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AN INDEX TO ASSESS THE SENSITIVITY OF GULF OF MEXICO SPECIES TO CHANGES IN ESTUARINE SALINITY REGIMES

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ABSTRACT An index of biological sensitivity to changes in freshwater inflow was developed for 44 species in 22 Gulf of Mexico estuaries for adult and juvenile life stages of fishes and macroinvertebrates. The BioSalinity Index (BSI) provides an innovative approach to quantify estuary-specific sensitivity of organisms to changes in estuarine salinity regimes based upon our knowledge of species salinity habitat preferences, the availability of this preferred habitat, and the relative abundance and distribution of species in time and space. We found that a significant difference exists between adult and juvenile life stage sensitivity, with juveniles exhibiting a lower sensitivity to salinity changes than adults, and that a considerable disparity exists in species-specific sensitivities among Gulf estuaries. Likewise, when the full complement of 44 species-level BSIs are averaged, marked differences in assemblage-wide sensitivity are evident across estuaries. The availability of preferred salinity habitat had a greater influence on the BSI for estuarine species than did their relative abundance and temporal distribution. The BSI was applied by members of a 1995 Gulf of Mexico freshwater inflow workshop to identify a subset of estuaries which appear more sensitive to freshwater inflow changes and are candidates for further study.

Introduction

The effects of changes in freshwater inflow on estuarine systems and their associated biological communities are of great interest to coastal living resource managers. Most efforts to predict changes in estuarine and near-shore community structure in response to environmental stress are directed towards describing species responses to habitat alteration and point and/or non-point source pollutant discharge, not to system-wide changes in hydrological character (Hoff and Ibara 1977). This paper is intended to address this information gap and to describe the development of an objective method to predict and assess both species and estuary-level response to shifts in estuarine salinity structure. Our approach was applied to U.S. Gulf of Mexico estuaries to assess the bio-sensitivity of species and their estuarine distribution based on salinity preferences (Christensen et al. 1996).

Natural episodic fluxes of freshwater 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), yet 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 resulting long-term community change.

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

It has been suggested that 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 and provide a measure of stability and strength to local coastal economies of Mozambique. Although these approaches exhibit great promise, it is imperative that resource managers are able to accurately predict which species would be displaced by such management techniques. Likewise, Ulanowicz and Tuttle (1993) exhibited via an ecosystem model how increasing oyster populations and their associated filtering capacity impact phytoplankton standing crop in Chesapeake Bay. The degree of estuarine community change expected from a permanent alteration in salinity structure is difficult to predict quantitatively from the existing literature because of the lack of field-based species salinity range data available (Monaco 1995). Moreover, most field reports rely on instantaneous observations, not on long-term assessments of average conditions, and available correlations and experimental information have not been extensive enough to reflect the variety of salinity regimes found at particular sites (Montague and Ley 1993).

The BioSalinity Index (BSI) was conceived as a screening tool for natural resource managers to provide a quantitative estimate of the effect which a measurable shift in salinity structure has on the relative abundance and distribution of a species, as well as on estuarine biological assemblages. The National Oceanic and Atmospheric Administration (NOAA) Strategic Environmental Assessments Division (SEAD) convened a workshop in cooperation with the U.S. Environmental Protection Agency (EPA) Gulf of Mexico Program Freshwater Inflow Committee to identify important relationships between freshwater inflow alteration, estuarine habitat, and biological resources in 29 Gulf estuaries (Christensen et al. 1996; SEA 1995). The BSI was developed specifically for this workshop, and was one of three evaluating/screening tools used synergistically to rank the relative potential for significant changes in estuarine hydrodynamic character and in their associated biological communities among major Gulf of Mexico estuaries. This was the first test of BSI applicability and validity in resource management decision-making.

MATERIALS AND METHODS

The NOAA Estuarine Living Marine Resources Program (ELMR) has spent several years assembling an extensive inventory of the relative abundance and distribution of 44 important finfish and macroinvertebrates in Gulf estuaries, with considerable effort spent on documenting ontogenetic shifts in salinity habitat associations (Nelson 1992; Patillo et al. in preparation). A list of the 44 ELMR species is provided in Table 1. This biological data set, coupled with estuarine salinity information, provided the foundation upon which the BSI was developed for selected Gulf species.

Salinity Zonation

A framework of salinity zonation was developed based on species response to, and partitioning of, the estuarine salinity gradient in nature, and this analysis was a prerequisite in developing the BSI. Biologically-based salinity zone boundaries were defined based on

TABLE 1

List of 44 ELMR species for Gulf of Mexico estuaries

Common name	Scientific name
bay scallop	*Argopecten irradians*
Eastern oyster	*Crassostrea virginica*
Atlantic rangia	*Rangia cuneata*
quahogs	*Mercenaria species*
bay squid	*Lolliguncula brevis*
brown shrimp	*Penaeus aztecus*
pink shrimp	*Penaeus duorarum*
white shrimp	*Penaeus setiferus*
daggerblade grass shrimp	*Palaemonetes pugio*
spiny lobster	*Panulirus argus*
blue crab	*Callinectes sapidus*
Gulf stone crab	*Menippe adina*
stone crab	*Menippe mercenaria*
bull shark	*Carcharhinus leucas*
tarpon	*Megalops atlanticus*
Alabama shad	*Alosa alabamae*
Gulf menhaden	*Brevoortia patronus*
yellowfin menhaden	*Brevoortia smithi*
gizzard shad	*Dorosoma cepedianum*
bay anchovy	*Anchoa mitchilli*
hardhead catfish	*Arius felis*
sheepshead minnow	*Cyprinodon variegatus*
Gulf killifish	*Fundulus grandis*
silversides	*Menidia spp.*
snook	*Centropomus undecimalis*
bluefish	*Pomatomus saltatrix*
blue runner	*Caranx crysos*
crevalle jack	*Caranx hippos*
Florida pompano	*Trachinotus carolinus*
gray snapper	*Lutjanus griseus*
sheepshead	*Archosargus probatocephalus*
pinfish	*Lagodon rhomboides*
silver perch	*Bairdiella chrysoura*
sand seatrout	*Cynoscion arenarius*
spotted seatrout	*Cynoscion nebulosus*
spot	*Leiostomus xanthurus*
Atlantic croaker	*Micropogonias ndulatus*
black drum	*Pogonias cromis*
red drum	*Sciaenops ocellatus*
striped mullet	*Mugil cephalus*
code goby	*Gobiosoma robustum*
spanish mackerel	*Scomberomorus maculatus*
Gulf flounder	*Paralichthys albigutta*
Southern flounder	*Paralichthys lethostigma*

Principal Components Analysis (PCA). This method of defining salinity zones was first introduced by Bulger et al. (1993) for Atlantic estuaries, and Lowery et al. (in preparation) replicated these procedures for the Gulf of Mexico. PCA is the preferred type of factor analysis when the goal is to reduce a large number of variables (e.g., 1 ppt salinity increments) to a smaller set of components, or salinity zones (Tabachnik and Fidell 1989). Correlations between a salinity increment and principal component (varimax rotated component loadings) greater than 0.5 and/or less than -0.5 were assigned to a specific salinity zone (component). The objective of this analysis was to develop a method for defining biologically-relevant estuarine salinity zonations which could be used to assess the potential impacts that changes in salinity may have on species distribution patterns in the northern Gulf of Mexico. An analysis by Lowery et al. (in preparation) was conducted on field-based salinity ranges and co-occurrences of 161 fish species collected from Mississippi Sound, in Mississippi and Mobile Bay and Weeks Bay in Alabama. Data for the analysis were obtained from the Alabama Coastal Area Board (ACAB) baseline survey of Mobile Bay and Mississippi Sound trawl survey from 1982-1991 (Bill Hosking, personal communication), Gulf Coast Research Laboratory (GCRL) Mississippi trawl survey data from 1982-1994 (James Warren, personal communication and Weeks Bay National Estuarine Research Reserve seine survey data from 1988-1989 (Rick Wallace, personal communication). Field collections were cross referenced with station salinity data to provide a measure of association.

In the analysis by Lowery et al. (in preparation), the original 34 salinity increments were considered as 34 separate variables which collectively explained 100% of the variance in the original data matrix. Application of PCA to the salinity range data indicated that the underlying structure of species distributions along the salinity gradient in Gulf estuaries could be represented by five principal components, which collectively explained 91% of the variance in the original data. Each component had a suite of salinity variables with which it was most highly associated, and each principal component corresponded to a unique biologically-based salinity zone. Plots of varimax rotated loadings (VRL) of the five principal components relative to the original 34 variables (salinity increments) are displayed in Figure 1. Rotation of principal axes is commonly used to maximize the variance explained along each axis and to improve the interpretability and scientific utility of the results without changing the underlying

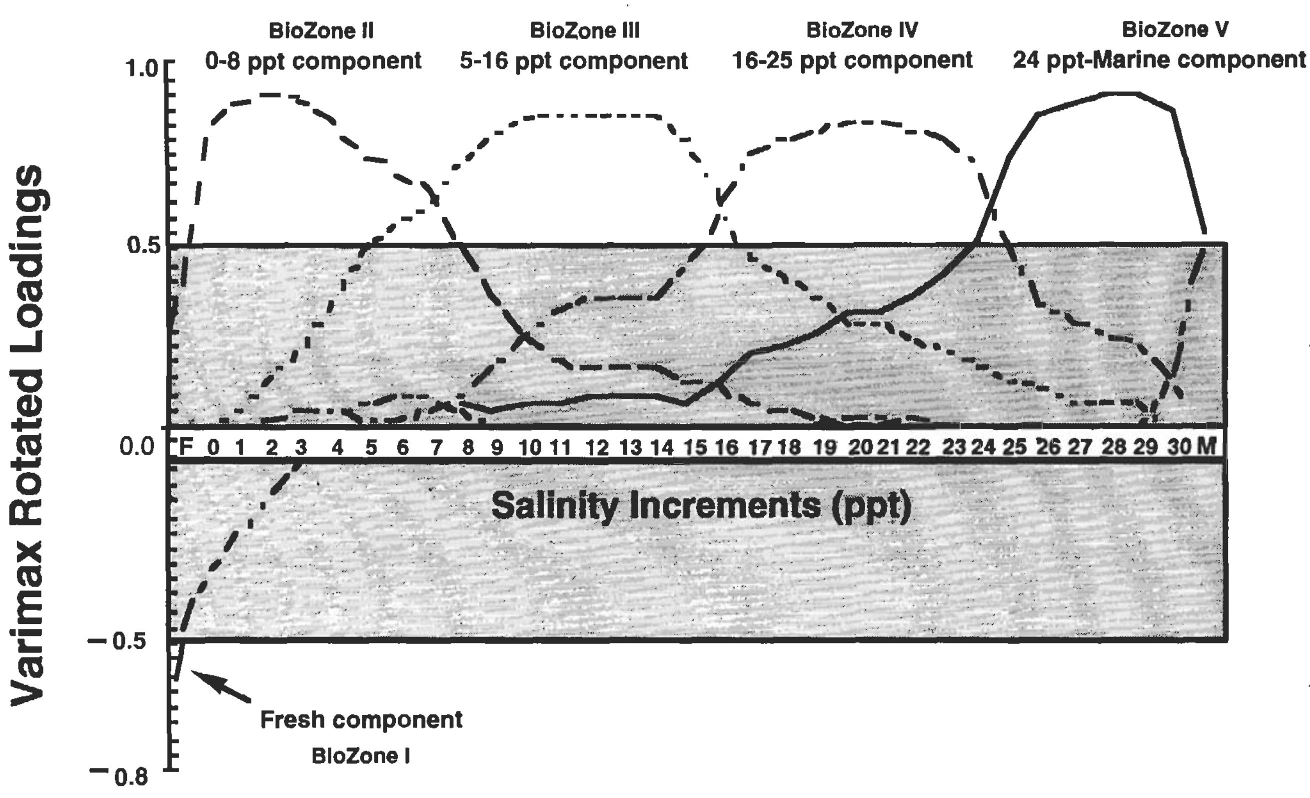


Figure 1. Five biologically-based salinity zones corresponding to principal components (Lowery et al. in preparation)

mathematical properties (Bulger et al. 1993). Component 1 (fresh) consists of waters which typically are inhabited by stenohaline freshwater fishes in areas with little or no tidal influence. Salinity ranges for the remaining overlapping components inhabited by estuarine species are component 2 (0-8ppt), component 3 (5-16ppt), component 4 (16-25), and component 5 (24-marine), which is inhabited primarily by marine species.

Species Abundance and Distribution

Very few states have fisheries monitoring programs with consistent sampling protocols and schedules, and no two states have identical monitoring programs. To allow inter-estuarine BSI comparisons, it was necessary to devise a method to standardize estuarine fish distribution and abundance information across Gulf of Mexico estuaries. This task was undertaken by the NOAA ELMR Program (Nelson 1992). ELMR categorical spatial and temporal distribution and relative abundance data for Gulf estuaries were compiled from data sets, survey reports, and scientific literature on species ecology, behavior, and/or physiology (Monaco 1995). To filter out environmental variability (wet year, cold year, etc.), biological variability (strong vs. weak recruitment year) and anthropogenically induced variation (extreme fishing mortality, sampling error, etc.), information was synthesized to best define current relative abundance and distribution patterns for 44 Gulf species. These abundance estimates were verified through an extensive peer-review process utilizing the knowledge and field experience of Gulf Coast fisheries scientists, managers, and biologists (Nelson 1992).

ELMR relative abundance categories of highly abundant (5), abundant (4), common (3), rare (2), no information (1), and not present (0) were intended to simulate categories often used and regularly encountered by fisheries biologists. This consistent format is readily understandable by fisheries scientists in the field, resource managers, and academic biologists. An ordinal relative abundance scheme of this type is typically adopted in the field. The abundance of the life-stage of a species was ranked relative to that of the same life-stage of other similar species which, were defined as those species characterized by similar life-history strategies and gear susceptibilities. Catch data for these species were then transformed into categorical ranks using an order of magnitude break.

Species salinity range/tolerance data compiled by the ELMR Program were used to assign 44 Gulf fish and invertebrate relative abundance ranks to the PCA derived biologically-based salinity zones (Patillo et al. in prep). ELMR species spatial and temporal distributions and their monthly relative abundance ranks are organized by three estuarine salinity zones: tidal fresh zone (0-0.5 ppt), mixing zone (0.5-25 ppt), and seawater zone (>25ppt)(Nelson 1992). These salinity zones have been delineated in the NOAA National Estuarine Inventory (NEI) (NOAA 1989). In addition, the ELMR habitat association data also is organized by the Venice system salinity zonation scheme: limnetic (0-0.5 ppt), oligohaline (0.5-5 ppt), mesohaline (5-18 ppt), polyhaline (18-30 ppt), and euhaline (>30 ppt)(Anonymous 1959; NOAA 1989).

Biophysical Salinity Zone Integration

The NEI tidal fresh zone (0-0.5 ppt) was considered equivalent to the fresh zone (0.0 ppt) of the biologically-based zonation scheme. Similarly, the 24-marine zone and the NEI seawater zone (>25 ppt) were considered equivalent (Figure 2). Thus, species relative abundance data were directly transferred to the fresh and marine biologically-based zones. NEI mixing zone relative abundance data

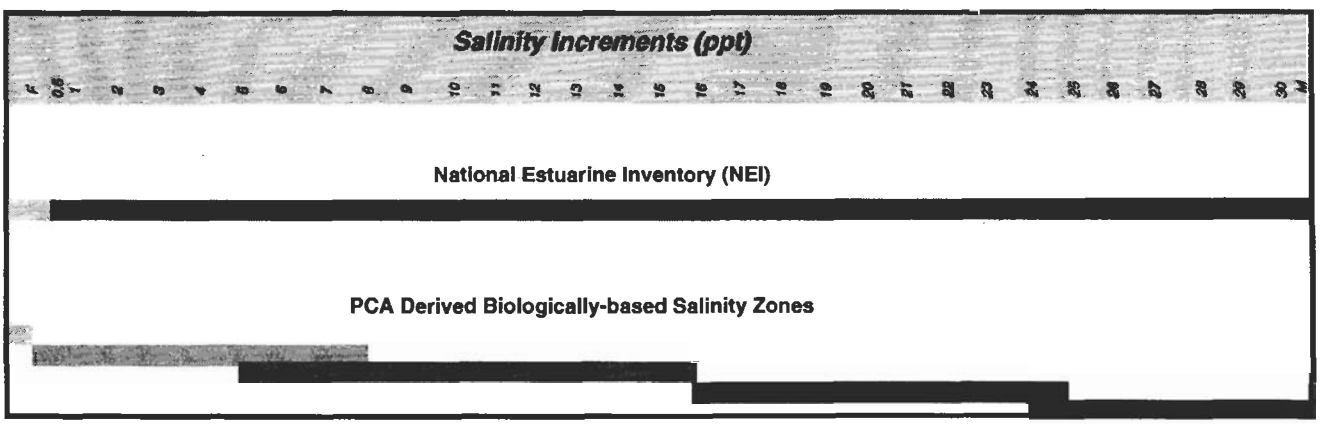


Figure 2. Biologically-based salinity zonation schemes derived from the National Estuarine Inventory (NEI) and Principal Components Analysis (PCA).

encompassed three biologically-based salinity zones (0-8 ppt, 5-16 ppt and 16-25 ppt zones) and were realigned by transferring NEI mixing zone species relative abundance estimates to biological zones based on species habitat associations with the oligohaline, mesohaline and/or polyhaline zones of the Venice system (Figure 3).

ELMR spatial, temporal, and relative abundance data provided information defining species monthly habitat utilization patterns across Gulf of Mexico estuaries. To assess how species distributions may be impacted by increasing or decreasing estuarine salinity habitat, it was necessary to calculate the spatial extent of each salinity zone in each of the 22 estuaries. Relative salinity zone surface areas (km^2) for 5 ppt isohalines in Gulf estuaries were provided by the NOAA Physical Environments Characterization Branch (PECB) (Orlando et al. 1993). To maximize BSI sensitivity to a freshet, isohaline surface areas were calculated for 20 year averaged "normal" three month low-flow/high-salinity periods. Moreover, this high-salinity period generally represents summer months during which fish diversity is usually at its maximum in Gulf estuaries (Nelson 1992). The 5 ppt isohaline surface areas were then re-aligned to fit biologically-based salinity zones to provide an estimate of salinity zone areas (Table 2). The following alignments were made: BioZone I <0.5 ppt (corresponding to the fresh zone), BioZone II >0.5-8 ppt (corresponding to 0-8 ppt zone), BioZone III 5-15 ppt (corresponding to 5-16 ppt zone), BioZone IV 15-25 ppt (corresponding to 16-25 ppt zone), and BioZone V 25-35 ppt (corresponding to 25-marine zone). To calculate the 0-8 ppt biologically-based zone area, we multiplied the 5-10 ppt zone area by 0.6 (3 of 5 ppt's from the 5-10 ppt zone) and added it to the >0.5-5 ppt zone area to achieve an estimated area proportionate to a >0.5-8 ppt zone. This

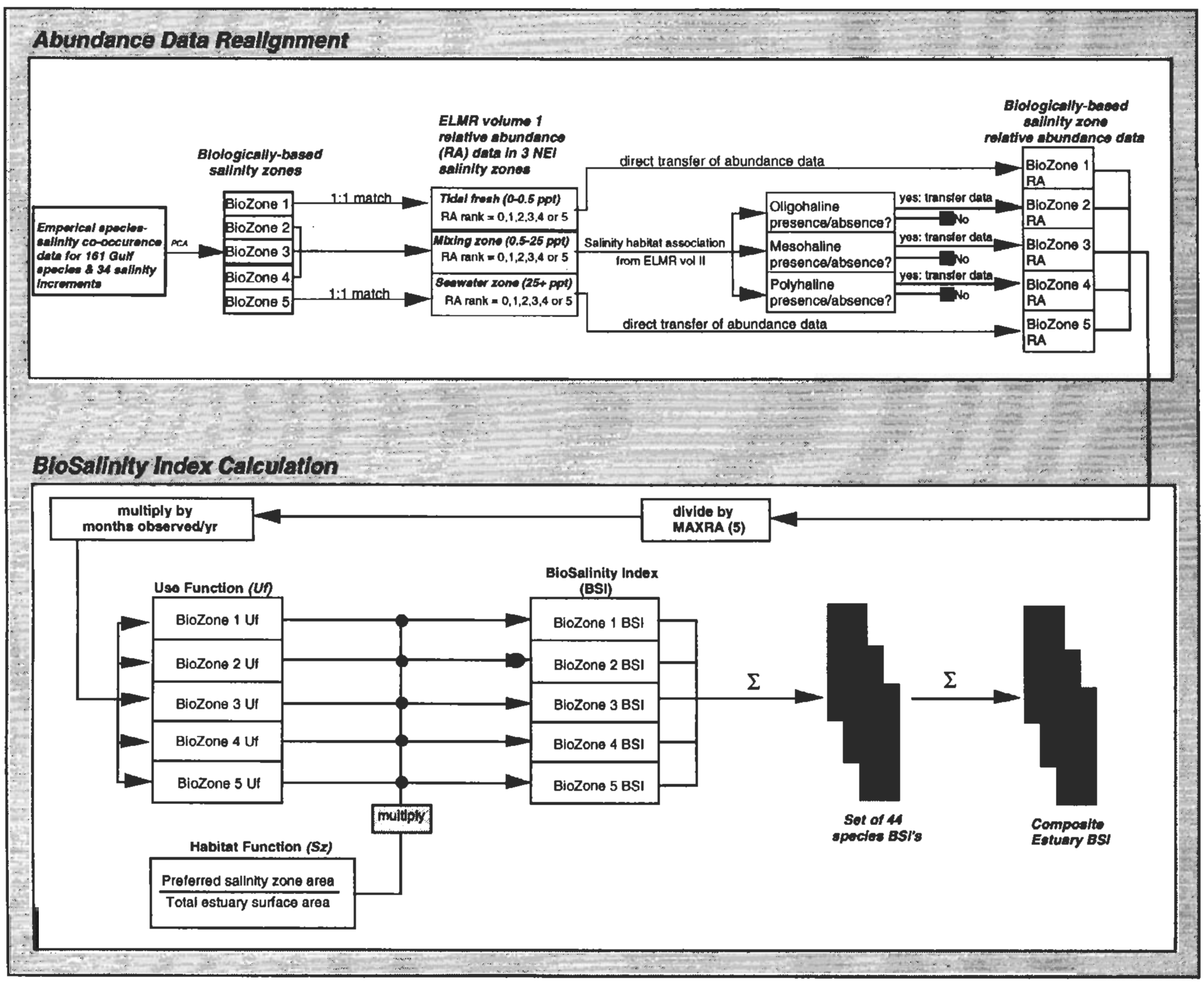


Figure 3. Salinity realignment and BSI calculation framework.

TABLE 2

Biologically-based salinity zone surface areas (km^2) during high salinity/low flow periods for Gulf of Mexico estuaries.

Estuary	BioZone I	BioZone II	BioZone III	BioZone IV	BioZone V	Total Area
Tampa Bay	000.00	000.00	000.00	179.43	165.83	*345.26*
Suwannee River	002.81	000.56	003.25	011.18	050.06	*067.86*
Apalachee Bay	000.00	003.86	007.81	016.19	139.89	*167.75*
Apalachicola Bay	000.00	015.17	030.15	071.01	115.65	*231.98*
Choctawhatchee Bay	000.00	000.00	000.68	112.33	016.24	*129.25*
Pensacola Bay	000.00	000.00	004.72	058.85	081.28	*144.85*
Perdido Bay	000.00	000.23	007.12	023.42	007.80	*038.57*
Mobile Bay	000.00	021.74	087.21	176.38	144.44	*429.77*
Mississippi Sound	000.00	002.83	089.63	447.31	330.37	*870.14*
Lake Pontchartrain	000.00	663.53	194.22	000.00	000.00	*857.75*
Breton/Chandeleur Sounds	000.00	000.00	046.73	381.99	078.59	*507.31*
Barataria Bay	086.29	052.40	054.60	149.97	000.00	*343.26*
Terrebonne/Timbalier Bays	000.00	000.00	027.04	325.76	134.71	*487.51*
Lake Calcasieu	000.00	000.00	000.00	009.12	090.20	*099.32*
Sabine Lake	000.00	033.58	094.22	008.09	000.00	*135.89*
Galveston Bay	000.00	024.37	108.96	271.09	182.85	*587.27*
Brazos River	000.00	000.00	000.53	001.75	000.00	*002.28*
Matagorda Bay	000.11	008.57	046.24	272.79	110.36	*438.07*
San Antonio Bay	003.54	018.22	045.24	132.64	026.73	*226.37*
Aransas Bay	000.00	000.00	032.96	099.46	070.39	*202.81*
Corpus Christi Bay	000.00	000.00	000.00	012.50	208.04	*220.54*
Laguna Madre	000.00	000.00	000.00	000.00	506.13	*506.13*

assumes that 1 ppt increments within the 5-10 ppt isohaline are isometric. Table 2 depicts biologically-based salinity zone surface areas for Gulf estuaries included in this study. Figure 3 depicts the pathways used to realign species abundance and distribution data to the biologically-based salinity zones which were subsequently used to calculate BSI values.

BSI Components

Development of this assessment capability was accomplished by integrating empirical species-salinity habitat association data, estuary-specific monthly relative abundance data for Gulf species, and the areal extent of species' preferred salinity zones for the species. This integration permitted simultaneous assessments of species habitat utilization in time and space, resulting in a synoptic measure of habitat utilization termed the Use Function (Uf). The amount of preferred salinity habitat available (Habitat Function) (km^2) to each species, coupled with the Use Function, provided the components necessary to calculate the BSI, where RA_{jmax} is the estuary/species specific observed maximum abundance rank which ranges from 0-5. By including U_{fmax} in the equation, we arrive at a product between 0 and 1 which fits the conventional protocol of many biological indices (Monaco 1995).

$$BSI = (U_f / U_{fmax})(Sz).$$

where

$$U_f = (\text{months observed} \cdot yr^{-1})(RA_{jmax}/5)$$

and

$$Sz = (\text{area of species' preferred habitat / total estuary area})$$

Species on the low end of the BSI continuum may be highly sensitive to changes in freshwater inflow, and those approaching 1.0 are more tolerant to such changes. Individual salinity zone BSI values were calculated for each species and summed to achieve an estuary/species-specific BSI value for the entire system (Figure 3).

RESULTS

Estuary/Species Level

The BSI is most reliable at the species level. Results of individual species-level BSI values for each estuary are summarized in Figures 4 a and 4 b for adults and juveniles, respectively. These matrices provide a quick and objective means for inter-estuarine comparisons of species sensitivity to changes in freshwater inflow. Because estuarine species often exhibit an ontogenetic shift in habitat requirements and/or preferences, adult and juvenile life stages were treated independently. Analysis of variance (ANOVA)

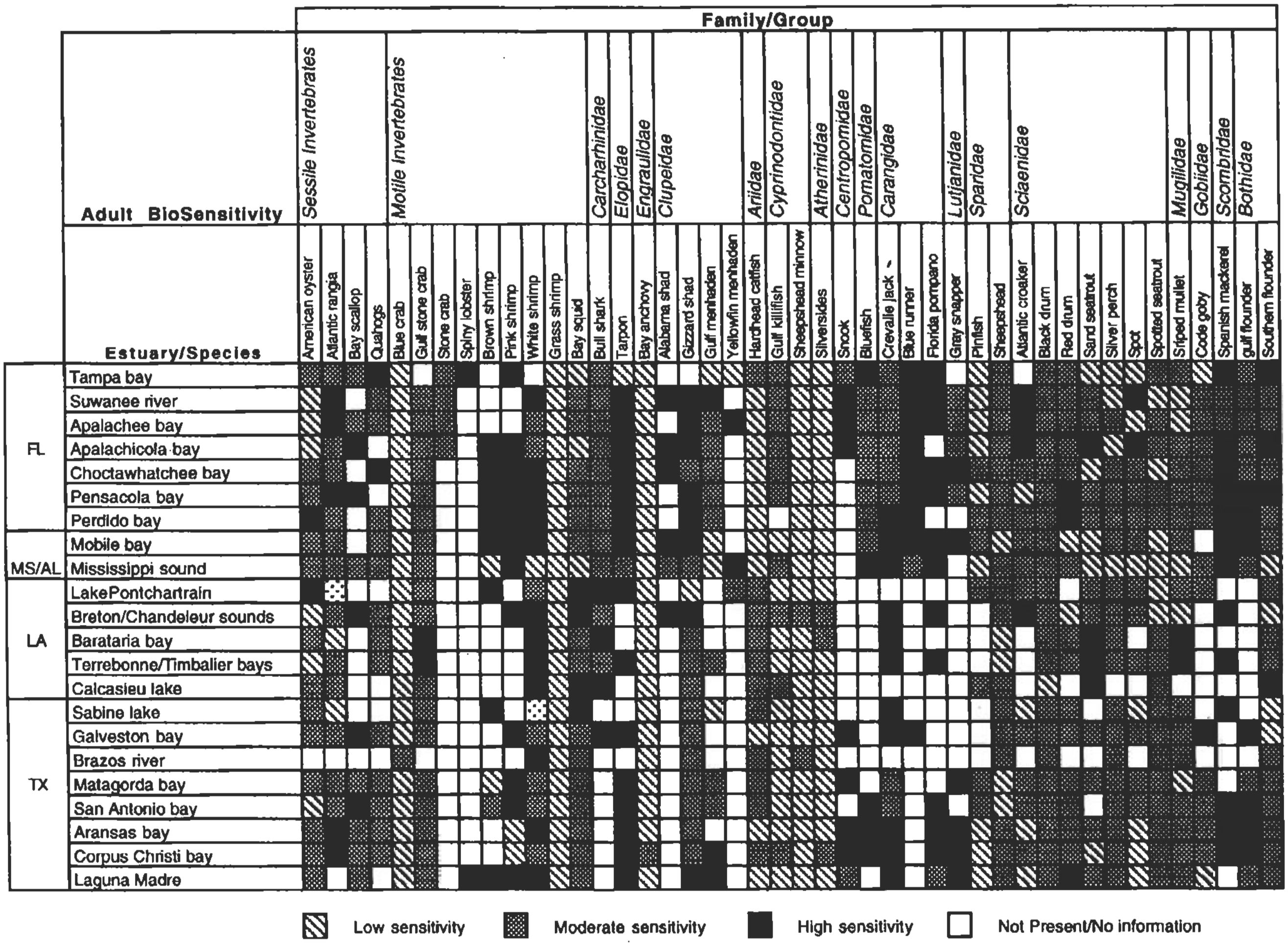


Figure 4a. Adult estuary-specific categorical BSI ranks (high sensitivity ≤ 0.33, moderate sensitivity = 0.34 - 0.66, and low sensitivity ≥ 0.67).

indicated a significant difference in mean BSI values between these two life stages (P<0.001), with adults consistently exhibiting lower BSI values (higher sensitivity) than their juvenile counterparts. Species/estuary-specific BSI values were assigned to categorical ranks based on their relative sensitivity to a significant change in salinity. Categorical rank boundaries were chosen to partition the results into thirds. The boundaries are defined as: high sensitivity (≤0.33), moderate sensitivity (0.34 - 0.66), and low sensitivity (≥ 0.67). These limits do not represent a critical value which is statistically unique from the other. Rather they provide a reasonable means of categorizing salinity sensitivity.

A total of 968 possible species/estuary combinations exist for each life history stage, of which 18.8% (N=182) for adults and 16.6% (N=151) for juveniles exhibited a high potential sensitivity to changes in freshwater inflow. Thirty-six percent (N=348) of adults exhibited moderate sensitivity and 20.2% (N=196) low sensitivity, while 38.5% (N=372) and 28% (N=271) of juveniles exhibited moderate and low BSI values, respectively. The remaining cases were either not present, or reliable sources of information pertaining to their abundance and distribution were not found.

Individual BSI values for all estuary/species/life stage combinations were then broken down into their two components (use function and habitat function) to isolate the component which exacted the greatest influence on individual BSI values. These two components are plotted in Figure 5 for all estuary/species/life stage cases (N=1936). Those species (cases) which are least sensitive to changes in salinity structure reside in quadrant I of Figure 5. These are species which are generally found in high numbers throughout the year and tolerate a wide range in salinities. Cases residing in this quadrant are classic estuarine species such as Engraulids (anchovies) and Atherinids (silversides). The majority (60%) of Gulf estuary/species/life history stage combinations reside in quadrant III. These are cases whose species have ample preferred habitat in their respective estuaries. However, their usage of, and distribution in that habitat might be limited by other physical and biological constraints (i.e., seasonality and predation risk, etc.). Cases which fall in quadrant III also

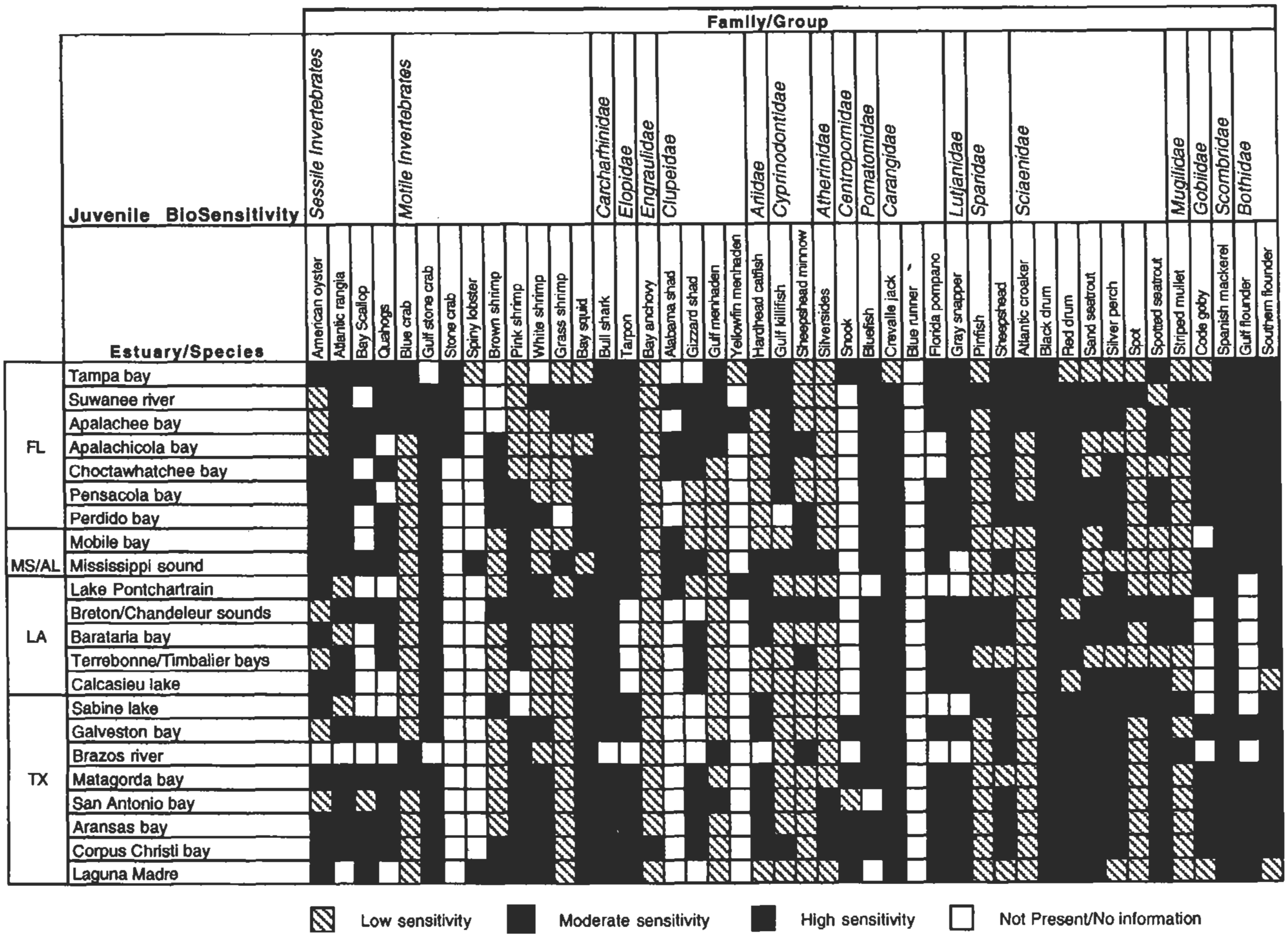


Figure 4b. Juvenile estuary-specific categorical BSI ranks (high sensitivity ≤ 0.33, moderate sensitivity = 0.34 - 0.66, and low sensitivity ≥ 0.67).

may be species whose salinity tolerance may be as broad as those residing in quadrant I, but whose relative abundance is lower.

Species residing in quadrants II and IV are those that may be most susceptible to change via altered salinity structure. As such, these species may be amenable to management via freshwater inflow regulation into their respective estuarine systems. Atlantic rangia (*R. cuneata*) is unique to quadrant II, while a number of species reside in quadrant IV. Species in quadrant IV represent species which can be placed into four major taxonomic groupings. These include sessile invertebrates (e.g., Eastern oyster and scallops), Clupeids with an affinity for fresher waters (e.g., Alabama and gizzard shads), predominately marine species (e.g., blue runner and Gulf flounder), and motile invertebrates which are generally restricted to Floridean waters (e.g., spiny lobster). It is important to note that many of the species in quadrant IV reside there because of extremely low abundances relative to other more abundant Gulf estuarine species. Nevertheless, the composite BSI values and component "quad plots" provide managers with simple and objective tools to assess potential impacts of salinity habitat alterations on fishes and invertebrates.

Composite Estuary BSI

Species BSI values can be averaged for an estuary to provide a composite estuary-level BSI value (Figure 3). This composite value provides coastal resource managers with a vehicle for regional strategic assessments of differences in biological sensitivity to salinity changes across estuaries. The upper histogram in Figure 6 represents estuarine composite BSI values based on the 44 ELMR species and enables comparative analysis of estuaries across the Gulf. For example, these results indicate that the average Mississippi Sound species assemblage (std.dev≈ 0.2) is less sensitive to salinity changes than the Perdido Bay assemblage. This may be attributed to either a difference in community structure or to a difference in the availability and homogeneity of preferred salinity habitat for each of the representative species. A change in either of these factors has the potential to significantly

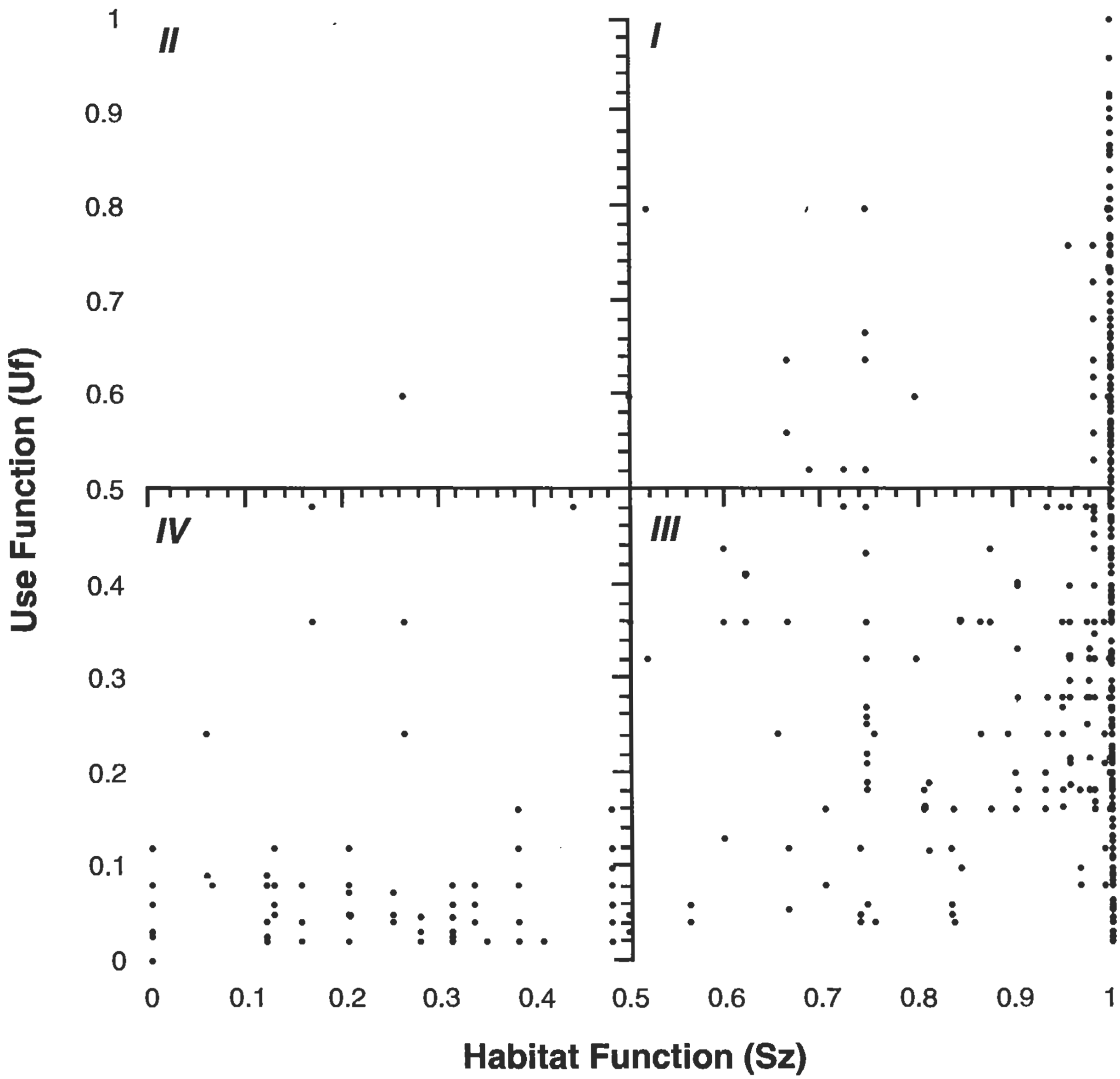
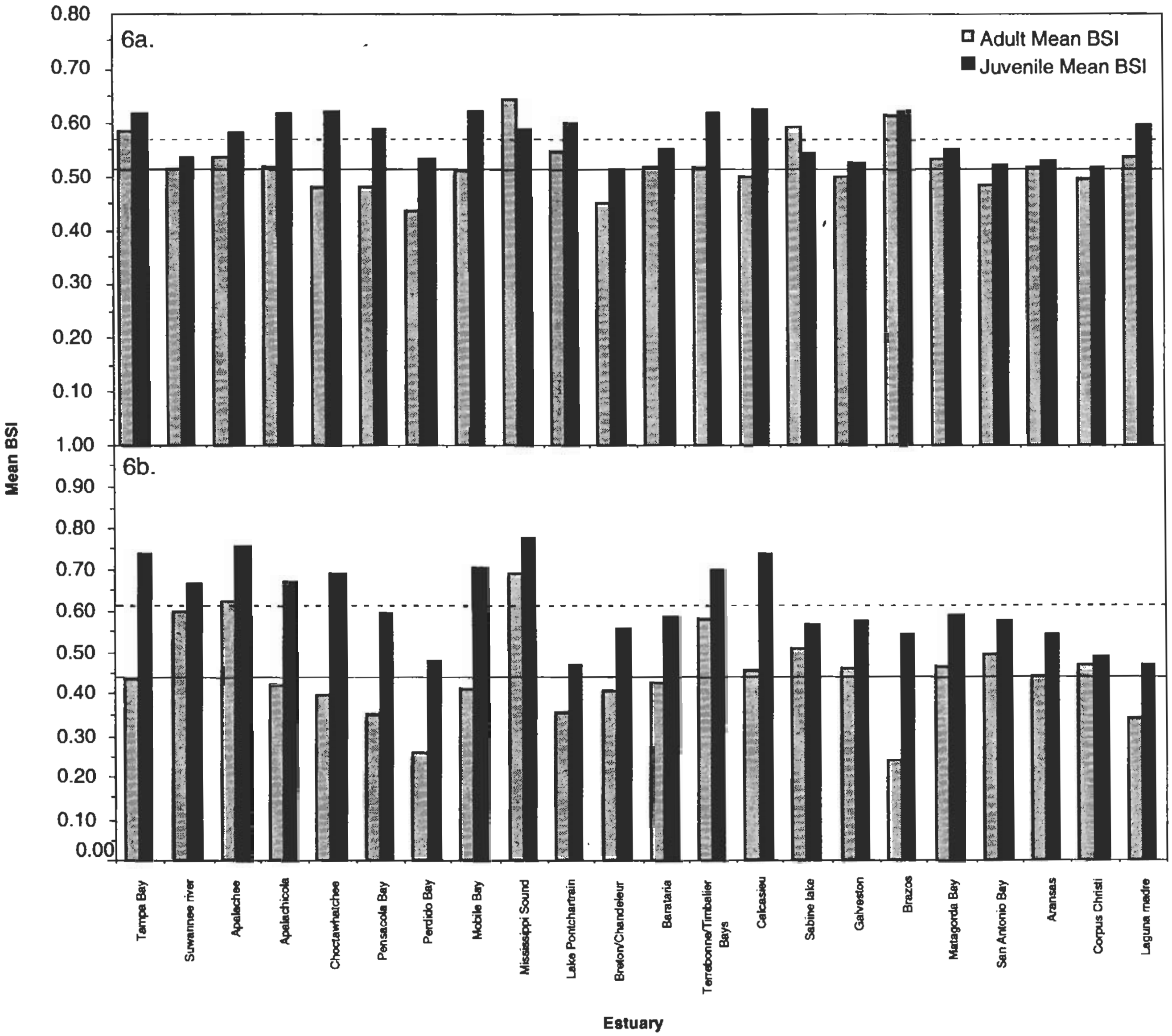


Figure 5. Quadrant plot of BSI component (use function and habitat function) values for all estuary/species/life history stage cases in Gulf of Mexico estuaries.

alter estuary composite BSI values. For this reason, natural resource managers must proceed with caution when interpreting composite BSI values. In an effort to evaluate economically important species that represent the geographical extent of the northern Gulf of Mexico, participants in the EPA freshwater inflow workshop identified five "indicator" species to analyze (NOAA 1995). The mean BSI values for the five species (brown shrimp, pink shrimp, white shrimp, American oyster, and spotted seatrout) are shown in the upper histogram of Figure 6. Mean BSI histograms were markedly different between the five and 44-species assemblages, with the former exhibiting greater variability across estuaries (Figure 6). However, the indicator species revealed similar trends in salinity sensitivity across Gulf estuaries when compared to the 44-species assemblage results (SEA 1995). These results suggest that factors other than salinity may have a greater influence over the abundance and distribution of the 44 ELMR species. The relatively low proportion of species exhibiting high sensitivity to changing freshwater inflow can be attributed in part to the fact that most of the 44 Gulf species in this study are estuarine dependent and are characterized by a variety of physiological and behavioral adaptations for life in estuarine waters. The degree of change in community structure would, in large part, be dictated by which salinity zones were affected, the magnitude of that change, and the initial composition of the estuarine assemblage. Estuaries which are



Figures 6a. Adult and juvenile mean BSI values for 44 ELMR species assemblages. Dashed line represents the assemblage-wide juvenile mean BSI. Full line represents assemblage-wide adult mean BSI. 6b. Adult and juvenile mean BSI values for five indicator species assemblages. Dashed line represents the assemblage-wide juvenile mean BSI. Full line represents assemblage-wide adult mean BSI.

frequented by marine and/or freshwater species would undoubtedly exhibit lower composite BSI ranks than the average estuary. Increasing the number of species included in this analysis would provide more insight into the sensitivity of the BSI to the presence of such species.

DISCUSSION

Because the BSI incorporates individual species habitat preferences in time and space, those species which are thought of as "classically estuarine" exhibit highest BSI values. These species generally exhibit euryhalinity and often are one of the more numerically dominant species in a system. Moreover, elevated BSI values for these species may be due to the fact that these species spend the majority, if not all, of their lives, in estuarine waters. In addition, although the BSI does not include measures of ecological interaction (i.e., predator-prey oscillations, recruitment, competition, etc.), it is assumed that this type of information is builtin to the index by incorporating empirical monthly species relative abundance and distribution data for Gulf estuaries. We assume these data represent ecological interactions and their influence on the abundance and distribution of Gulf species. Management of these species by freshwater inflow regulation should be complemented by other measures of ecological interaction and improvement to habitat. Depending on the management objectives, use and interpretation of the index can differ when comparing species-level BSI relative to assemblage-level BSI.

Our ultimate intent in developing the BioSalinity Index was to establish a quantitative method to rank Gulf estuaries according to their relative biological sensitivity to changes in freshwater inflow. In this study, sensitivity was defined as a the potential for species and subsequent assemblages to exhibit a change in total available habitat utilization in response to significant alterations in estuarine salinity structure. For example, if a species exclusively uses the freshwater zone within an estuary, its population may exhibit a decline in reproductive or competitive fitness if this zone decreased in size. As coastal zone managers learn more about local and regional estuarine salinity character and dynamics, the BSI will provide a valuable, objective tool to assess and predict potential changes in species populations and estuarine community structure resulting from a measurable change in salinity structure.

Acknowledgments

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