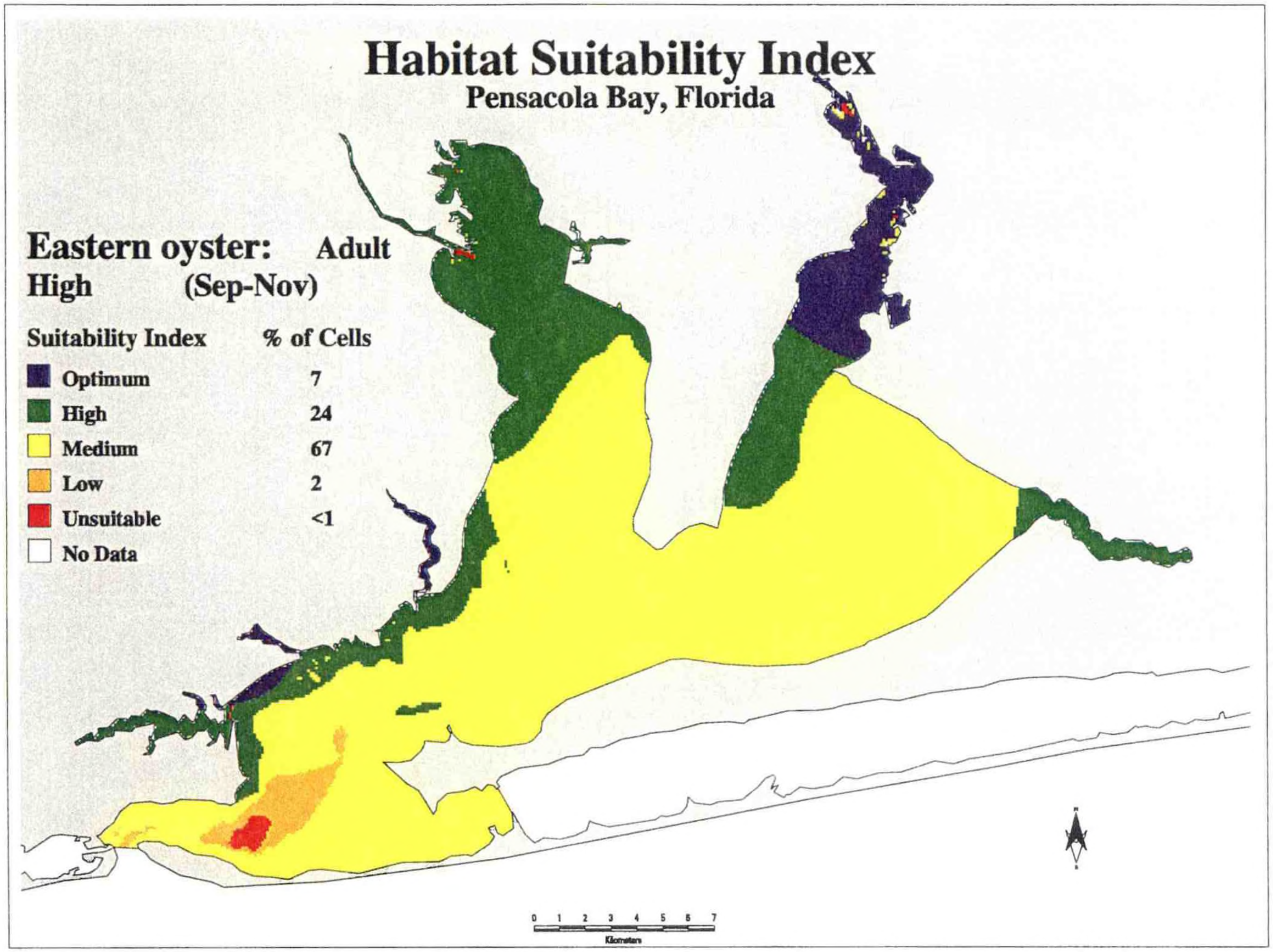


Figure 18. *HSI Model results for American oyster adults during the high salinity time period (Sep-Nov).*

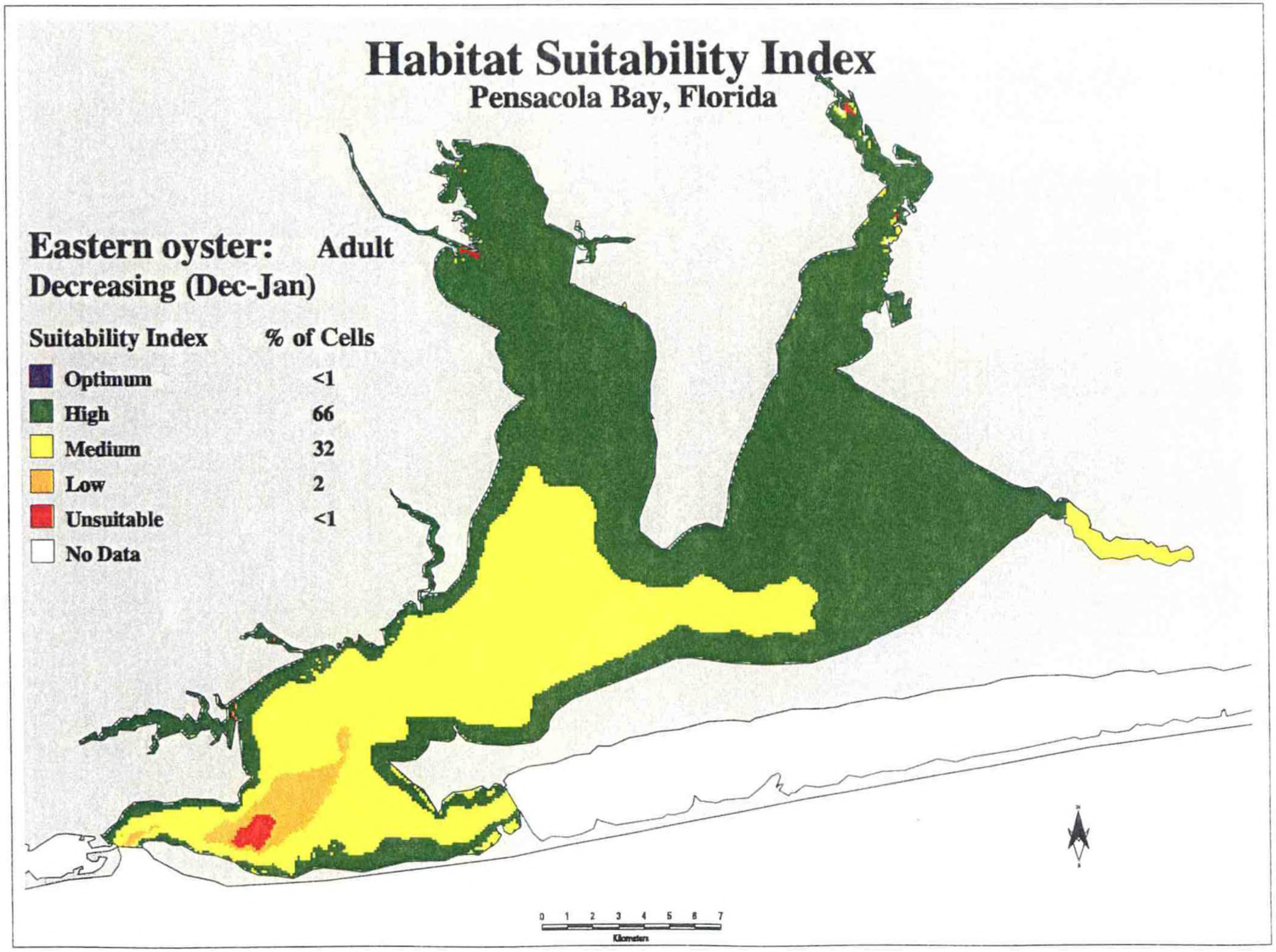


Figure 19. *HSI Model results for American oyster adults during the decreasing salinity time period (Dec-Jan).*

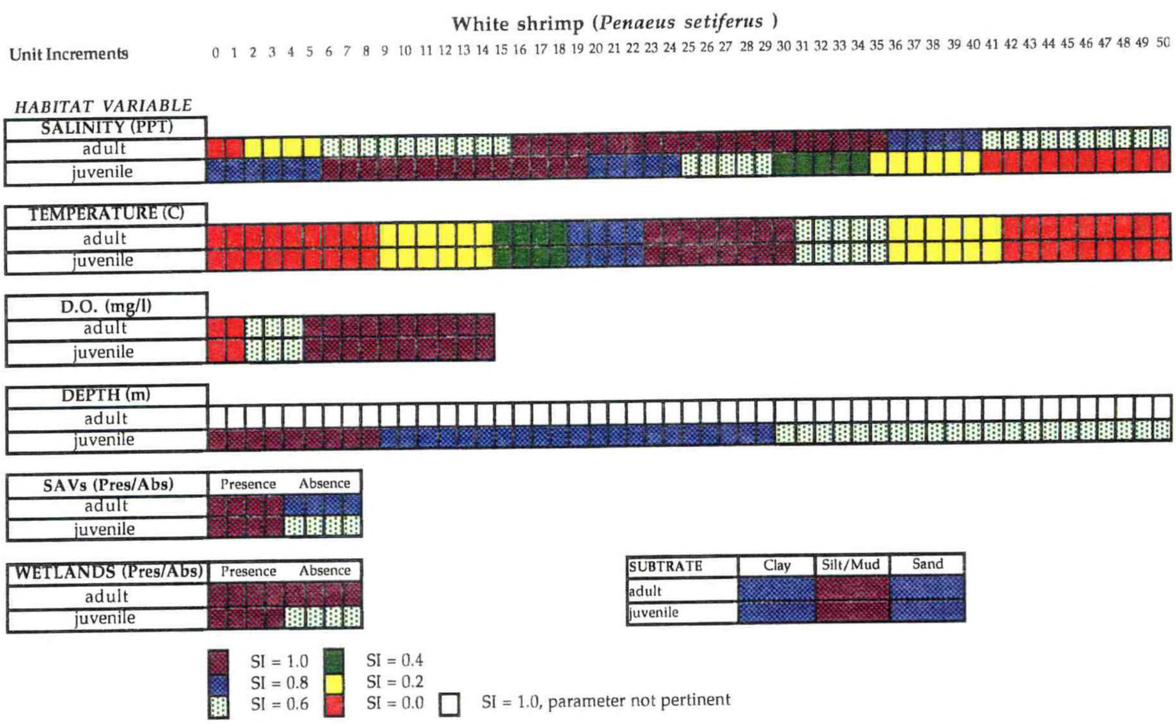
Pensacola Bay complex was <1%, 66%, 32%, 2%, and <1% for optimum, high, medium, low, and unsuitable, respectively.

Because oysters are a sessile bivalve, HSI models for this species must be carefully interpreted. Even though instantaneous environmental parameter values at a given location may be optimal, the habitat may not be as suitable for the remaining seasons. This scenario would overestimate the potential distribution of oysters for that location. Likewise, the transpose would underestimate suitability during any one given season. For this reason, it would be beneficial to generate HSI models based on annual average salinities and water temperatures to provide a more realistic representation of potential oyster distributions.

White shrimp (Penaeus setiferus)

Table 3 depicts the suitability index values assigned for each parameter included in the white shrimp adult and juvenile models. The following references were used in developing these values: Gleason and Zimmerman (1984); Muncy (1984); Turner and Brody (1982), Zein-Eldin and Renaud (1986); Patillo et al. (in prep.); Copeland and Bechtel (1974); Franks et al. (1972); Giles and Zamora (1973); Rozas et al. (1995); Pullen and Trent (1969); (Perez-Farfante 1969); Lindner and Cook (1970); Muncy (1984); Williams (1984); Nelson et al. (1992); Klima et al. (1992), Christmas and Etzhold (1977); Zein-Eldin and Griffith (1969).

***Table 3.** Suitability index (SI) values for white shrimp (Penaeus setiferus).*



Adult white shrimp habitat suitability was in the medium to low category for approximately 84% of the bay during the low-salinity time period (Figure 20). Of the

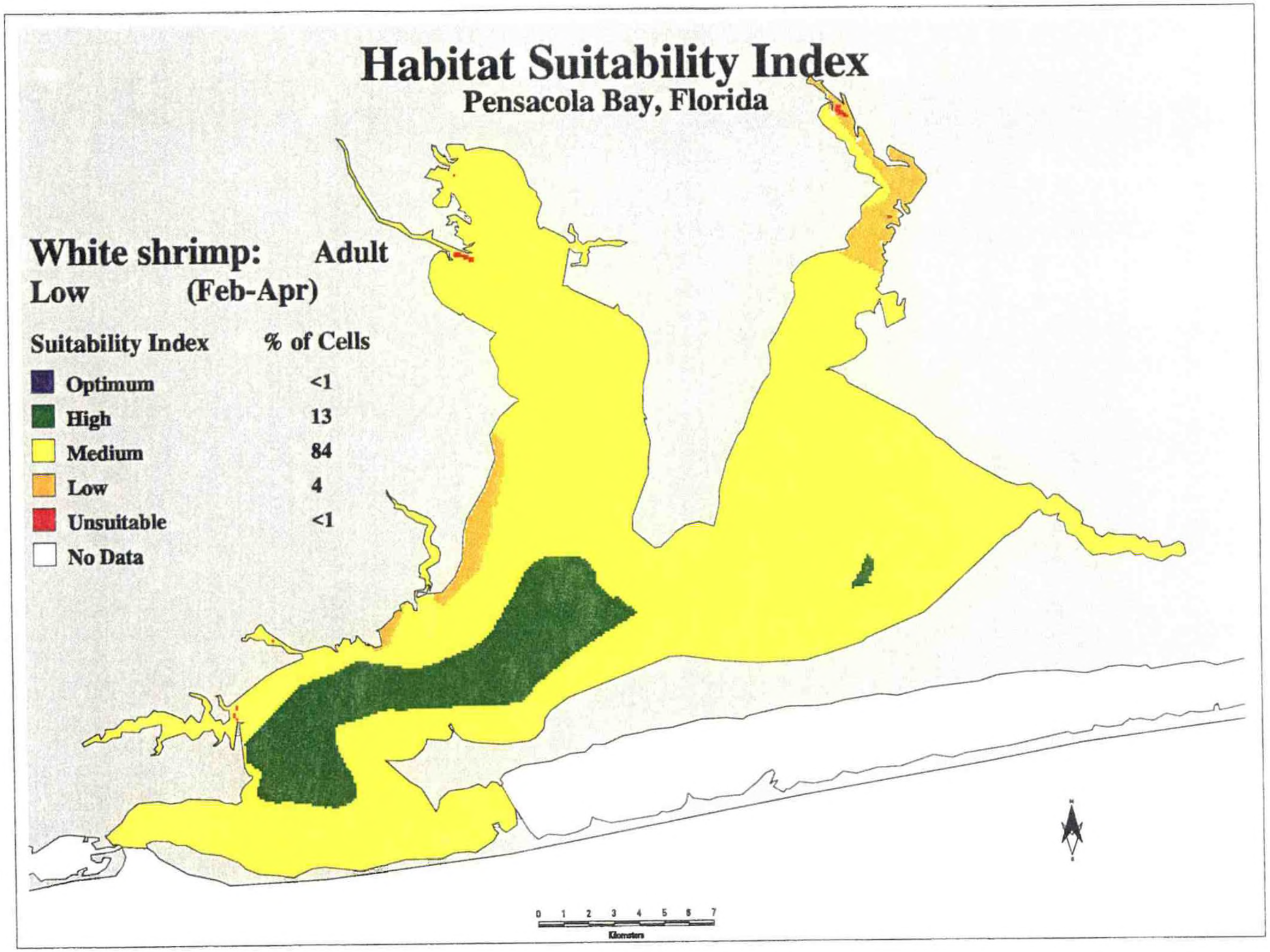


Figure 20. *HSI Model results for white shrimp adults during the low salinity time period (Feb-Apr).*

remaining grid cells, 13% fell within the high suitability range, and 4% in the low category. Suboptimal salinities ranging from 5-15 ppt in much of Escambia, Blackwater, and East bays during these months, combined with cool springtime water temperatures (16-20° C), resulted in the low HSI values observed for white shrimp adults. Areas of high suitability in the lower reaches of Escambia and East Bays resulted from the presence of optimum salinities, ranging from 15-25 ppt, coupled with muddy substrates in which adult white shrimp can easily burrow. Muddy bay bottoms are considered an essential habitat component to support adult Penaeid shrimp populations in Gulf estuaries (Perez-Farfante 1969, Lindner and Cook 1970, Muncy 1984, Williams 1984, Patillo et al. in press).

A marked increase in the overall habitat suitability of Pensacola Bay resulted from increased water temperature and salinity during the increasing salinity time period (Figure 21). Areas in Escambia and East Bays that were moderately suitable in the antecedent time period became highly suitable, resulting in an 84% increase in high suitability habitats. As seen in the low-salinity time period, areas of high-suitability were associated with soft substrates. The presence of SAV and EV adjacent to shorelines in the lower reaches of Pensacola Bay also resulted in areas of high suitability.

Overall habitat suitabilities for adult white shrimp further increased across the Pensacola Bay complex during the high-salinity time period, with a 50% gain in high suitability habitats relative to previous months (Figure 22). Adult associations with higher salinities, coupled with favorable water temperatures across much of the bay, resulted in the highest average HSI values observed throughout the entire year. Moreover, the presence of SAVs and EVs near shorelines in the lower reaches of the bay resulted in areas of high suitability.

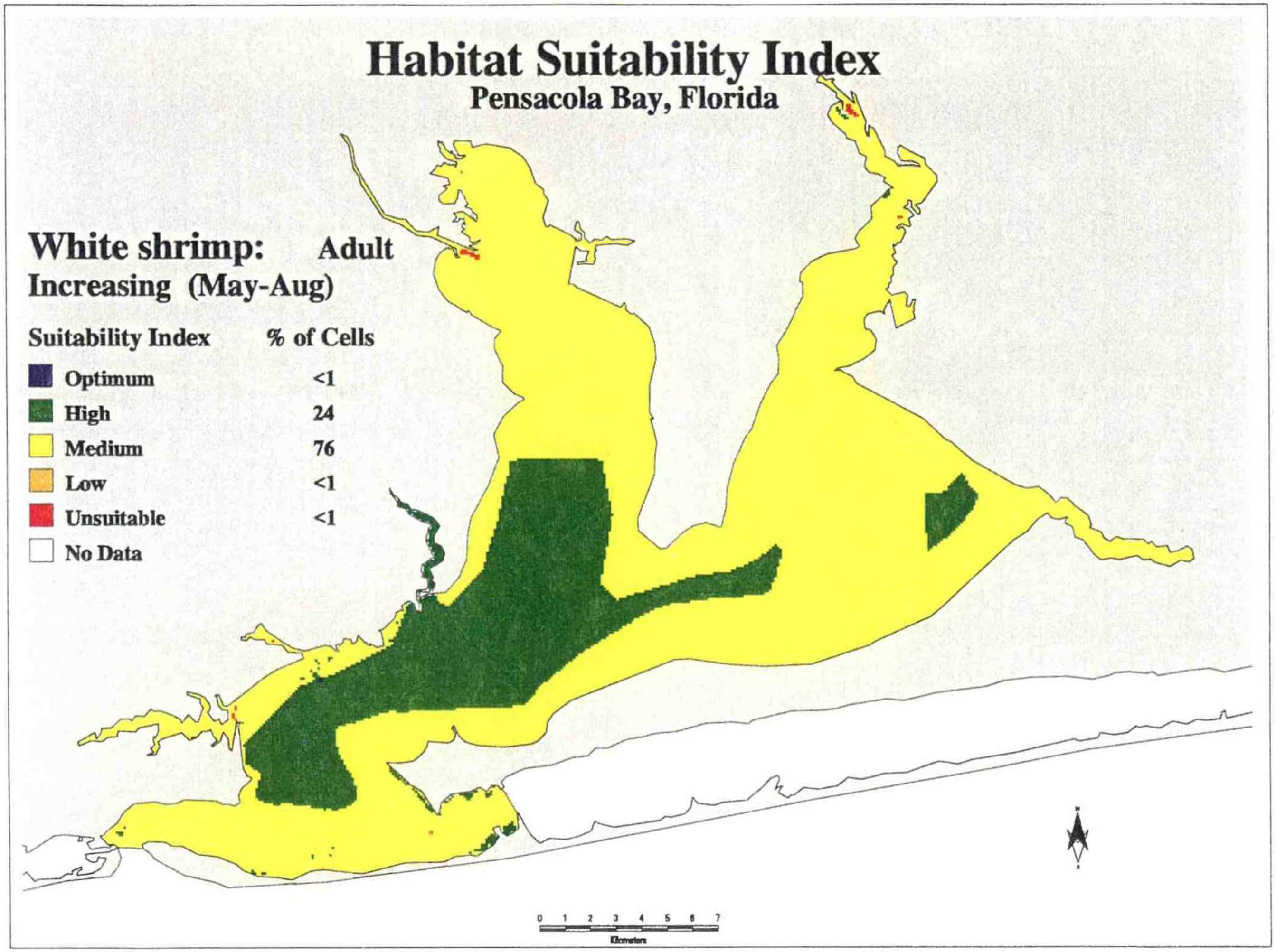


Figure 21. *HSI Model results for white shrimp adults during the increasing salinity time period (May-Aug).*

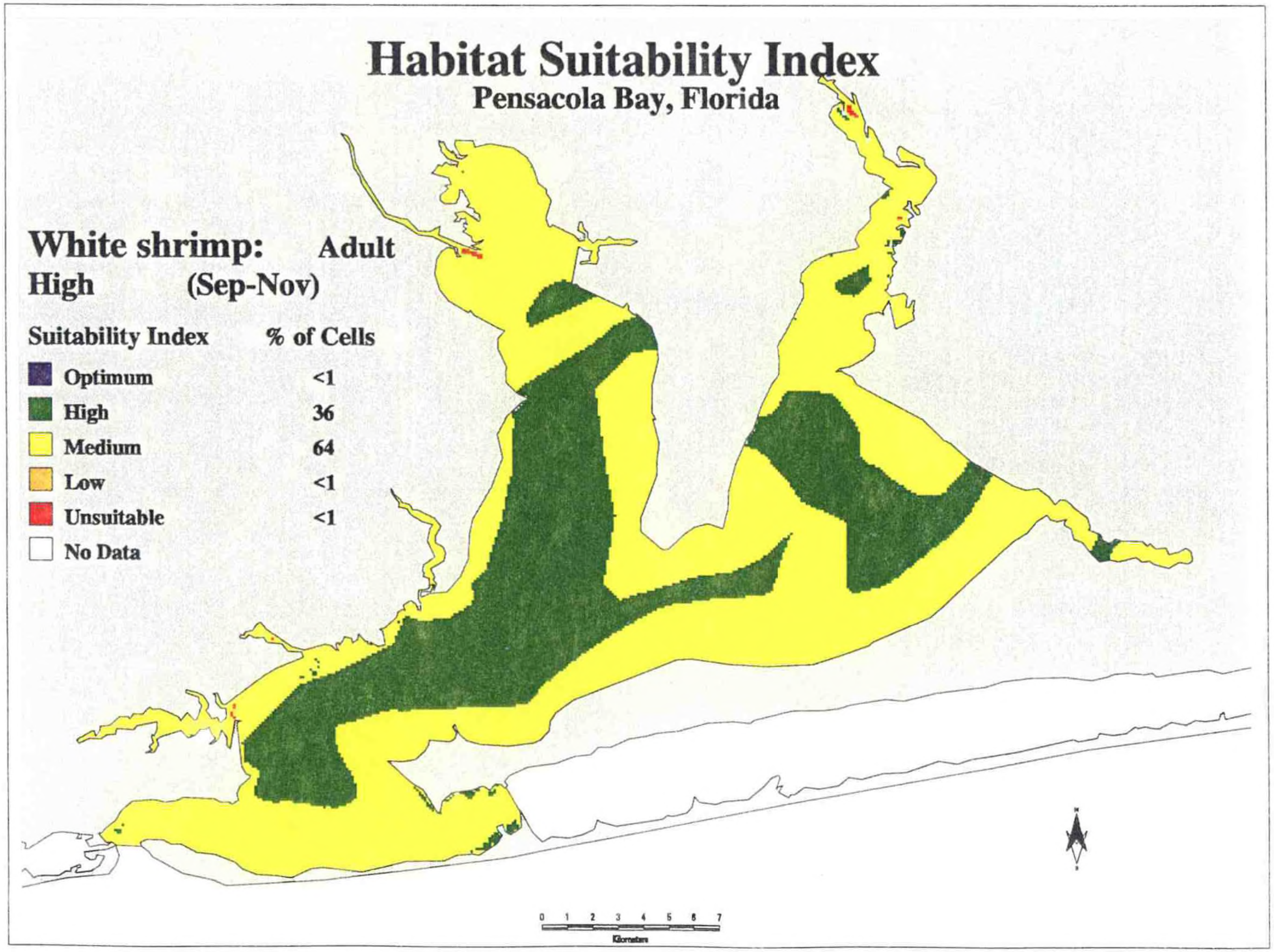


Figure 22. HSI Model results for white shrimp adults during the high salinity time period (Sep-Nov).

Adult white shrimp habitat suitability exhibited a drastic decline during winter months, corresponding to the decreasing salinity time period (Figure 23). Habitat suitability for the entire bay complex fell into the low category, as maximum average water temperatures reached only 14° C.

The dynamic pulse observed in habitat suitability through time resulted from the strong effect of temperature, and to a lesser extent salinity, on Penaeid shrimp distributions in central Gulf estuaries (Patillo et al. in prep, Gleason and Zimmerman 1984, Muncy 1984, Turner and Brody 1982, Zein-Eldin and Renaud 1986). Substrate type was a static parameter that consistently influenced model results through time.

Again, model results for adult white shrimp must be interpreted with care. White shrimp generally enter the estuary as postlarvae (Patillo et al. in press), where they live and grow throughout much of the year; however, most begin their emigration to offshore waters prior to reaching sexual maturity. As such, model predictions for the decreasing salinity time period, though very low, may actually overestimate the relative abundance and distribution inferred from habitat suitability for adult white shrimp. The aforementioned life history strategy employed by white shrimp indicates that it is in fact probable that adults are completely absent from the system altogether during this time (Nelson et al. 1992).

Juvenile white shrimp habitat suitability during the low-salinity time period was in the medium category across the entire bay complex (Figure 24). Water temperatures ranging from only 16-20° C had the greatest effect on model results. The general lack of extensive SAV in the upper reaches of Escambia Bay, where salinities were most favorable for juvenile white shrimp, kept suitability in the medium category. A few cells (< 1.0%) were in the high suitability category. These cells corresponded to the location of SAVs or EV's. SAVs and EVs in the lower reaches of the Pensacola Bay complex had no such effect on model

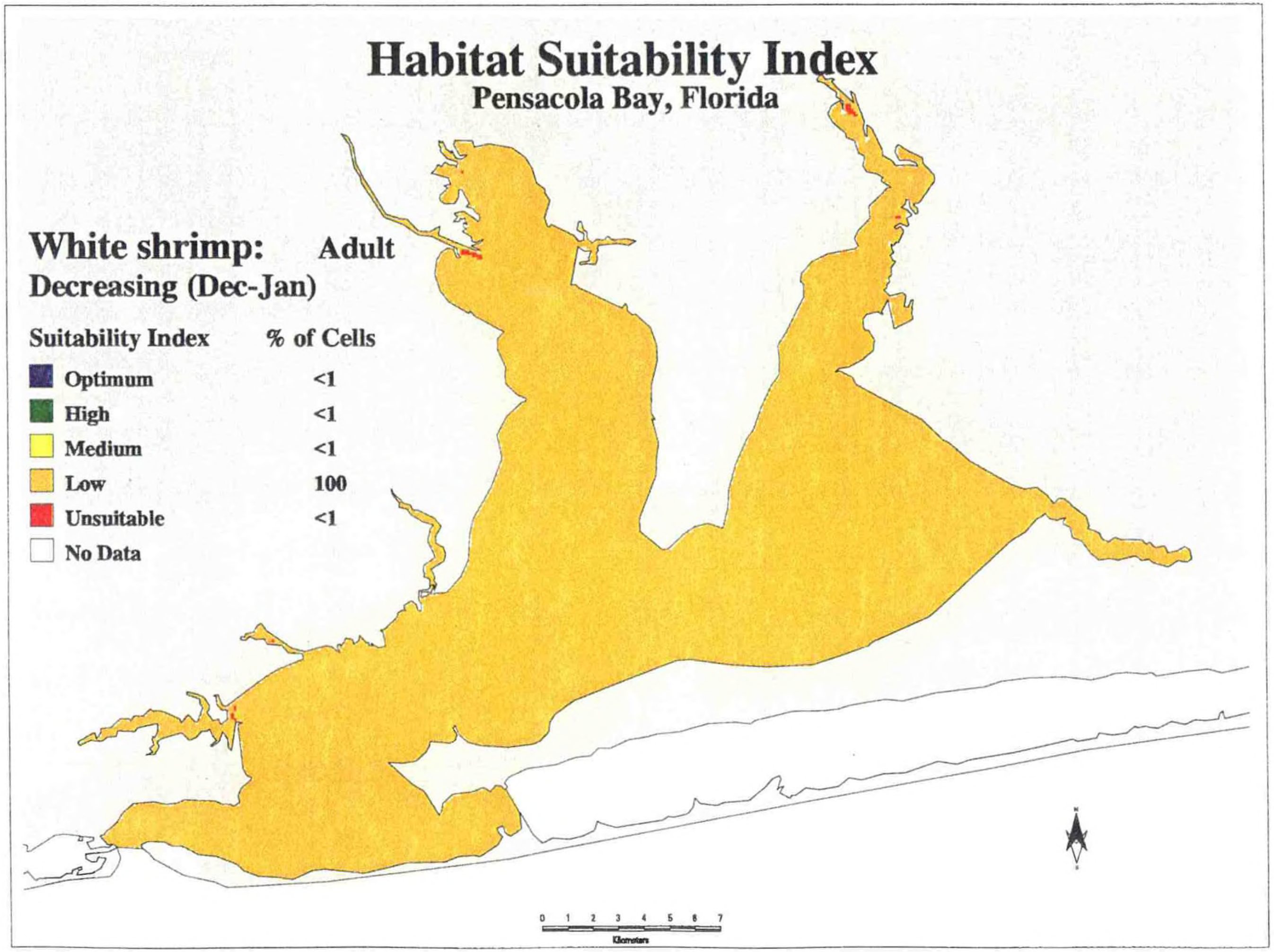


Figure 23. *HSI Model results for white shrimp adults during the decreasing salinity time period (Dec-Jan).*

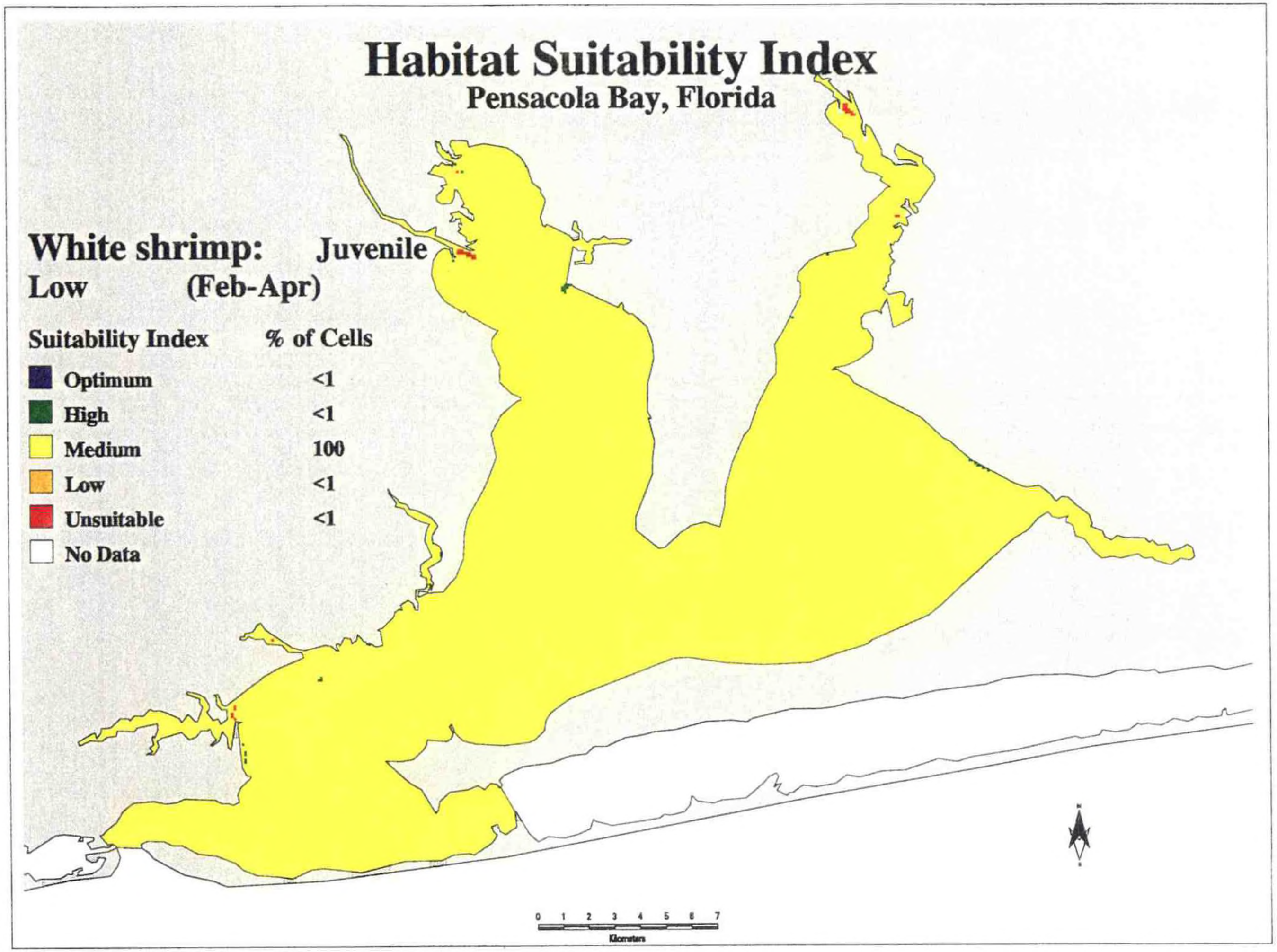


Figure 24. *HSI Model results for white shrimp juveniles during the low salinity time period (Feb-Apr).*

results, because salinities in this portion of the bay exceeded optimum values for juvenile *P. setiferus*.

As water temperatures increased from May through August, juvenile white shrimp habitat suitability increased significantly across the bay. Thirty-five percent of the bay fell within the high suitability range, while the remainder was in the medium category (Figure 25). As with adults, substrate type was a key variable in predicting potential distributions of juvenile white shrimp. All areas of high suitability coincided with locations containing soft, muddy substrates. The effect of SAVs and EVs near shorelines was evident throughout much of the bay; however, high salinities near the opening of Santa Rosa Sound and the Pensacola Inlet suppressed HSI values in these habitats. Also evident in juvenile model results for this time period was the effect of depth. The circular feature of medium HSI values due south of the terminus of Bayou Texar resulted from bathymetry exceeding optimum values. Habitat suitability for white shrimp juveniles was more favorable during the increasing salinity time period than in all other seasons. Peak abundances of juvenile white shrimp in central Gulf of Mexico estuaries during the late spring and summer months have been widely documented (Klima et al. 1992, Christmas and Etzhold 1977, Zein-Elden and Griffith 1969). Model results for this time period supported these historical data.

The encroachment of high-salinity waters ranging from 20-25 ppt into the upper reaches of Pensacola Bay between September and November decreased the amount of high-suitability habitats by 74% (Figure 26). The high salinity time period is typically when juveniles and subadults begin their emigration from Gulf estuaries to offshore waters (Patillo et al. in prep). As such, it is critical to understand that juveniles, in their transit through the estuary, may be captured in surrounding habitats of lesser suitability. Again, interpretation of model results must be made with care. As with the adult population, juvenile white shrimp

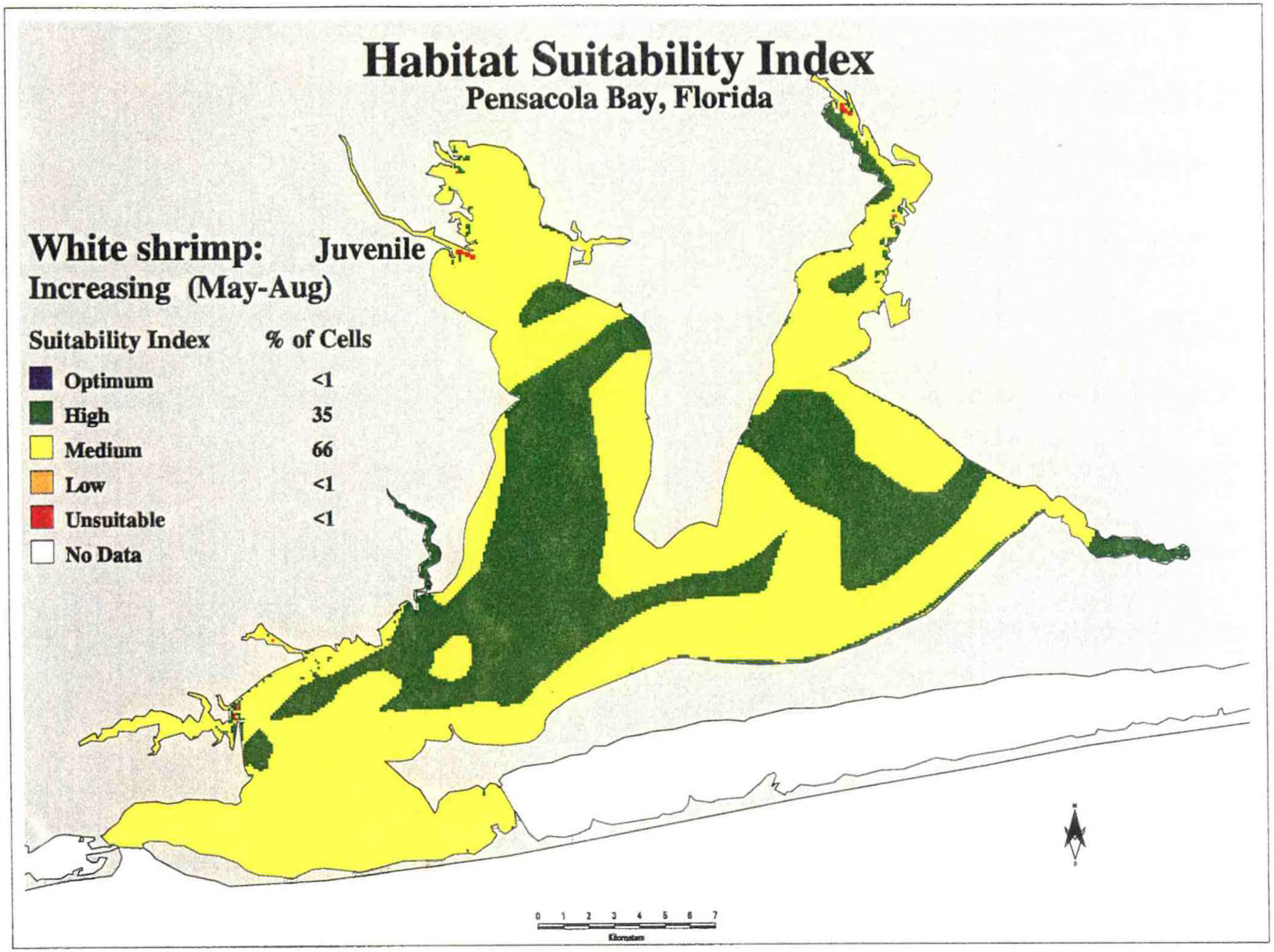


Figure 25. *HSI Model results for white shrimp juveniles during the increasing salinity time period (May-Aug).*

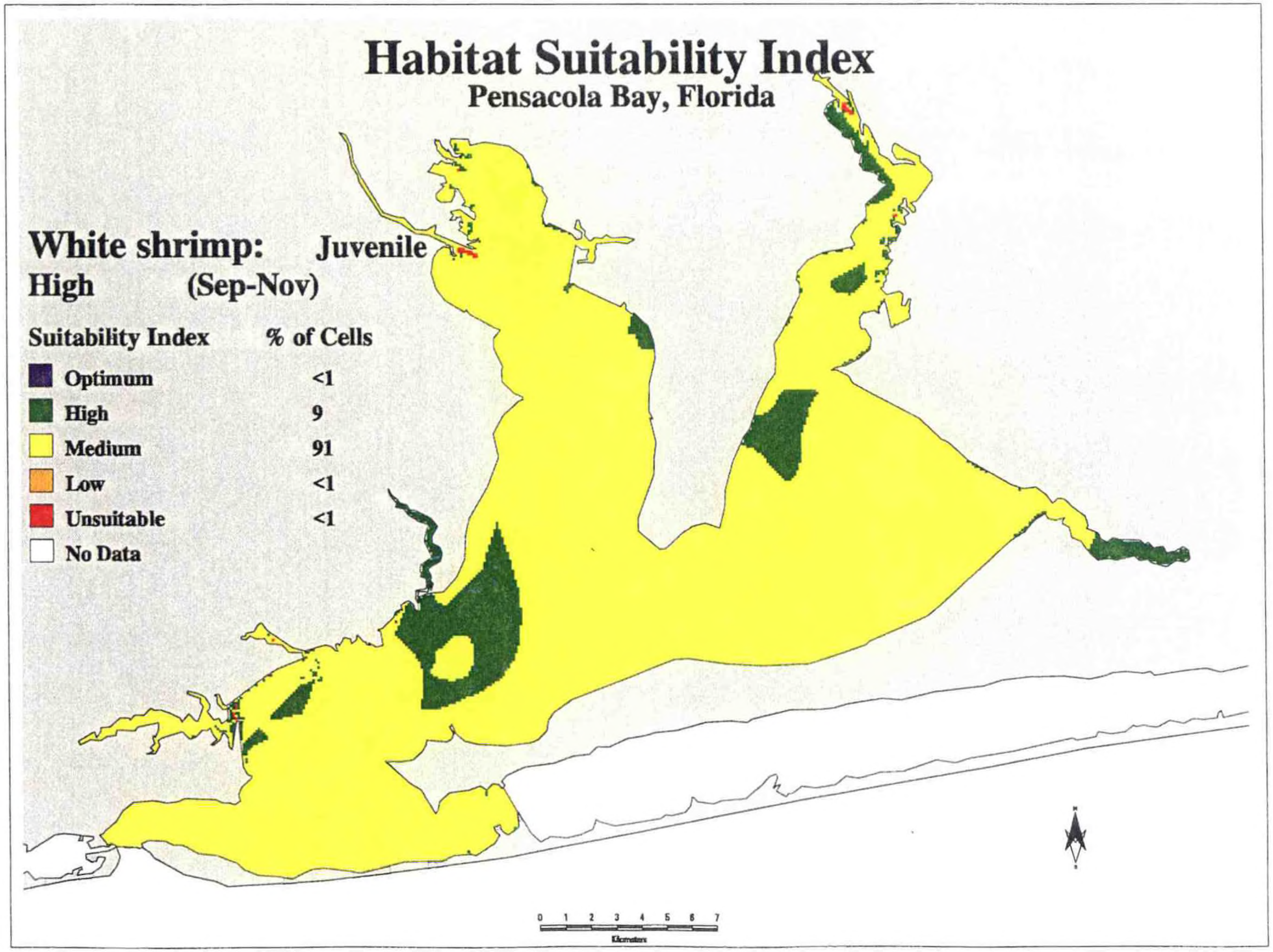


Figure 26. *HSI Model results for white shrimp juveniles during the high salinity time period (Sep-Nov).*

habitat suitability exhibited a marked decline during winter months, corresponding to the decreasing salinity time period (Figure 27). Habitat suitability for the entire bay complex fell into the low category, as maximum average water temperatures reached only 14° C.

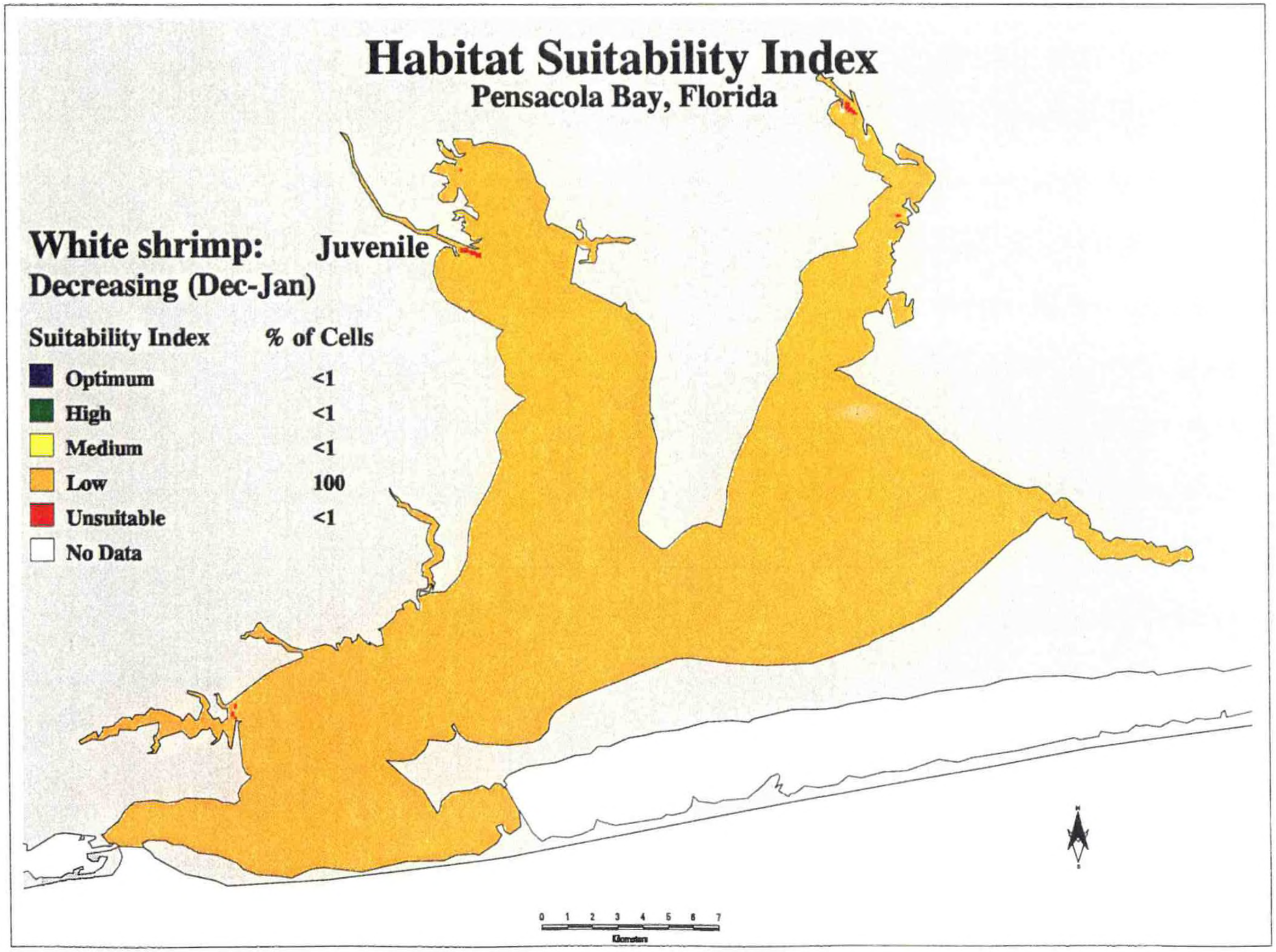
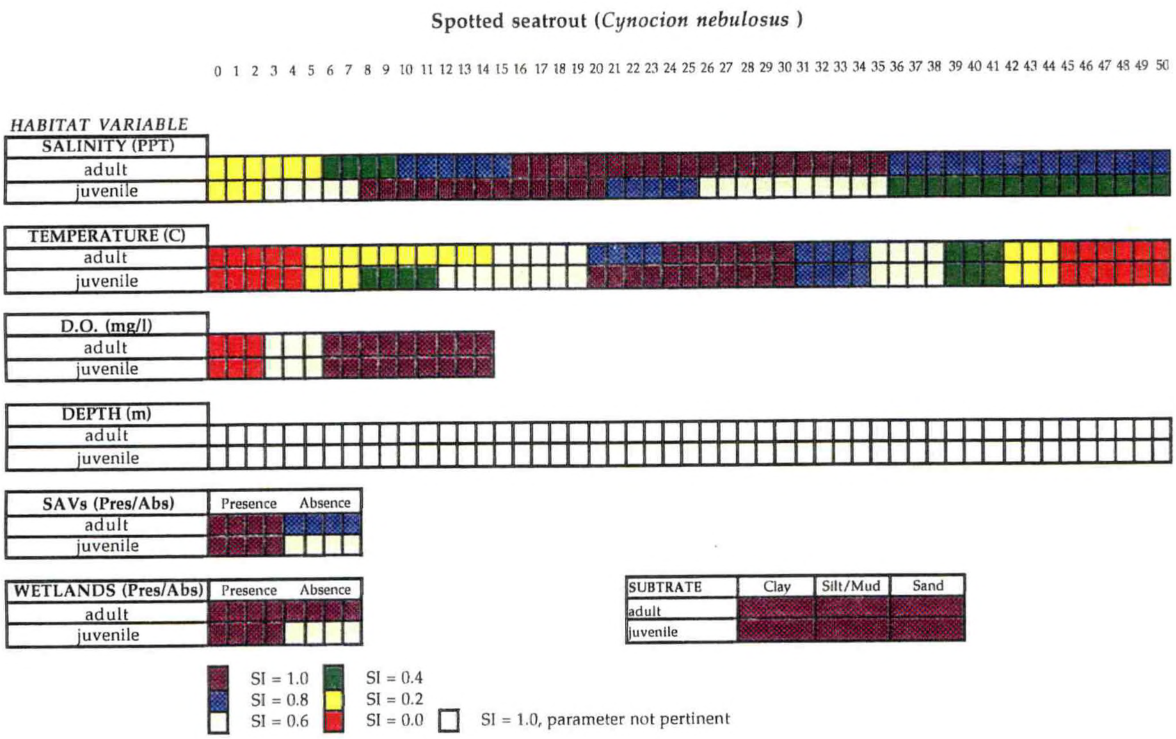


Figure 27. *HSI Model results for white shrimp juveniles during the decreasing salinity time period (Dec-Jan).*

<u>*Spotted seatrout (Cynoscion nebulosus)*</u>

Table 4 depicts the suitability index values assigned for each parameter included in the spotted seatrout adult and juvenile models. The following references were used in developing these values: Copeland and Bechtel (1974); Helser et al. (1993); Johnson and Seaman (1986); Kosteki (1984); Lassuy (1983); McMichael and Peters (1989); Peebles and Tolley (1982); Patillo et al. (in prep.); Van Hoose (1987); Tabb (1966); Bryan et al. (1989); Ried (1954); Taniguchi (1980); Stewart (1961).

Table 4. *Suitability index (SI) values for spotted seatrout (<u>Cynoscion nebulosus</u>).*



Adult spotted seatrout habitat suitability during the low-salinity time period was moderate throughout the bay. Areas with seagrass patches in the lower, more saline portions of the bay, resulted in high suitability (Figure 28). Growth of spotted seatrout is temperature-dependent (Johnson and Seaman 1986), with optimum temperatures for somatic

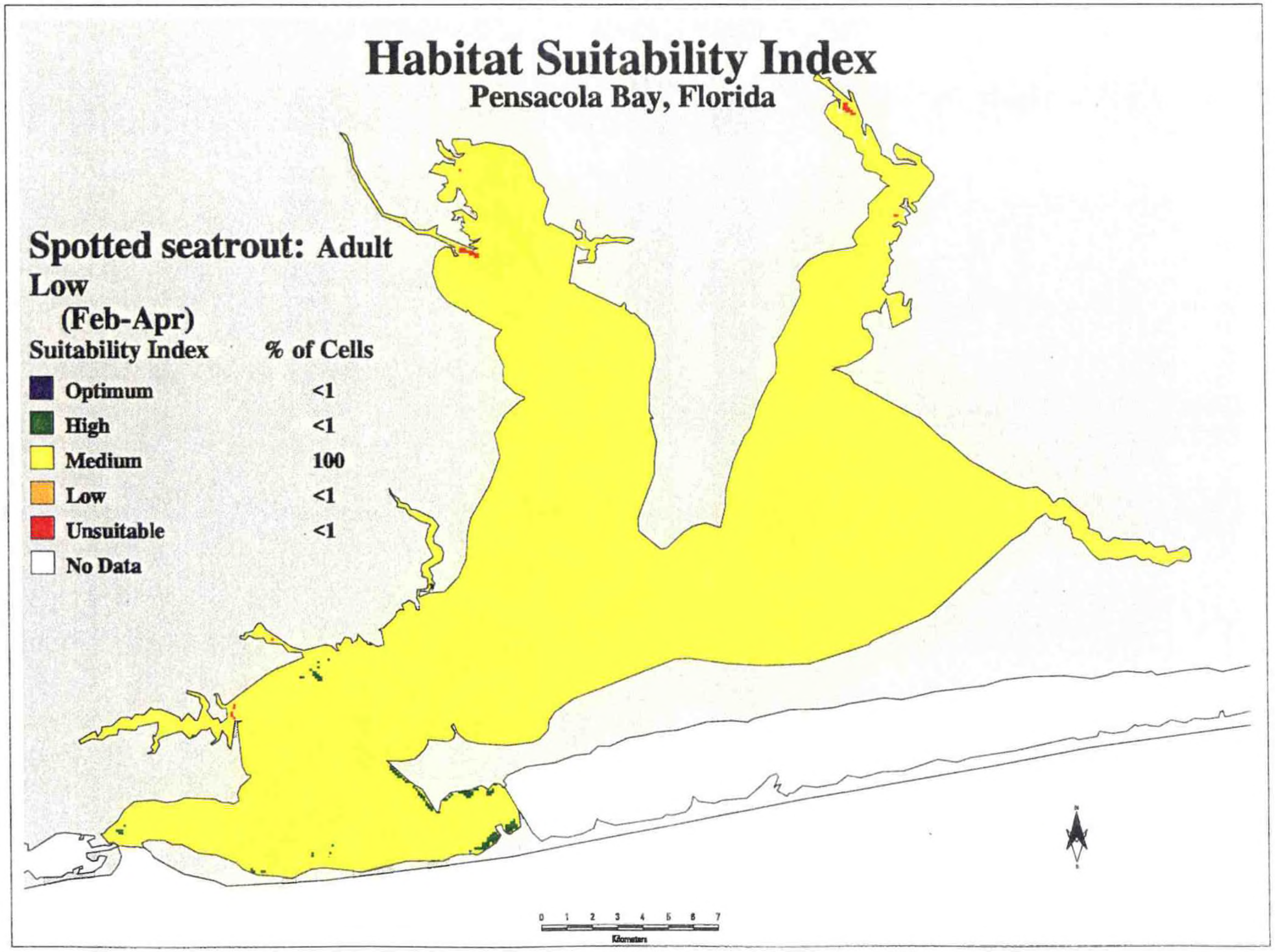


Figure 28. *HSI Model results for spotted seatrout adults during the low salinity time period (Feb-Apr).*

growth and condition (K) consistently reported to range between 25-30° C (Tabb 1958, Taniguchi 1980, Stewart 1961, Pattillo et al. in prep). The condition factor reflects the nutritional state of an individual fish, and is often used as an index of growth (Schreck and Moyle 1990). Depth-averaged water temperatures ranging from only 16-20° C suppressed adult trout HSIs across the bay.

Adult spotted seatrout habitat suitability peaked from May through August as average temperatures increased to 28° C across the bay (Figure 29). Optimum temperatures combined with increasing salinity resulted in 91% coverage by high-suitability habitats. Salinities ranging from 5-10 ppt in the upper reaches of Blackwater Bay, East Bay, and Mulatto Bayou decreased habitat suitability to the medium category. However, this accounted for less than 8% of the total available habitat. Areas containing seagrass beds in lower Pensacola Bay and near the entrance to Santa Rosa Sound resulted in optimum suitability. These were areas in which all environmental and biological parameters were optimal. These areas contributed less than 1% of the total available habitat for adult spotted seatrout. Although seagrasses are often considered critical habitat for adult seatrout, the species is still common throughout Gulf estuaries lacking such habitats (Darnell 1958, Johnson and Seaman 1986).

As cooler water temperatures permeated the bay during the high-salinity time period, a conspicuous band of medium-suitability habitat appeared near the Pensacola Inlet for adult spotted seatrout (Figure 30). This feature was an artifact of depth-averaged water temperatures dropping below 20° C. Areas in the lower reaches of the bay that scored optimum suitability in the antecedent time period fell to high suitability as a result of decreasing water temperatures. An area of medium suitability also appeared in the northern extent of Escambia Bay. This feature resulted from low salinities coupled with temperatures slightly below optimum. Areas containing seagrasses in upper Blackwater Bay resulted in

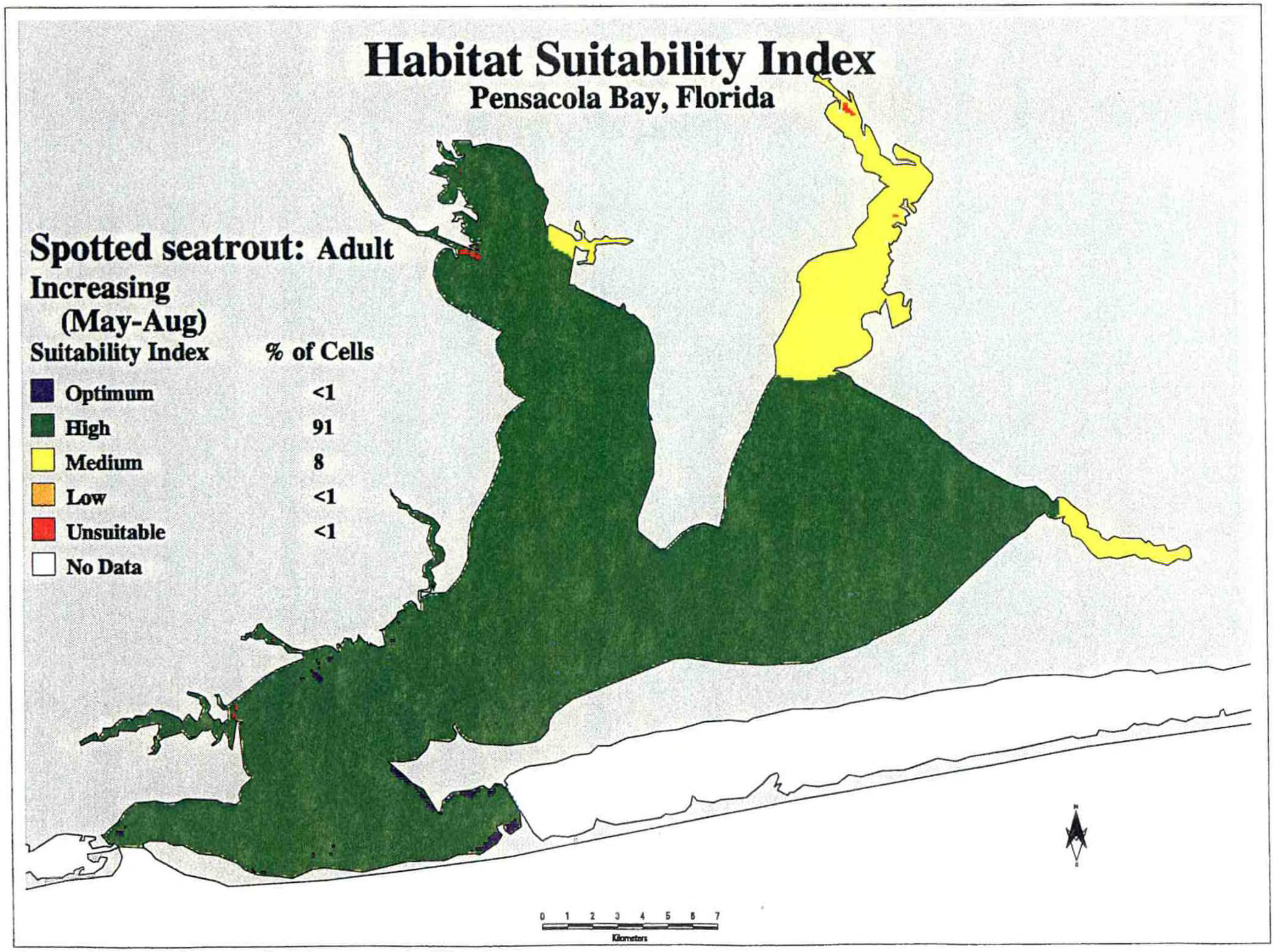


Figure 29. *HSI Model results for spotted seatrout adults during the increasing (May-Aug) salinity time period.*

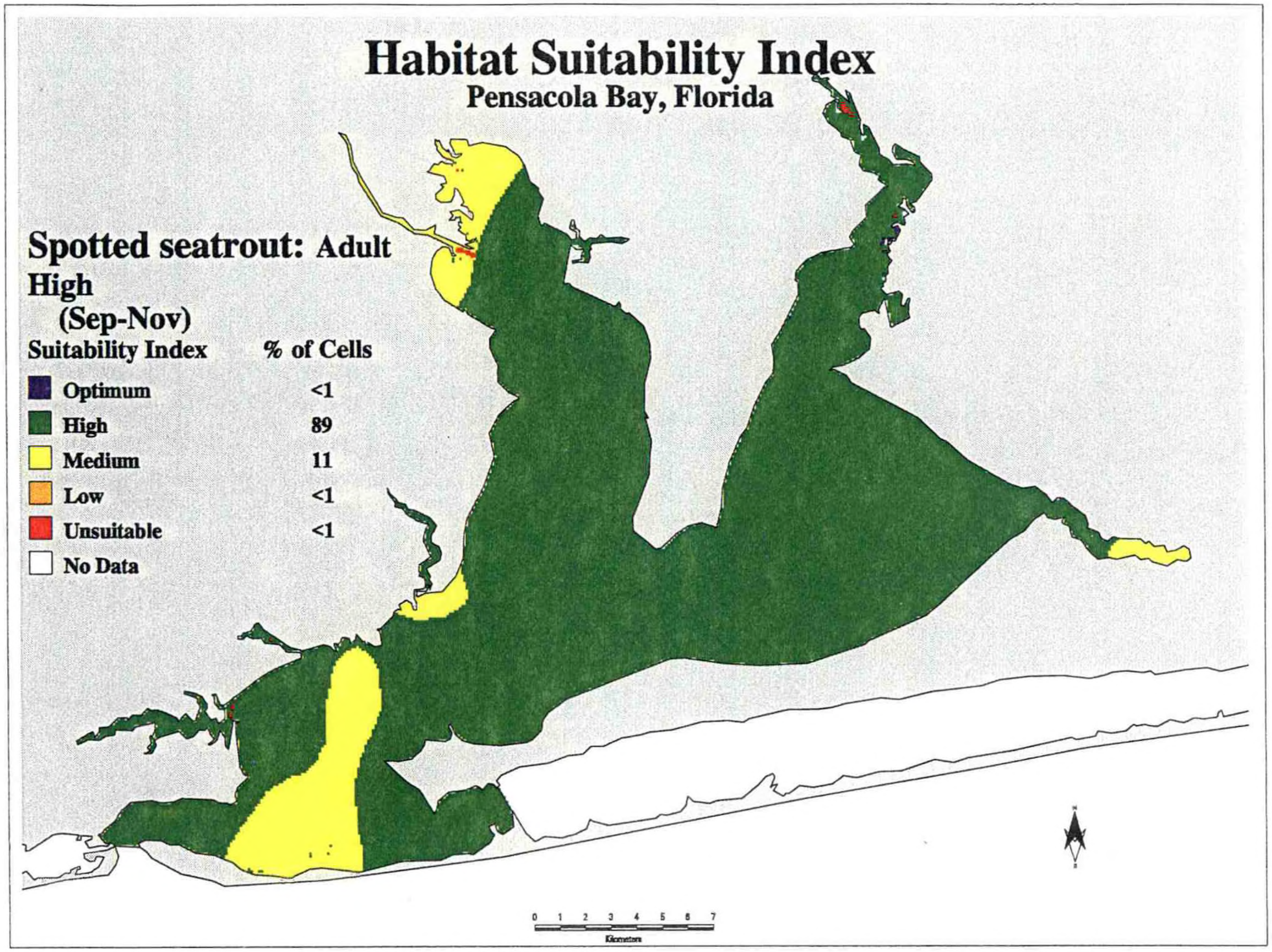


Figure 30. *HSI Model results for spotted seatrout adults during the high salinity time period (sep-Nov).*

optimum habitat suitability during this time period.

A substantial change in the overall suitability of Pensacola Bay for adult spotted seatrout was observed during the decreasing salinity time period (December-January) (Figure 31). This dramatic shift in suitable habitat resulted from average water temperatures decreasing to 14° C throughout the bay. Spotted seatrout tend to spend their entire lives in estuaries in the Gulf region, rarely if ever, emigrating to offshore waters. As such, it is important to interpret model results accordingly. The low suitability observed baywide during the winter months does not indicate that adult trout are vacating the estuary; rather, it is a comparison of suitabilities relative to the remaining salinity-defined seasons. Persistent cold water temperatures, though tolerable, increase the likelihood of reduced mobility, foraging success, metabolic rates, and subsequent growth (Johnson and Seaman 1986). Moreover, decreased salinities during this time period introduce osmoregulatory stresses to the now hyperosmotic fish. Excess ions that are passively transported across membranes with the influx of water must be actively removed from the individual via chloride cells associated with the gills, a process requiring significant energy expenditure (Bond 1979). The composite effect of these physiological stresses was to reduce habitat suitability across the bay for adult spotted seatrout.

Juvenile spotted seatrout HSI models exhibited greater sensitivity to fluctuating environmental parameters throughout the year. Approximately 88% of the bay exhibited medium suitability during the low-salinity time period (Figure 32). Salinities ranging from 20-25 ppt in the lower reaches of the bay reduced habitat suitability for juveniles to the low category; however, the presence of SAVs in this area sustained moderate suitabilities. Suboptimal temperatures, ranging from 16-20° C, also suppressed HSIs across the entire bay.

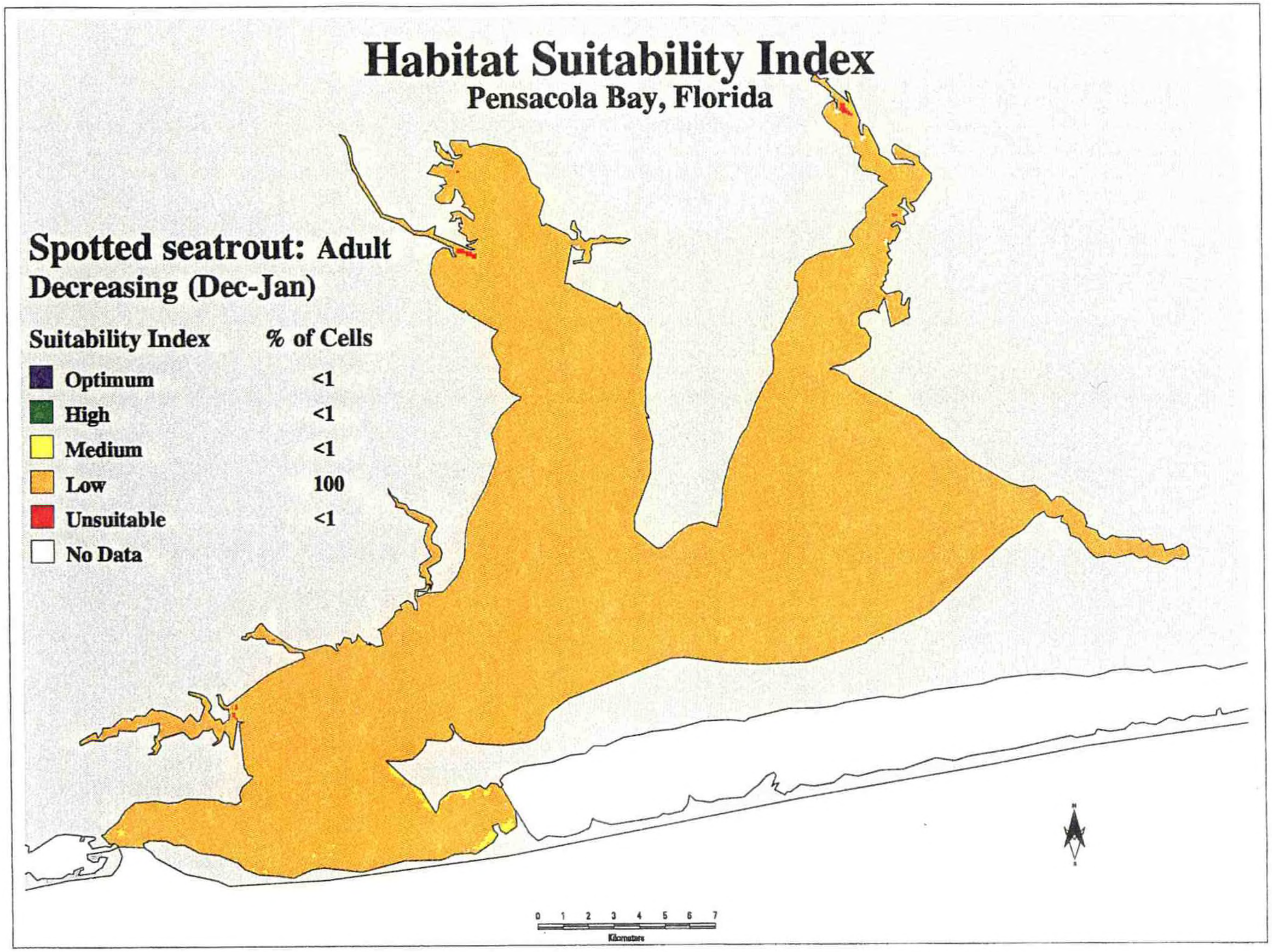


Figure 31. *HSI Model results for spotted seatrout adults during the decreasing salinity time period (Dec-Jan).*

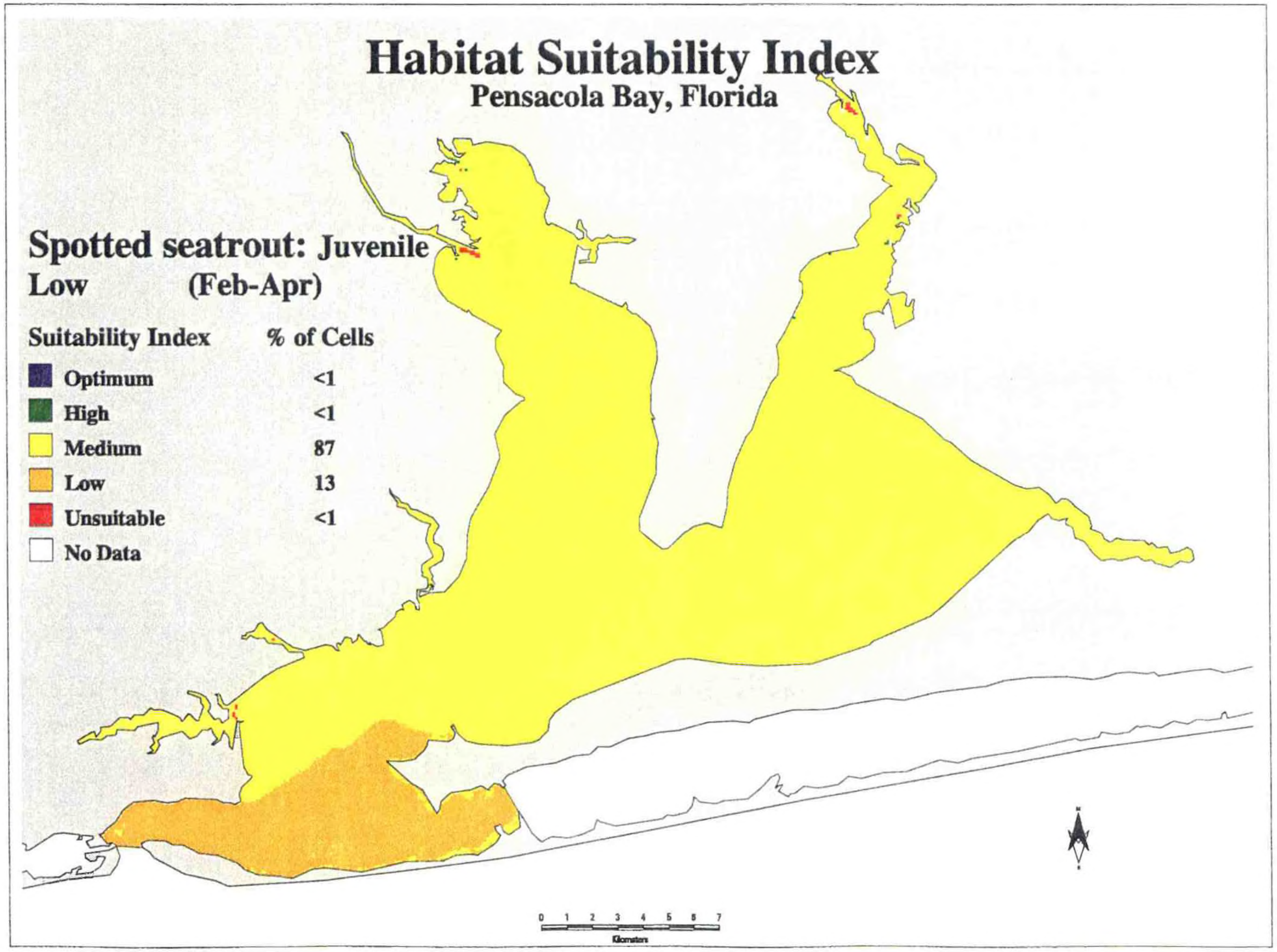


Figure 32. *HSI Model results for spotted seatrout juveniles during the low salinity time period (Feb-Apr).*

As water temperatures increased into the optimum range, all areas containing SAVs and EVs exhibited high suitability (Figure 33). Juvenile spotted seatrout prefer habitats with extensive SAV and EV distributions that can be used as refugia from predation pressures (Johnson and Seaman 1986). Moreover, these habitats generally contain greater concentrations of copepods and postlarval penaeid shrimp, a primary foraging target of juvenile seatrout. Although large juveniles and subadults may exhibit distribution patterns consistent with mature individuals, young-of-the-year spotted seatrout exhibit strong associations with vegetated habitats. As such, juvenile models resulted in lower suitabilities across the bay year-round.

Most of the high-suitability areas associated with vegetation were reduced to medium suitability as a result of increasing salinities from September through November (Figure 34). Only those vegetated habitats in Blackwater Bay remained high during this period, as salinities in the upper reaches of the bay remained optimal. Decreasing water temperatures also decreased suitabilities across the bay, with the exception of warm water masses limited to the shallow upper reaches of the bay system.

As with adults, juvenile habitat suitability exhibited a dramatic decline during the decreasing salinity time period (Figure 35). Water temperatures ranging from 10-14° C reduced suitabilities to the low category throughout the bay. Again, the low suitability observed baywide during the winter months does not indicate that juvenile trout are leaving the estuary; rather, it is a comparison of suitabilities relative to the remaining salinity-defined seasons.

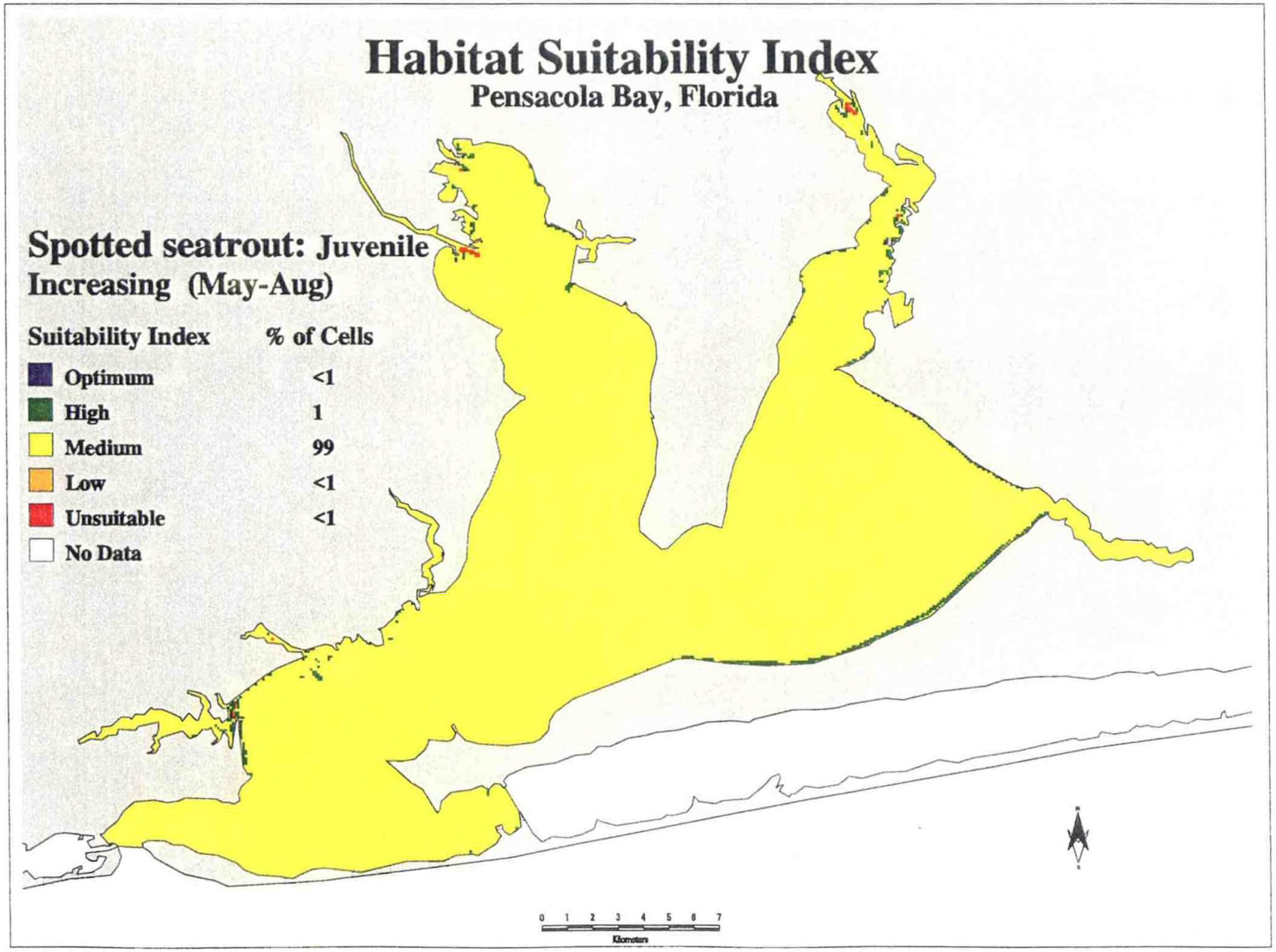


Figure 33. *HSI Model results for spotted seatrout juveniles during the increasing salinity time period (May-Aug).*

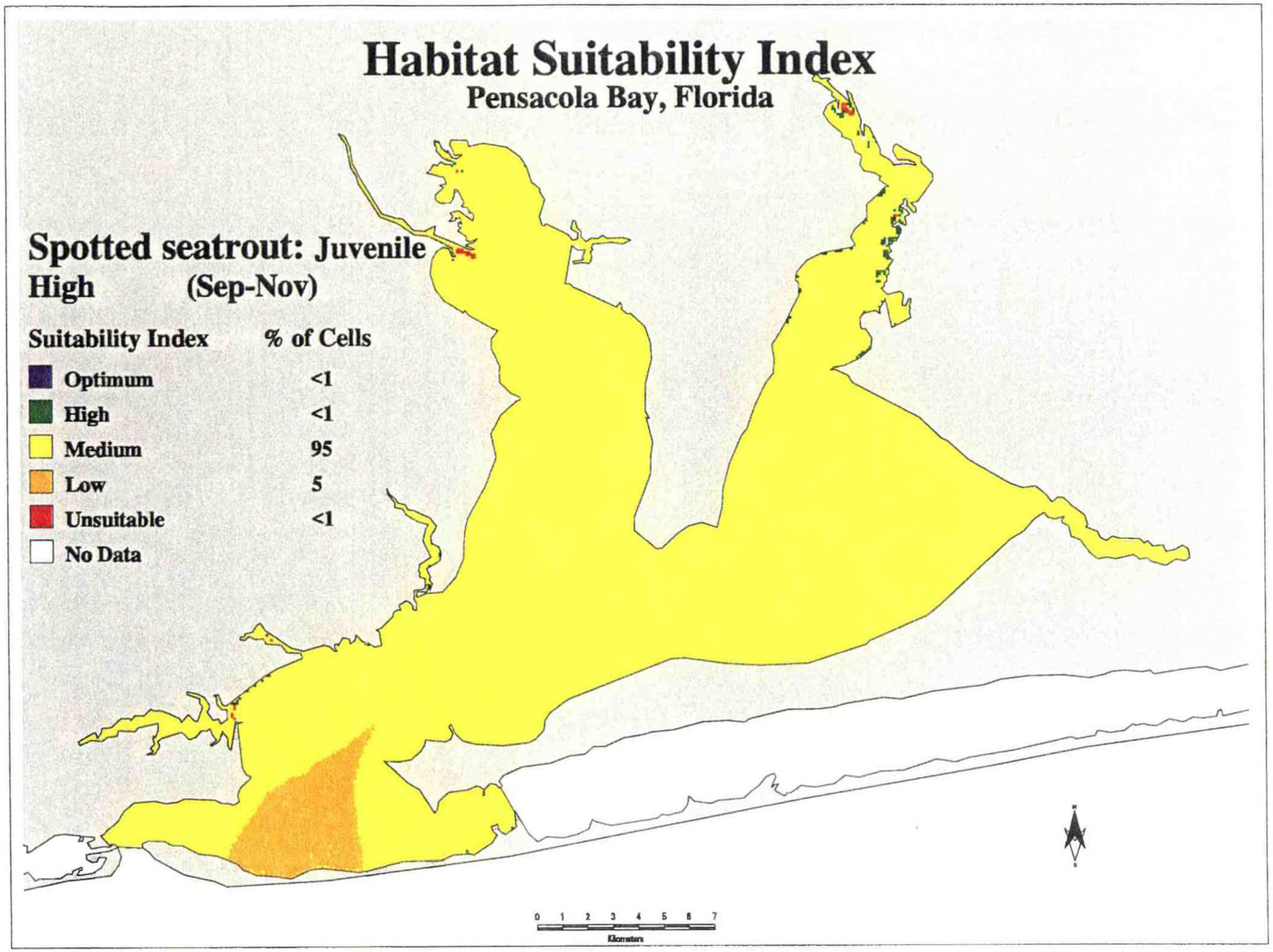


Figure 34. *HSI Model results for spotted seatrout juveniles during the high salinity time period (Sep-Nov).*

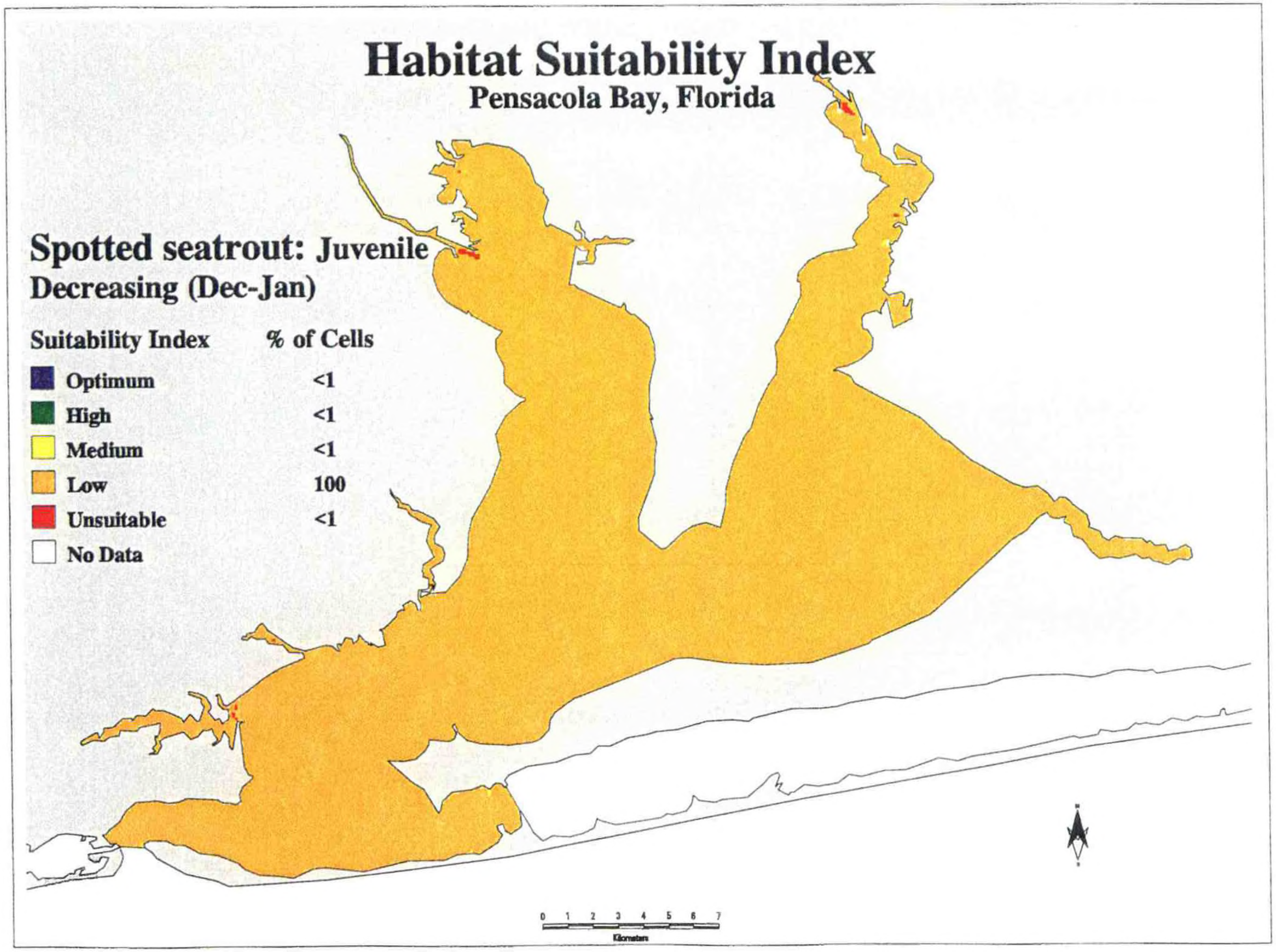


Figure 35. *HSI Model results for spotted seatrout juveniles during the decreasing salinity time period (Dec-Jan).*

Model Validation & Analysis

Due to the lack of consistent and robust fisheries independent data for white shrimp and spotted seatrout in Pensacola Bay, a quantitative approach to model validation and statistical analysis was performed only for American oyster model results. A comprehensive survey of oyster reef locations was conducted by Florida's Department of Natural Resources (FLDNR) from 1971-1972. These georeferenced data were superimposed on model results for the increasing salinity time period to assess the relationship between actual and predicted oyster locations (Figure 36). Of the 37,000 grid cells modeled in the Pensacola Bay complex, only 347 contained oysters based on the FLDNR survey (Mark Berrigan, FLDNR - Pers. Comm., Little and Quick 1976, McNulty et al. 1972). Approximately 86% (N = 300) of all observed oysters fell within the optimum habitat suitability class range, while the remaining 14% (N = 47) fell within the high HSI class. There were no oysters observed in the medium, low, or intolerable habitat suitability classes.

Mean values were plotted for each HSI class to investigate the relationship between model results and environmental variable. A Pearson correlation matrix also was calculated between each variable and HSI class to quantify and test the significance of these relationships (SAS 1992). Bathymetry exhibited a significant inverse relationship with predicted oyster distributions (Figure 37). Average water depth in the optimum HSI class was 3 m (≈ 9 ft), and increased to 11.3 m (≈ 34 ft) in the unsuitable HSI class. Salinity also exhibited a significant inverse relationship with oyster distributions. Mean salinity in the optimum range was 16 ppt, and increased to 22 ppt in the unsuitable HSI class (Figure 37). These two environmental variables acted collectively to produce highest HSI values in the shallow waters of Escambia and East Bays during all seasons.

Although probability values indicate significance (based on the unusually high number of observations, N = 37,000), substrate type and water temperature did not exhibit

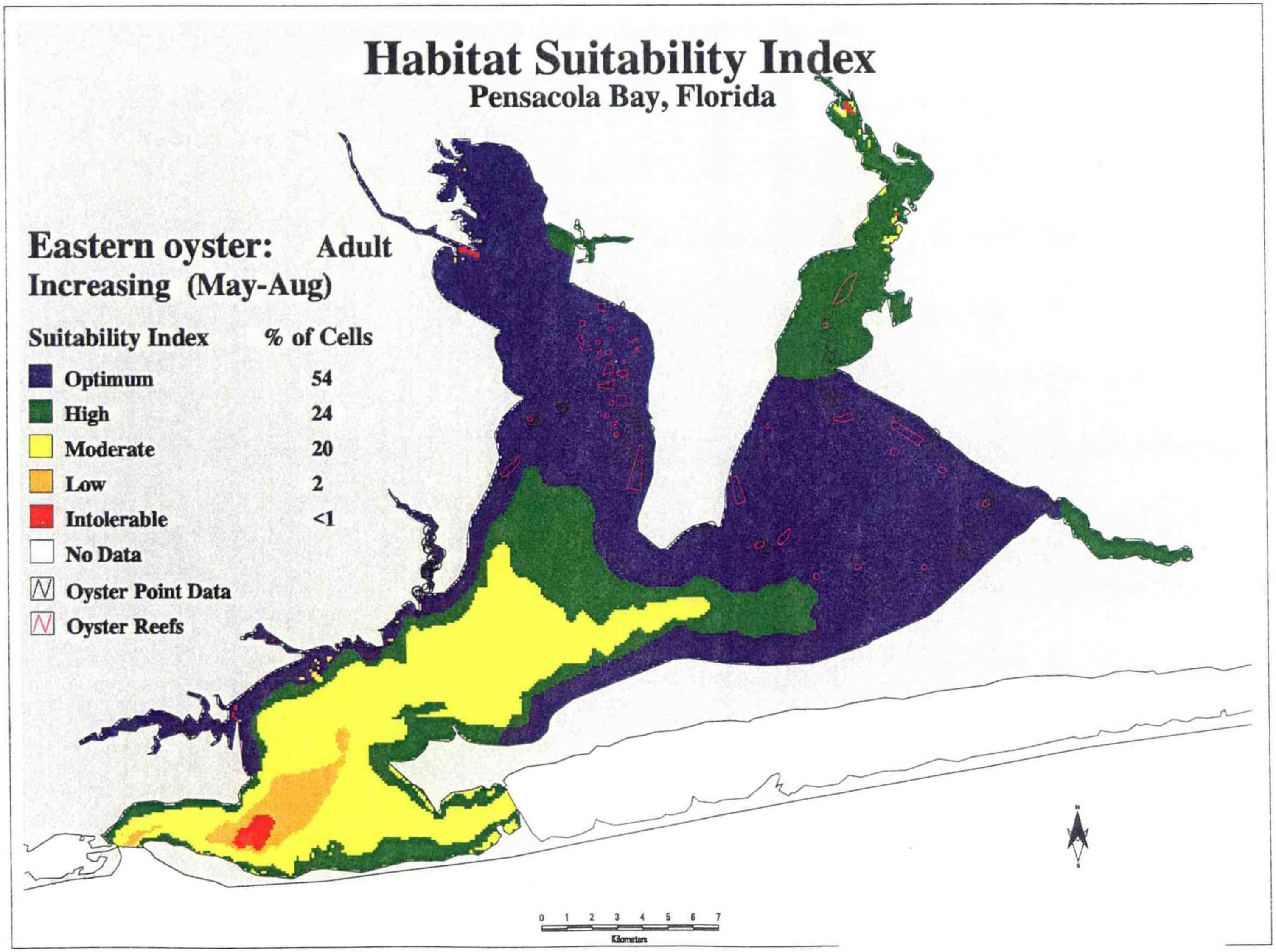
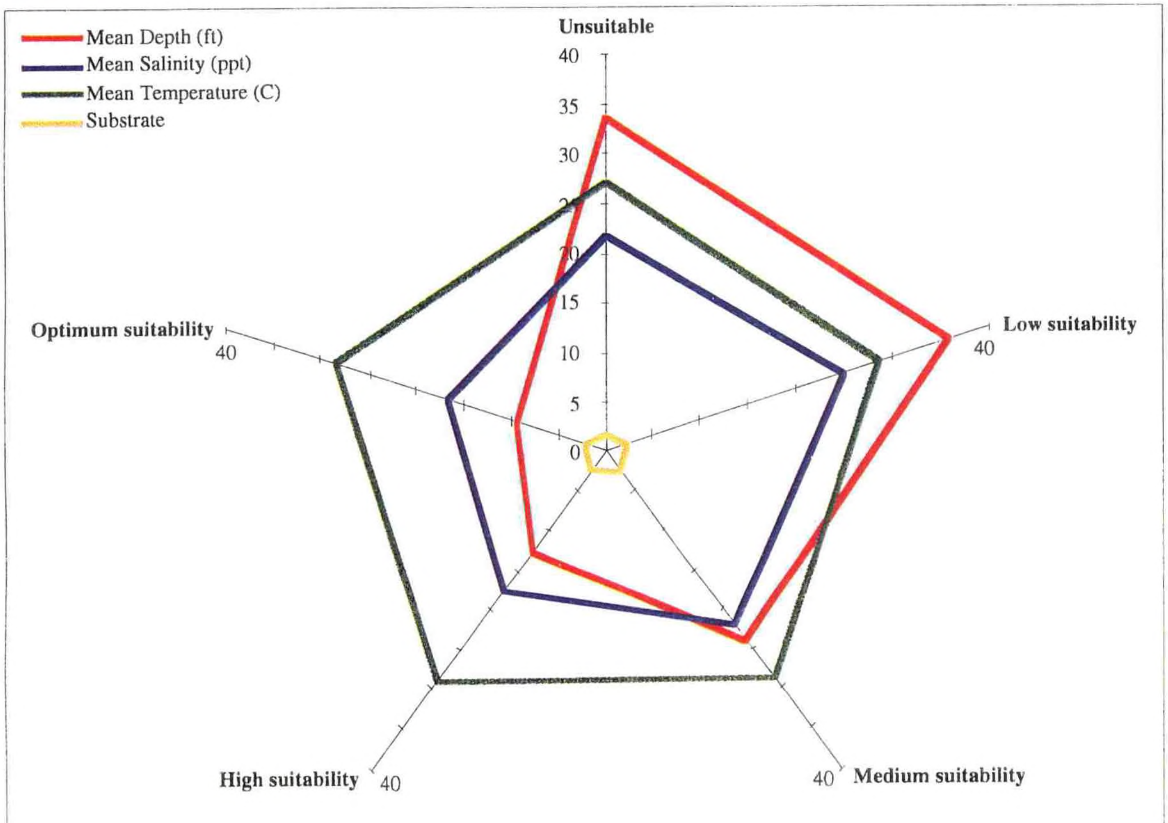


Figure 36. *Adult American oyster spatial model validation during the increasing salinity time period (May-Aug).*

conspicuous relationships with predicted oyster distributions. Average water temperature was 27° C for the unsuitable HSI class, and 28° C for the optimum category (Figure 37). Substrate types were categorized into sand, silt, and clay, and were numbered as 1, 2, and 3, respectively. Substrate type 1 (approaching pure sand) exhibited the lowest mean values in the unsuitable class; however, remaining HSI classes exhibited similar mean substrate values (Figure 37).



Variable	Correlation Coefficient	Probability
Depth	-0.81062	0.0001
Salinity	-0.50030	0.0001
Temperature	0.05233	0.0001
Substrate	-0.23353	0.0001

Variable Scale

Depth (ft):	Min = 0; Max = 42
Salinity (ppt):	Min = 5; Max = 35
Temperature (C):	Min = 26; Max = 30
Substrate:	1 = Sand; 2 = Silt; 3 = Clay

Figure 37. *Wire diagram of mean environmental variable value vs. HSI class for American oysters during the increasing salinity time period. Correlation coefficients between oyster locations and environmental variable are shown in the lower left corner.*

The lack of fisheries independent data necessitated a qualitative approach to white shrimp and spotted seatrout HSI model validation. A panel of local fisheries biologists and commercial fishermen compared model results to their collective expertise on the distribution and abundance of these species in Pensacola Bay. Consensus was reached that model results portrayed a reasonable representation of the potential distribution of white shrimp and spotted seatrout.

Management Implications

The effects of changes in freshwater inflow on estuarine systems and their associated biological communities have become of great interest to coastal living resource managers (Christensen et al. 1997, SEA Division 1995). Most efforts to predict changes in estuarine and near-shore community structure in response to environmental stress are directed toward describing species responses to habitat alteration and to point and/or non-point source pollutant discharges, not to systemwide changes in hydrological character (Hoff and Ibara 1977). These models attempt to address this information gap, and provide an objective method to predict and assess species distribution changes in response to a shift in estuarine salinity structure.

Natural episodic fluxes of freshwater into estuaries are common in U.S. estuaries, and most often result from random meteorological events (Ward 1980, Ward and Armstrong 1980). Literary accounts of altered estuarine community structure in response to storm-induced freshwater pulses are numerous (Drinkwater et al. 1991, Nielsen and Kioerboe 1991, Moffat and Jones 1991, Goeghegan et al. 1992), and most report that physical forcing mechanisms (i.e., tidal flushing and wind-induced surface currents), which occur within relatively fine temporal scales, act collectively to reduce the chance for long-term community changes. Anthropogenic flow changes into estuaries often are of greater duration (chronic, if not indefinite), and therefore harbor the potential to permanently alter a system's biological community.

People have subjected most of the nation's estuaries and their associated watersheds to significant modifications, the most important of which include: 1) flow diversions and reservoir construction, which significantly alter the volume and/or timing of freshwater delivery to an estuary; 2) creation or deepening of navigation channels, facilitating high-salinity bottom-water intrusion; and 3) large-scale dredge material disposal site construction (including diked disposal islands), which can alter estuarine circulation patterns (Orlando et al. 1993).

Freshwater Inflow Alteration

HSI models can be used to assess potential impacts of these and other environmental modifications. To emphasize this point, two hypothetical salinity scenarios were modeled to evaluate the impact of freshwater inflow changes into the Pensacola Bay system. To simulate decreased freshwater inflow (scenario A), models were developed for adult American oyster, white shrimp, and spotted seatrout in artificially increased salinity habitats. To accomplish this, salinities from the high-salinity time period were increased by 5 ppt across the bay. Likewise, baywide salinities were decreased by 5 ppt for the low-salinity time period to simulate increased freshwater inflow (scenario B).

Potential oyster distributions exhibited drastic changes in scenario A. Approximately 60% of the bay resulted in low suitability, whereas only 2% was of low suitability during the actual high-salinity time period (Figure 38). The total amount of optimum and high-suitability habitats were reduced by 71% and 63%, respectively. The artificial reduction of salinities (scenario B) also resulted in significant changes to potential oyster distributions. Nearly 27% of the bay exhibited low suitability, a twelvefold increase in this HSI class

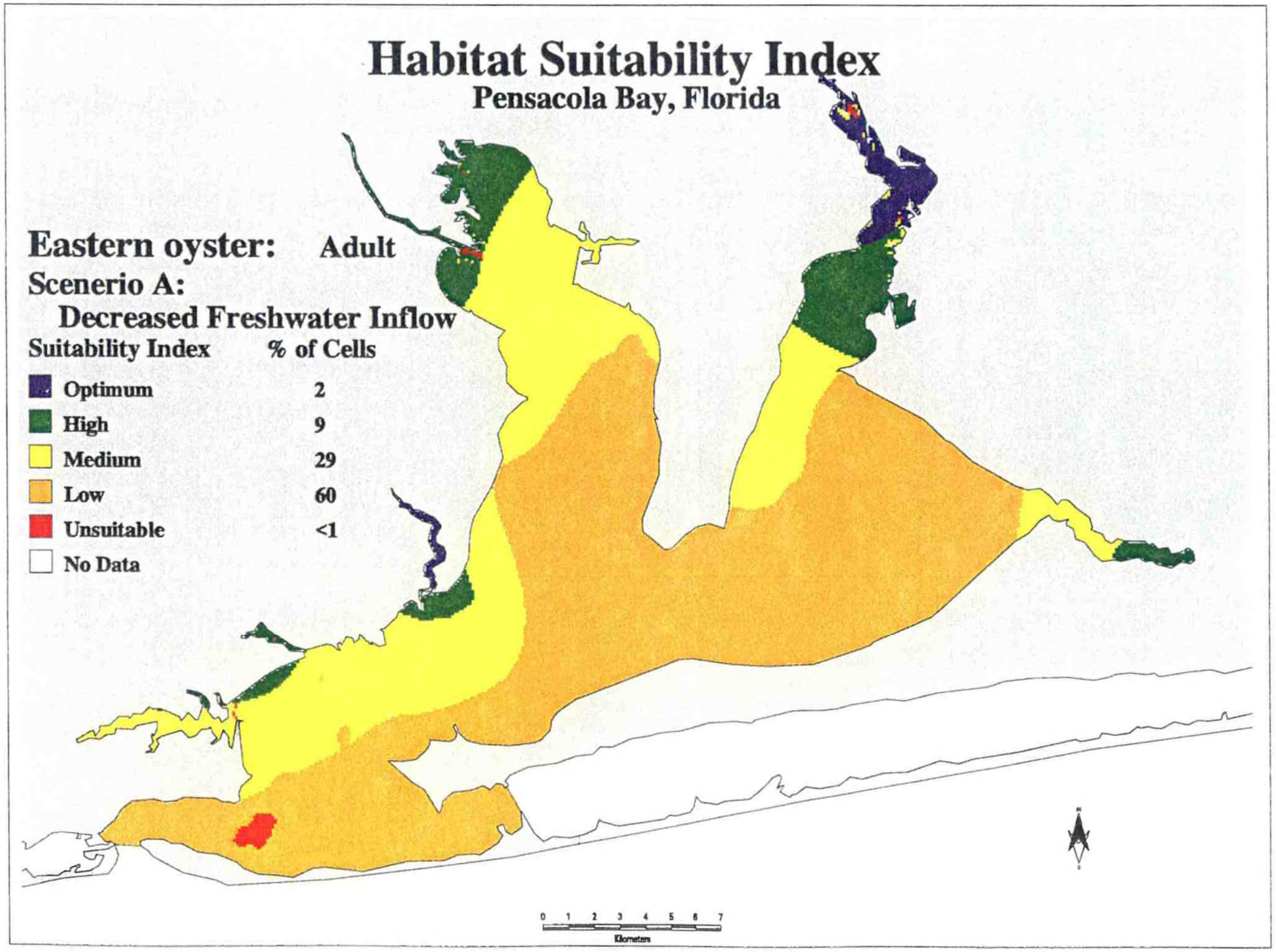


Figure 38. *HSI Model results for American oyster adults. Scenario A: decreased freshwater inflow.*

(Figure 39). Suitabilities in the lower portions of the bay increased from medium to high, as depressed salinities in this area would now be conducive to oyster survival.

Adult white shrimp scenario A HSI model results varied only slightly from the original high-salinity time period results. High suitability habitats increased by 5%, and medium suitability habitats decreased by 3%, indicating a slight preference for higher salinities (Figure 40). Low-salinity time period model results for adult shrimp varied significantly from those produced using decreased salinities in scenario B (Figure 41). Low-suitability habitats increased by 550%, while high suitability habitats decreased by a factor of 12.

Adult spotted seatrout scenario A HSI model results exhibited only slight changes from the original high-salinity time period results. Increased salinities in the upper reaches of Escambia Bay increased suitabilities from medium to high (Figure 42). Likewise, model results for scenario B were similar to low-salinity time period results, with the exception of upper Escambia and East Bays. Salinities ranging from 0-5 ppt in these habitats reduced HSIs to the low category (Figure 43). Results of these two scenarios indicate that the upper portions of Pensacola Bay may be conducive to management via freshwater inflow regulation; however, the central and lower portions of the bay would exhibit little change based upon the magnitude of these changes.

Concluding Comments

It has been suggested that future fisheries biologists use freshwater inflow as a tool for fisheries management by providing preferred hydrological conditions for commercially important species. DaSilva (1986) reported that by regulating the Zambizi River runoff in an appropriate manner, *Penaeid* shrimp yields from the Sofala Bank would likely increase, providing a measure of stability and strength to the local coastal economies of Mozambique.

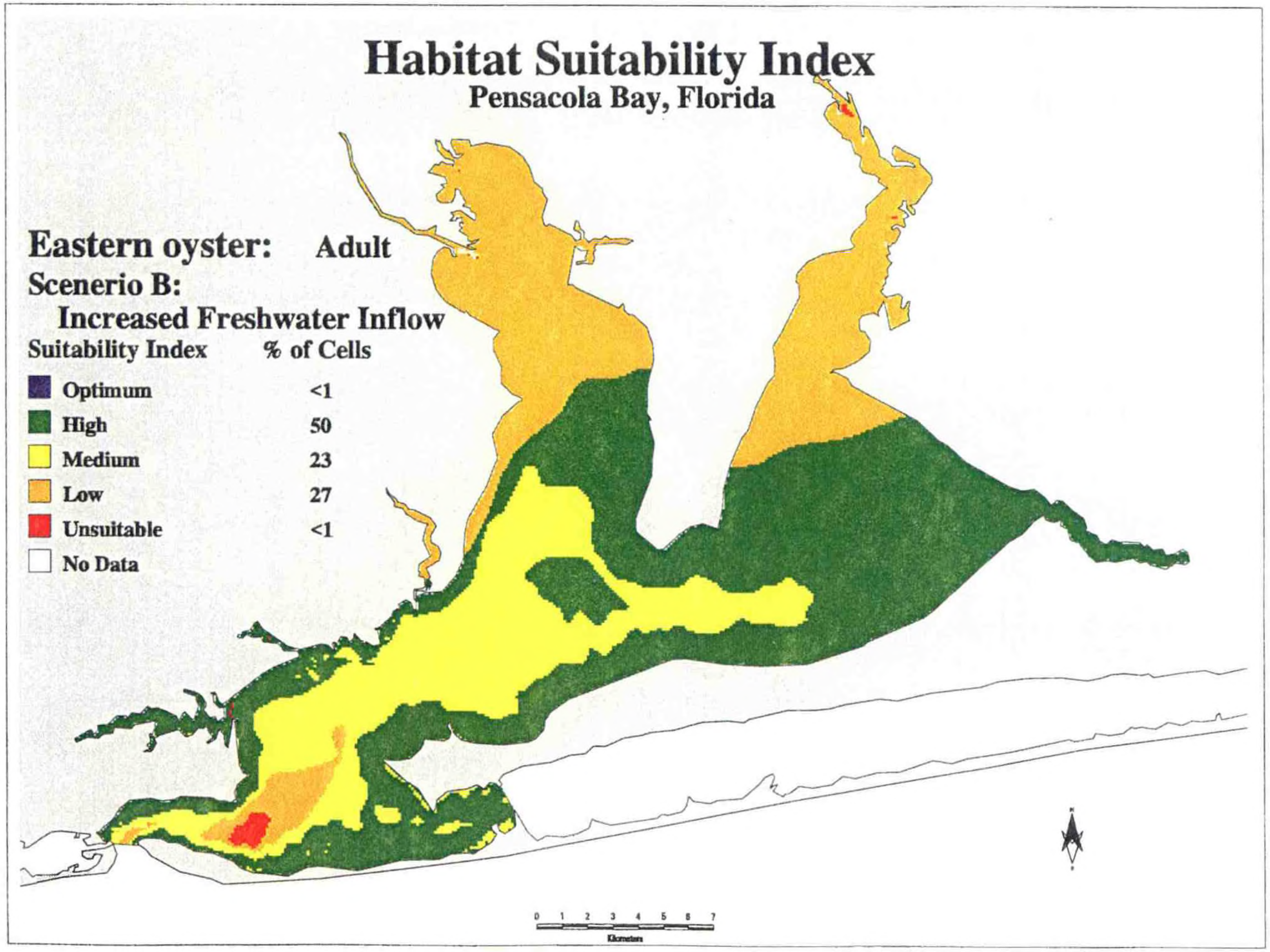


Figure 39. *HSI Model results for American oyster adults. Scenario B: increased freshwater inflow.*

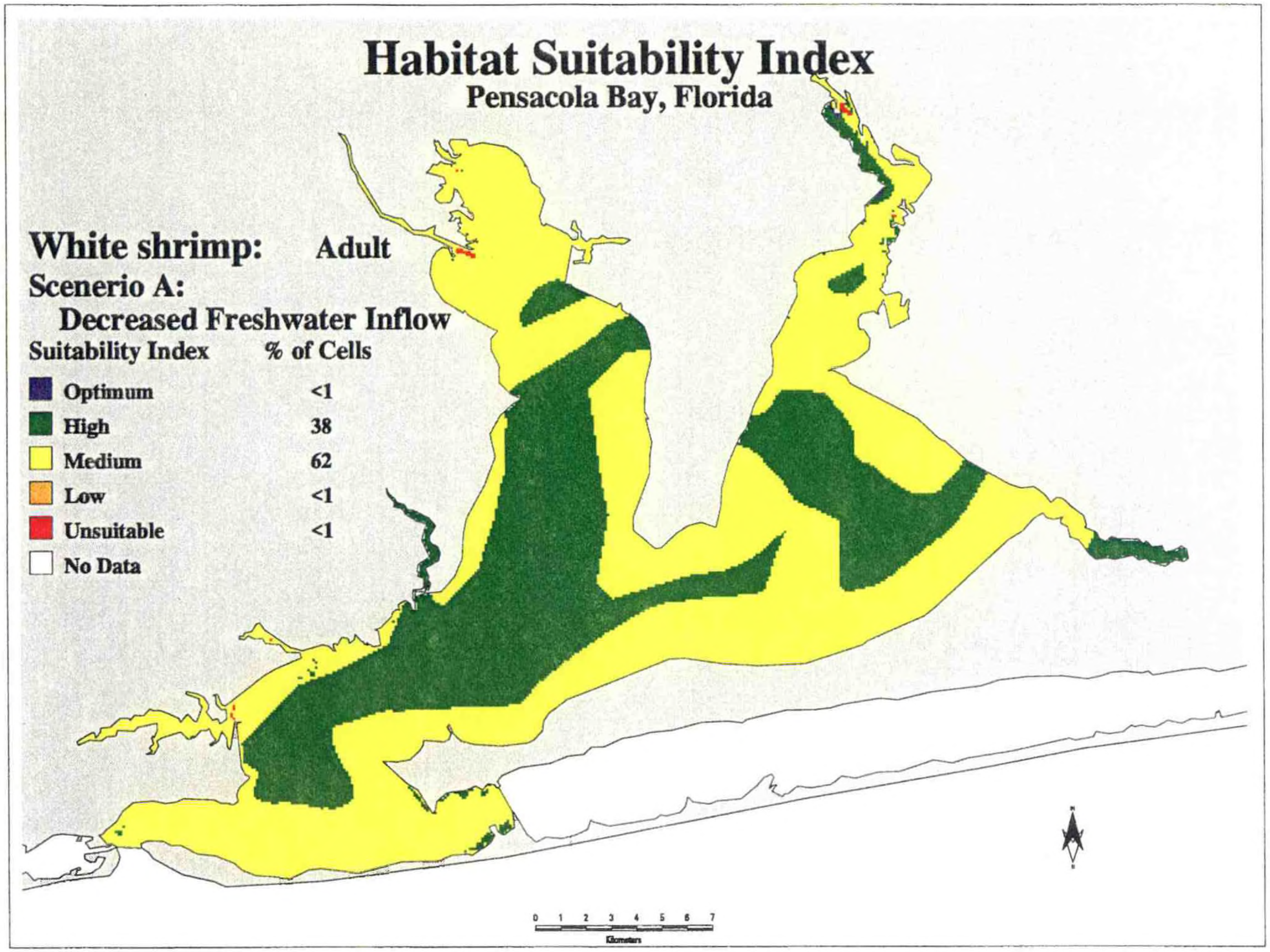


Figure 40. *HSI Model results for white shrimp adults. Scenario A: decreased freshwater inflow.*

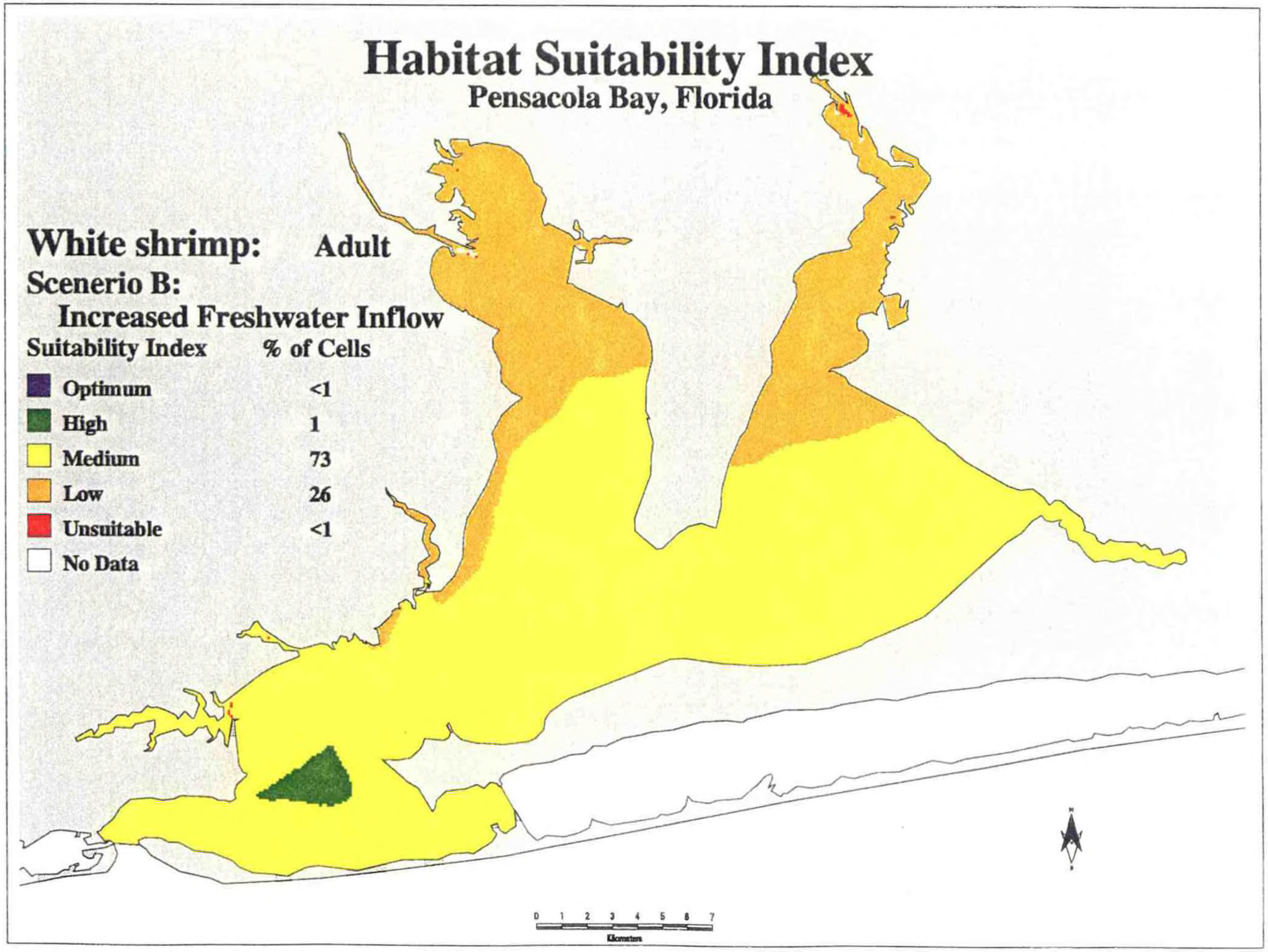


Figure 41. *HSI Model results for white shrimp adults. Scenario B: increased freshwater inflow.*

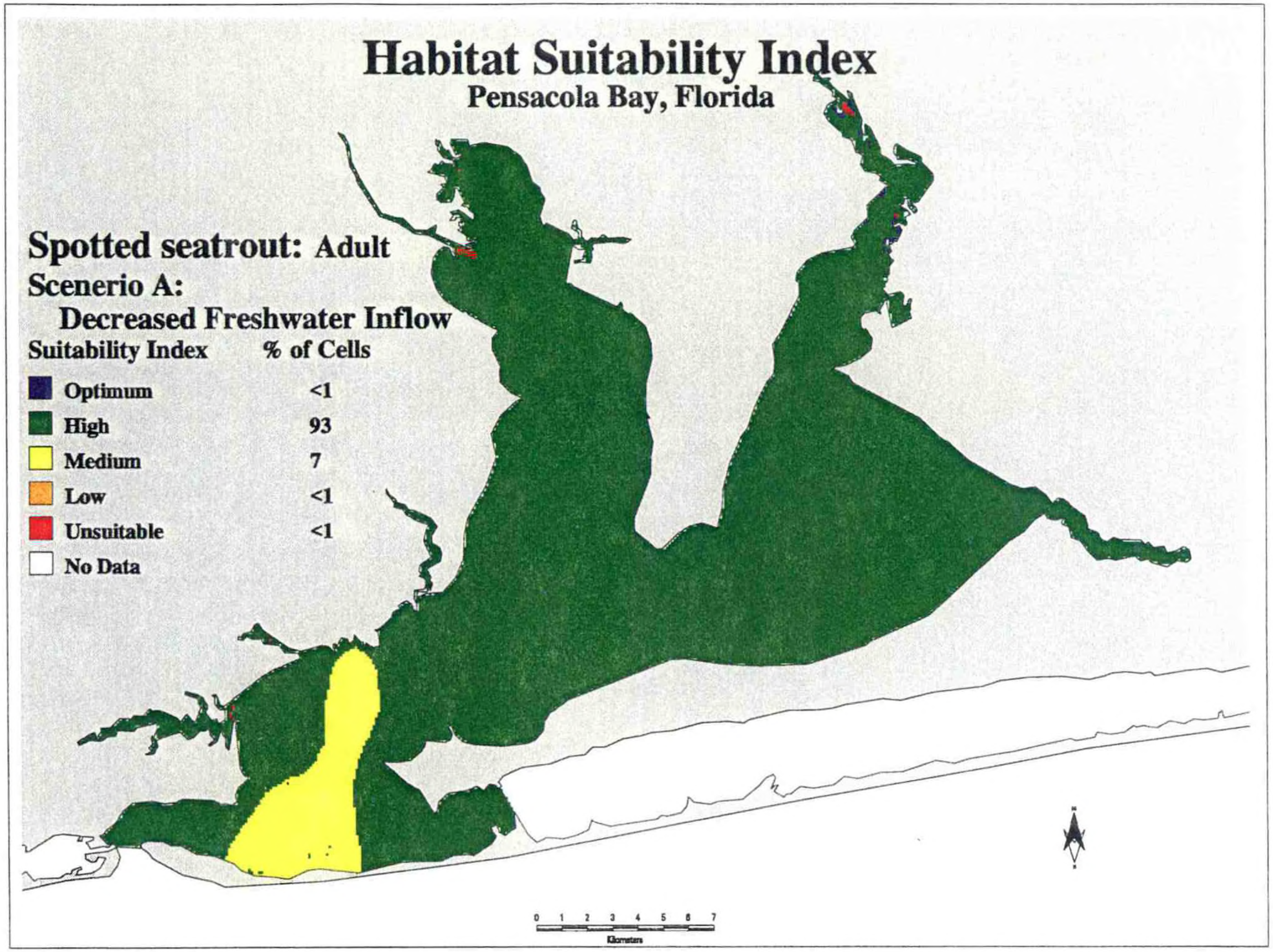


Figure 42. *HSI Model results for spotted seatrout adults. Scenario A: decreased freshwater inflow.*

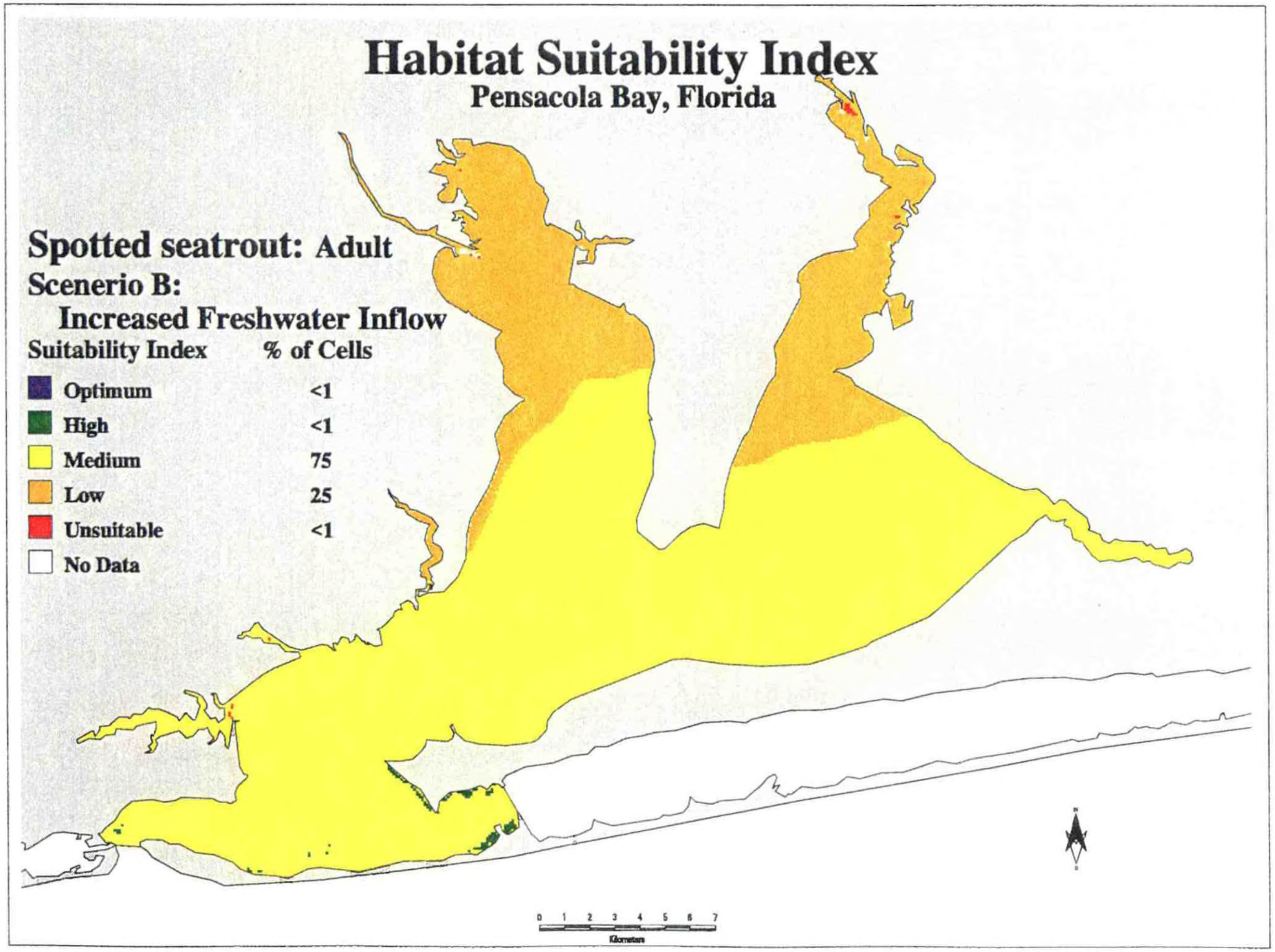


Figure 43. *HSI Model results for spotted seatrout adults. Scenario B: increased freshwater inflow.*

Although this method exhibits great promise, it is imperative for resource managers to accurately predict which species would be displaced by such management techniques. The use of HSI models may provide resource managers with the tools they need to make such predictions, thereby solidifying the ecosystem-based platform for prudent decision-making.

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APPENDIX 1
HSI DEVELOPMENTAL EFFORTS

The species HSI modeling efforts met the objectives to define important areas in Pensacola Bay for target species and to assess how a potential change in salinity habitat may impact species distributions. However, several experimental efforts are under development to continue the advancement and utility of the HSI work. Three examples are described below; they can be applied at both the estuary and regional scales.

Important Habitats

To address the need of managers to identify important areas within estuaries based on the results of HSI modeling efforts, one can overlay HSI maps for all species and life history stages for a particular season. The arithmetic mean HSI value for multiple species/life stages can be mapped by grid cell to provide a composite overview of habitat use. For example, a manager interested in defining important benthic habitats could map the mean HIS values of benthic species. Similarly, the HSI values of pelagic species could be mapped to identify potential areas of conflict between the management of two different species groups. The resulting maps are identical to the species-specific maps, but represent groups of species (Brown et al. 1997).

Species Interactions: Experimental Analyses

The current HSI modeling work focuses on single species results and interpretations. However, estuarine and marine resource management continues to move towards multispecies and habitat management approaches. The authors are exploring several approaches to determine the magnitude of increases or decreases in species interactions. This Pensacola Bay investigation addressed the interactions of white shrimp, an important prey species, and spotted seatrout.

Method 1. It is assumed predator/prey interaction is directional in the sense that predators benefit from increased interactions, while prey are adversely affected (e.g., consumed) (Pianka 1988). To assess changes in the potential predator/prey interaction between seatrout and white shrimp, the predation concepts of Lotka (1925) and Volterra (1926) were used. Thus, the interaction (I) equation:

$$I = [(HSI_2 * HSI_1) - (HSI_2)] ;$$

quantifies potential species interaction. The equation was scaled so that the interaction values could be mapped using a GIS. Thus, the interaction equation used in the predator/prey HSI models was:

$$I = [(HSI_2^2 * HSI_1^2) - (HSI_2^2)] /10.$$

HSI model class values (1-5) for white shrimp and spotted seatrout represent HSI_1 and HSI_2, respectively. High HSI values were assumed to correspond with relatively high abundance of a species.

Predator (HSI2)	Prey (HSI1)	$HSI2^2 * HSI1^2$	$HSI2^2$	$I = [(HSI2^2 * HSI1^2) - (HSI2^2)] / 10$	Predator (HSI2)	Prey (HSI1)	$HSI2^2 * HSI1^2$	$HSI2^2$	$I = [(HSI2^2 * HSI1^2) - (HSI2^2)] / 10$
5	1	25	25	*0.00*	2	4	64	4	*6.00*
4	1	16	16	*0.00*	3	3	81	9	*7.20*
3	1	9	9	*0.00*	5	2	100	25	*7.50*
2	1	4	4	*0.00*	2	5	100	4	*9.60*
1	2	4	1	*0.30*	4	3	144	16	*12.80*
1	3	9	1	*0.80*	3	4	144	9	*13.50*
2	2	16	4	*1.20*	5	3	225	25	*20.00*
1	4	16	1	*1.50*	3	5	225	9	*21.60*
1	5	25	1	*2.40*	4	4	256	16	*24.00*
3	2	36	9	*2.70*	5	4	400	25	*37.50*
2	3	36	4	*3.20*	4	5	400	16	*38.40*
4	2	64	16	*4.80*	5	5	625	25	*60.00*

Table 5. *Potential predator/prey interaction values.*

Potential predator/prey interactions were modeled for the increasing salinity time period (May-August) because both species populations exhibited maximum HSI results during this season. To investigate the theoretical impact of increasing freshwater inflow on the seatrout-white shrimp interaction, a hypothetical salinity scenario was created by decreasing salinities by 5 ppt for the entire bay during the summer salinity time period.

Results of potential predator/prey interaction between adult spotted seatrout and juvenile white shrimp during the increasing salinity time period are shown in Figure 44. Figure 45 depicts the same interaction during the same time period; however, baywide salinities were reduced by 5 ppt to simulate increased freshwater inflow. The overall effect of reducing salinities was to markedly decrease potential interactions in Escambia, Blackwater and East bays. Reduced salinities in these portions of the bay decreased HSI classes for spotted seatrout, and subsequently reduced potential species interactions.

Methods 2. The authors' second approach to model species interactions is based on assessing where the specific HSI classes (1-5) occurs for each species. There are 25 possible combinations, as shown in the matrix below. Each of the 25 categories can be mapped separately, or they could be grouped in any way that would be useful for a particular situation. The following is a simple way to group the categories. The approach is based on the assumption that the strength of an interaction is determined by the species with the lower HSI (i.e., the species for which the habitat is of lower quality will limit the degree to which the interaction can occur). In this case, the 25 categories collapse to five, as shown on page 88.

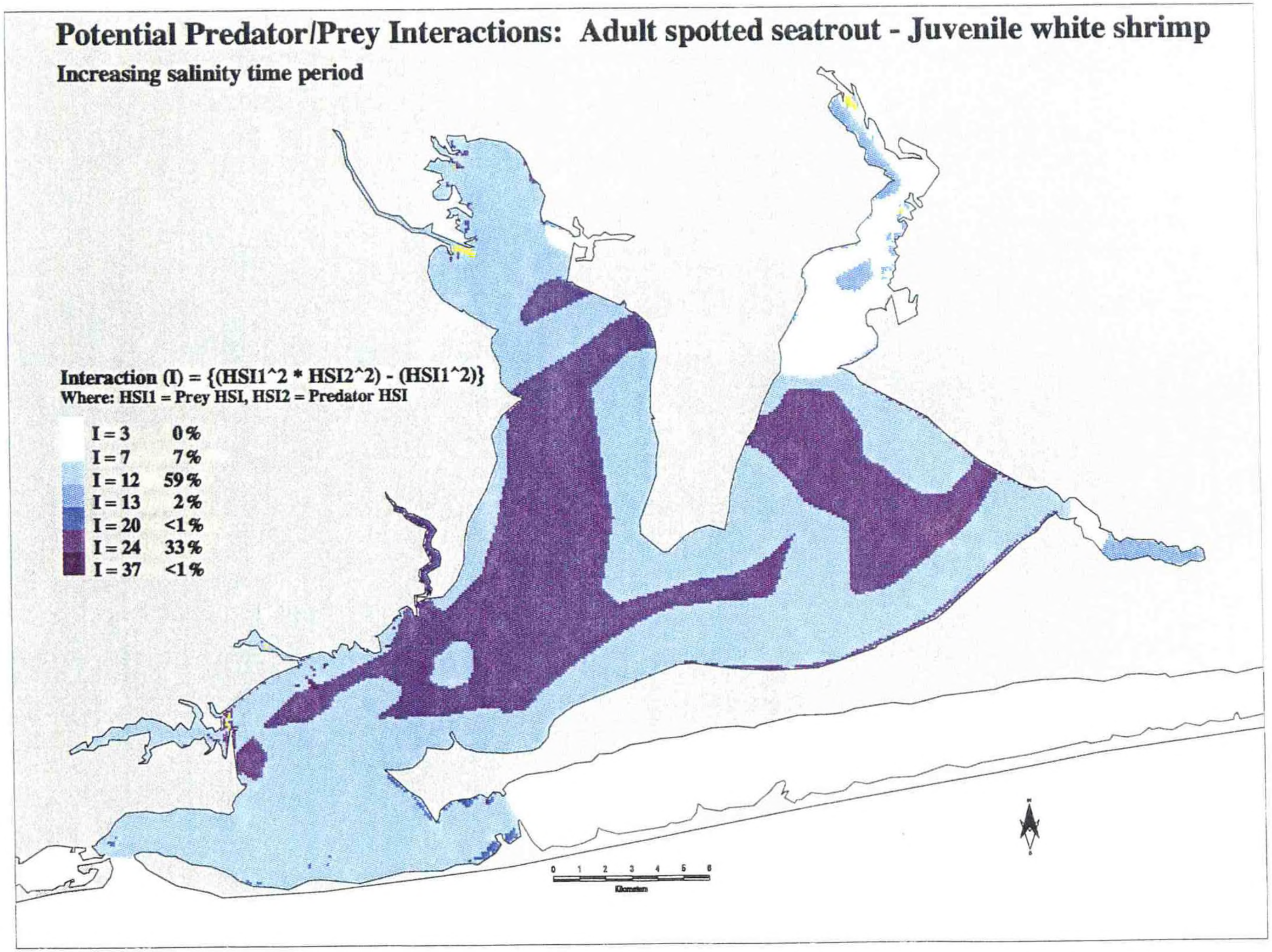


Figure 44. *Potential predator/prey interactions during increasing salinity time period: adult spotted seatrout - juvenile white shrimp.*

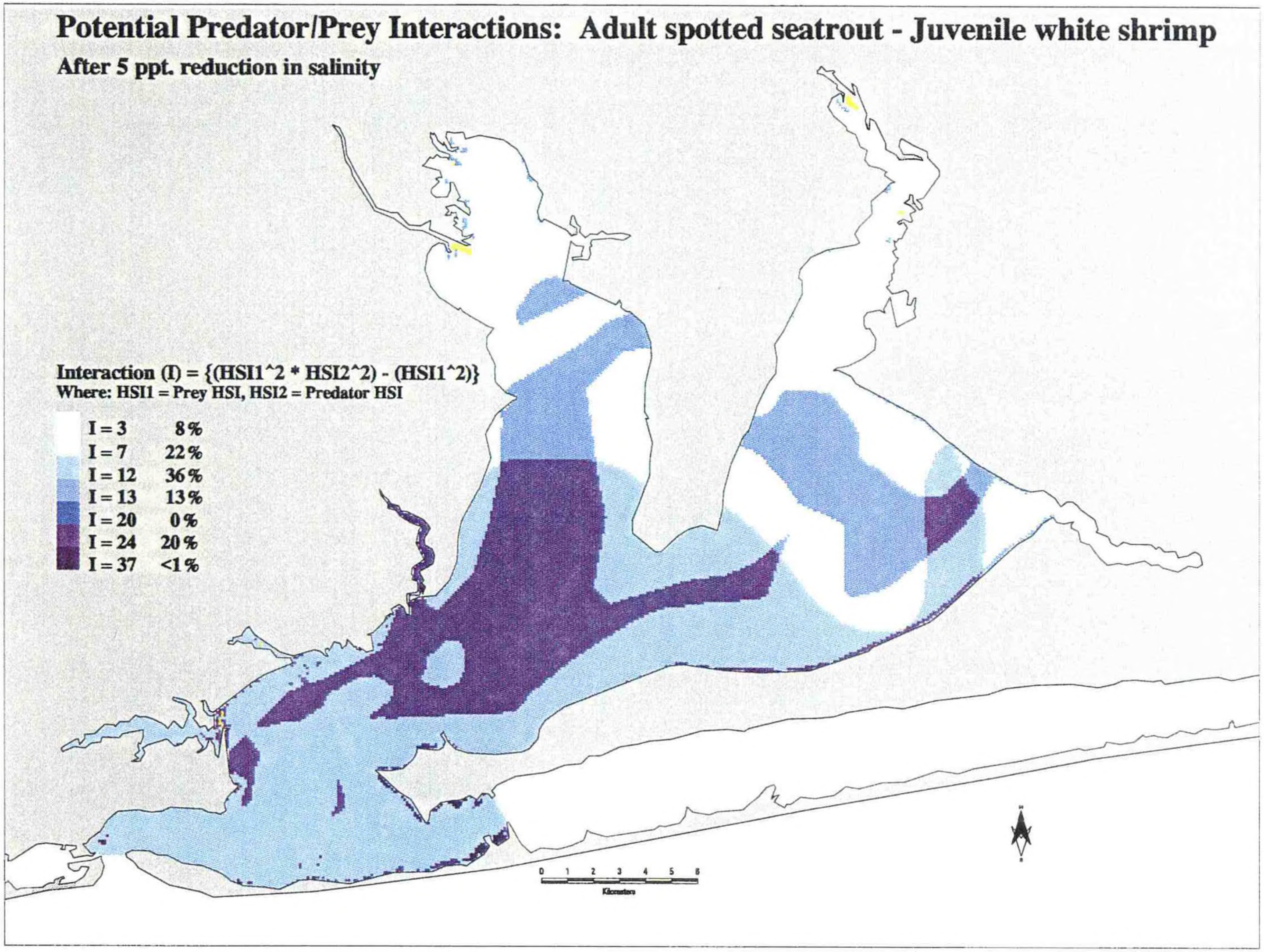
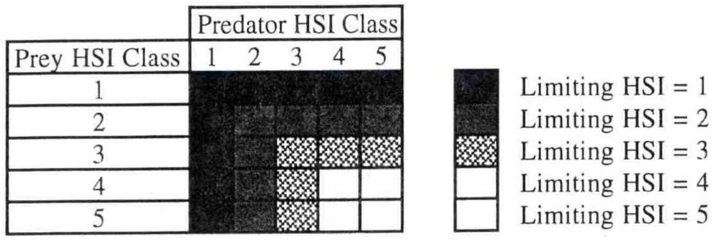


Figure 45. *Potential predator/prey interactions after salinity alteration: adult spotted seatrout - juvenile white shrimp.*



Maps for baseline and test scenarios can be generated using either the grouped or ungrouped approach, and can be compared visually and/or by providing grid-cell counts or percentages for the different categories. A final step is to develop a "change map" of species HSI classes. The change map combines the species interactions of the baseline and test scenarios into one map. Maps of the predator/prey interactions for both scenarios are overlaid. The resulting categories of interaction changes are then mapped. If no grouping of the interaction change categories are done, a 25 x 25 matrix of possible interaction changes is obtained, as shown below.

Test <u>Interactions</u>	<u>Baseline Interactions</u> 1/1	1/2	1/3	.....	5/3	5/4	5/5
1/1							
1/2							
1/3							
.							
.							
.							
5/3							
5/4							
5/5							

Without grouping, the number of possible interaction changes to be mapped and interpreted is overwhelming (625 combinations). One approach to reduce the number of interaction combinations is to make the same previously mentioned assumption (i.e., that the species for which the habitat is of lower quality will limit the degree to which the interaction can occur). This assumption collapses the 25 possible interaction categories of both the baseline and test scenarios into five categories, each resulting in the following matrix of 25 possible interaction changes.

	Baseline Limiting HSI Class				
Test Limiting HSI Class	1	2	3	4	5
1					
2					
3					
4					
5					

These categories can be grouped as necessary for mapping. In practice, the most extreme changes (e.g., from an HSI class of 1 to 5 for the limiting species) may be unlikely, so fewer than the 25 change categories would probably be needed for mapping the changes in a given scenario.

Quantitative SI values: Assessing Anthropogenic Impacts

In the same vein as the previous discussion, the authors are analyzing species catch rates from fishery independent monitoring programs to determine if significant differences in species HSI maps (i.e., habitat associations) are evident between anthropogenically impacted and nonimpacted areas. This type of analysis can be done with both qualitative and quantitative information. However, experiments with quantitatively derived (field-based) species suitability (SI) index values and environmental data are being done to classify areas as anthropogenically impacted (e.g., dissolved oxygen levels).

In the Pensacola study, a species SI value for a particular environmental variable was determined using available data and expert knowledge to "score" the SI value between 0 - 1. To quantify the SI value, a species habitat affinity index (HAI) was developed based on field data of species catch rate by environmental variable (Monaco et al. in press). The HAI quantifies species habitat affinities based on the relative concentration of a species in a specific habitat (e.g., depth zone) when compared to the relative availability of that habitat throughout the study area. For example, a species would have a high affinity for a habitat if the habitat comprised only 20% of the area in an estuary, yet contained 80% of the individuals of a particular species.

Using the field-based species SI values derived from the HAI index enables one to assess whether differences in species habitat affinities are evident in areas that are anthropogenically impacted (e.g., degraded versus nondegraded areas based on sediment toxicity). This experimental work is under development to formulate a screening tool to assess the potential impacts of anthropogenic activities using HSI models and maps.