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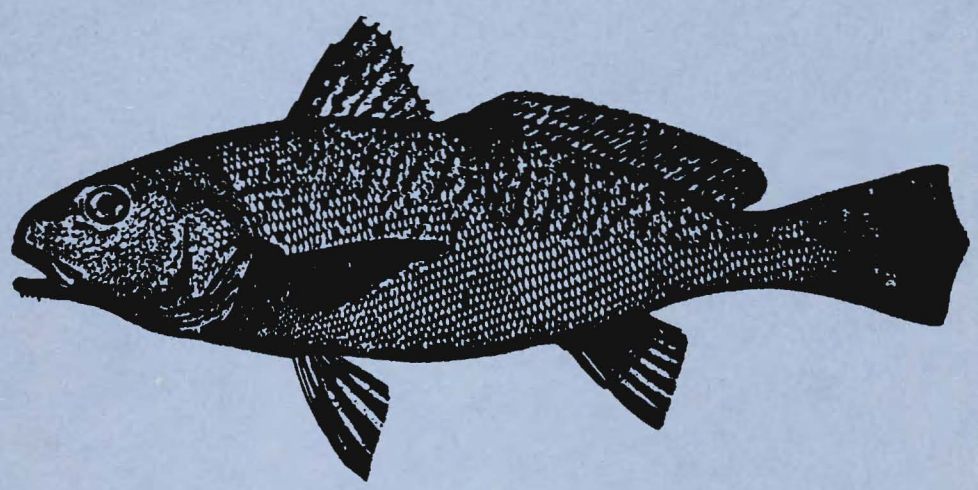
HABITAT SUITABILITY INDEX MODELS: JUVENILE ATLANTIC CROAKER



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The Biological Services Program was established within the U.S. Fish and Wildlife Service to supply scientific information and methodologies on key environmental issues that impact fish and wildlife resources and their supporting ecosystems. The mission of the program is as follows:

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- To gather, analyze, and present information that will aid decisionmakers in the identification and resolution of problems associated with major changes in land and water use.

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The Biological Services Program consists of the Office of Biological Services in Washington, D.C., which is responsible for overall planning and management; National Teams, which provide the Program's central scientific and technical expertise and arrange for contracting biological services studies with states, universities, consulting firms, and others; Regional Staffs, who provide a link to problems at the operating level; and staffs at certain Fish and Wildlife Service research facilities, who conduct in-house research studies.

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PREFACE

The habitat use information and habitat suitability index (HSI) model in this report on juvenile Atlantic croaker is intended for use in impact assessment and habitat management. The model was developed from a review and synthesis of existing information and is scaled to produce an index of habitat suitability between 0 (unsuitable habitat) and 1 (optimally suitable habitat). Assumptions used to transform habitat use information into the HSI model, and guidelines for model applications, including methods for measuring model variables, are described.

This model is a hypothesis of species-habitat relationships, not a statement of proven cause and effect relationships. The model has not been field-tested, but it has been applied to four hypothetical data sets which are presented and discussed. For this reason, the U.S. Fish and Wildlife Service encourages model users to convey comments and suggestions that may help increase the utility and effectiveness of this habitat-based approach to fish and wildlife management. Please send any comments or suggestions you may have on the croaker HSI model to:

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CONTENTS

	Page
PREFACE	iii
ACKNOWLEDGMENTS	vi
HABITAT USE INFORMATION	1
Food	1
Reproduction	1
Specific Habitat Requirements	2
HABITAT SUITABILITY INDEX (HSI) MODEL	4
Model Applicability	4
Model Description - Estuarine	6
Suitability Index (SI) Graphs for Model Variables	9
Component Index Equations	14
HSI Determination	15
Field Use of the Model	15
Interpreting Model Outputs	17
REFERENCES	19

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Development of the habitat suitability index model and narrative for juvenile Atlantic croaker was monitored, expertly reviewed, and constructively criticized by Dr. Michael Weinstein, Virginia Commonwealth University, Richmond, Virginia; Mr. John Lunz, Environmental Laboratory, U.S. Army Corps of Engineers, Vicksburg, Mississippi; and Dr. Brenda Norcross, Virginia Institute of Marine Science, Gloucester Point, Virginia. Thorough evaluations of model structure and functional relationships were provided by personnel of the U.S. Fish and Wildlife Service's National Coastal Ecosystems Team and Western Energy and Land Use Team. Model and supportive narrative reviews were also provided by representatives of the National Marine Fisheries Service and by Regional personnel of the U.S. Fish and Wildlife Service. Finally, funding for model development and publication was provided by the U.S. Fish and Wildlife Service.

ATLANTIC CROAKER (*Micropogonias undulatus*)

HABITAT USE INFORMATION

The Atlantic croaker is an important commercial and recreational species. Although it has a wide geographic range from the New England States to South America, the croaker is basically a southern species important in the Gulf of Mexico and South Atlantic Bight. During climatically warmer periods, such as the 1930's and 1940's when it was fished commercially in New York, the croaker extended its range north. Now Virginia or Delaware is considered to be the northern extent of the range of the species. The Atlantic croaker spawns in coastal marine waters and uses estuaries as nursery and feeding grounds.

Food

The croaker preys upon a variety of organisms (Darnell 1961; Parker 1971; Diener et al. 1974; Stickney et al. 1975; Chao and Musick 1977; Overstreet and Heard 1978; Etzold and Christmas 1979; Kobylinski and Sheridan 1979; Sheridan 1979; Weinstein 1979; Schwartz 1980). Mysids, decapods, amphipods, copepods and polychaetes form the bulk of the croaker's diet. At times, mollusks, finfishes, and detritus are also consumed in large quantities.

Copepods (calanoid and harpacticoid) are the major dietary component for larval and juvenile croaker. As fish grow into young adults (100 to 150 mm standard length; SL), their diet includes more fish. The reported consumption of detritus by all sizes of croaker may be incidental to the diet and of little nutritive value. Stickney and Shumway (1974) found croaker to lack the ability to digest cellulose. Detritus in the gut of croaker, therefore, is most likely a byproduct of bottom feeding over unconsolidated mud of high organic content.

Reproduction

Croaker spawn in the fall in marine waters. Spawning grounds are not clearly defined and can range from tidal passes and the mouths of estuaries to wide areas of the Continental Shelf to depths of at least 54 m (177 ft) (Pearson 1929; Hildebrand and Cable 1930; Hoese 1965; Fruge and Truesdale 1978; Johnson 1978; Etzold and Christmas 1979). Eggs are pelagic, and upon hatching, the larvae and postlarvae move into estuaries. Actual mechanisms for larval transport into the estuarine nursery grounds are unclear and may be a combination of both passive current transport (Weinstein et al. 1980b; Norcross and Austin 1981) and active swimming (Pearson 1929).

At first spawning, croaker vary in age from 1 to 4 years. Gulf of Mexico populations apparently spawn after 1 or 2 years of life. Atlantic populations

in the southern part of the range spawn perhaps after 1 year, but croaker in the northern part of the range may not spawn until they are 3 to 4 years of age (Herke 1971).

Specific Habitat Requirements

The juvenile is the dominant croaker life stage found in estuarine habitats and is the only life stage considered in this HSI model. Adults are tolerant of a broader range of environmental conditions than other life stages, and no specific habitat requirements can be identified at this time (Bearden 1964; Johnson 1978).

Once recruited from nearshore marine waters, in the fall and winter, larvae (8 to 15 mm SL) move up the estuary to areas of brackish water (Bearden 1964), where the transition to juvenile occurs at a size range of 15 to 25 mm SL. Juveniles then take up residence in the nursery areas (Yakupzack 1976). Oligohaline (0.5 to 5 parts per thousand; ppt) and middle mesohaline (5 to 12 ppt) salinities are preferred (Bearden 1964; Parker 1971; Kobylinski and Sheridan 1979; Weinstein 1979; Weinstein et al. 1980a). Juveniles are also common in tidal riverine habitats (Raney and Massmann 1953). With growth, juvenile croaker gradually move down the estuary to higher salinity waters. After about 1 year most of the previous fall's recruits, cueing on a combination of environmental factors, leave the estuary and return to nearshore marine waters (Clairain 1974). Older croaker (2+ years), after having entered the estuaries in the spring when temperatures rise to about 16°C (61°F) (Johnson 1978), also migrate to coastal waters with declining temperatures in the fall (Chao and Musick 1977; Johnson 1978; Etzold and Christmas 1979).

Juveniles have been reported to use marshes (Hildebrand and Cable 1930; Hansen 1964; Parker 1971; Sheridan 1979) and tidal creeks (Parker 1971; Arnoldi et al. 1974; Chao and Musick 1977; Weinstein 1979). The best combination of habitats seems to be marsh interspersed with tidal creeks. Expanses of marsh grasses undissected by creeks and rivulets are not considered to be good habitat for croaker. The attraction of juvenile croaker to marsh-associated tidal creeks is understandable if one considers their preference for small food items, particularly copepods. Copepods and zooplankton in general are abundant in marshes and tidal creeks, particularly in low salinity marshes (Pfannkuche et al. 1975) and deep open water (Williams et al. 1968). In addition to providing a food source, these small creeks also afford protection from predators.

The estuarine nursery areas for Atlantic and Gulf of Mexico croaker populations generally are different. Gulf of Mexico estuarine areas are shallow (generally less than 1.8 m or 6 ft) and have extensive marsh systems associated with them. In addition, these areas are not as tidally dominated as most of those on the Atlantic coast, and the accessibility of marshes to croaker is more consistent. The prime croaker nurseries on the Gulf of Mexico coast are, therefore, the marshes (Herke 1971; Yakupzack 1976). On the Atlantic coast, with typically deeper estuarine areas, much less extensive marshes, and more tidal influence, the prime croaker nurseries are deep tidal creeks (Weinstein 1979; Weinstein et al. 1980b). There are exceptions to these generalities that are dependent upon local conditions. For example, along the Texas coast

where marshes are not as extensive as they are in Louisiana, croaker do utilize open water as nursery areas (Parker 1971). Likewise, well-established marsh areas along the Atlantic coast serve the same function.

Main stream channels and deep subtidal channels with unconsolidated bottoms are also considered to be good nursery areas for croakers on both coasts (Pearson 1929; Haven 1957; Johnson 1978; Etzold and Christmas 1979; Weinstein 1979; Weinstein et al. 1980b). Areas with soft mud bottoms having a high organic or detrital content are also considered to be optimal habitats for juvenile croaker (Bearden 1964; Parker 1971; Chittenden and McEachran 1976; Kobylinski and Sheridan 1979; Sheridan 1979; Weinstein 1979; Weinstein et al. 1980a).

Croaker tolerate wide ranges of temperature and salinity. Juvenile croaker will grow over a range of 6° to 32°C (43° to 90°F) (Johnson 1978). Since croaker recruits immigrate from their spawning grounds and enter nursery grounds in the winter, excessively low temperatures may be a major density-independent factor controlling recruitment and abundance cycles (Weinstein et al. 1980b; Norcross and Austin 1981). Juvenile tolerance ranges from 6° to 20°C (43° to 68°F) (Parker 1971). In general, the earlier life stages of croaker are most cold tolerant and adults are least cold tolerant (Johnson 1978).

Along the Atantic coast the selection of deeper creeks and open water by juvenile croaker as a nursery ground may be keyed to temperature. For example, in spring when temperature variations are most severe in shallow areas, juveniles may stay in the more thermally stable channels. It seems certain, however, that no one factor is completely responsible for croaker distribution. Food, substrate type, salinity, protection from predation, and temperature interact, and distinguishing which of these factors is more important is difficult. The relative important of each factor may vary from place to place along a coast and among coasts. These varying interactions must be remembered when evaluating any habitat for croaker.

Declining temperatures in fall accelerate the migration of croaker from the estuaries to coastal waters. Other environmental factors, such as salinity changes, may be involved, however, in inciting migration (Clairain 1974). Sudden or prolonged periods of intense cold occurring while croaker are still in shallow areas can cause mass mortalities (Gunter and Hildebrand 1951).

The tolerance of croaker to salinity is impressive. The species has been found in waters ranging from 0 ppt (Johnson 1978) to 70 ppt (Simmons 1957); however, this is an extreme range which includes all life stages combined. Highest numbers of juveniles are associated with salinities in the oligohaline and middle mesohaline range (0.5 to 12 ppt) (Kobylinski and Sheridan 1979; Weinstein 1979; Weinstein et al. 1980a). As croaker grow, their tolerance to higher salinities increases (Herke 1971).

Stability of the salinity regime within croaker nursery areas is also a factor in controlling croaker distribution. Juvenile croaker tend to avoid areas of fluctuating salinity (Herke 1971; Gerry 1981). Gerry (1981) found croaker most abundant in habitats where salinity fluctuations were the least.

Avoidance of fluctuating salinity may in part be a reason croaker on the Atlantic coast seem to prefer deeper tidal creeks over shallower marshes, since the magnitude of salinity change should be less in deeper water for a given period. On the Gulf of Mexico coast, shallow low salinity marshes are the primary nursery ground for croaker. Croaker are more abundant in these marshes than in adjacent open water areas (Rogers 1979). Marshes with salinities greater than 18 ppt are not considered as good nursery habitat (Rogers 1979; Weinstein 1979).

Even though there are no published values for dissolved oxygen requirements of croaker, it is an important habitat variable. Dissolved oxygen (DO), when expressed as a summer minimum value, is particularly important in the deeper water habitats. When DO levels drop, most fish including croaker will leave the areas (Markle 1976; Chao and Musick 1977). Although deep, soft bottom channels in estuaries are good habitat for croaker, these areas may have oxygen deficiencies in the summer. In such cases, there may be a significant displacement of juvenile croaker to shallower water. Low DO in marshes, however, can kill juvenile croaker (Yakupzack 1976) or possibly cause their displacement to adjacent open waters.

Turbidity is an inverse measure of water clarity and can result from either dissolved materials such as tannins in the water or, more commonly, suspended particulates. Water with high turbidity is brown or nearly opaque from suspended material.

Turbid areas may provide croaker with protection from visual predators. Highly turbid areas, in general, also tend to have high organic loads which may cause an increase in food availability to croaker. Turbidity does not pose any feeding problem to croaker since they are morphologically adapted for tactile feeding (Chao and Musick 1977). Juvenile croaker tend to be found in highly turbid runoff areas (Bearden 1964; Parker 1971; Kobylinski and Sheridan 1979) and in the low salinity (0.5 to 5 ppt), maximum turbidity zone of estuaries (Weinstein et al. 1980a). The maximum turbidity zone is defined as the transitional zone of an estuary from fresh to salt water. It is typically an area of high sedimentation where salt water flocculates and traps much of the alluvial load brought into the estuary (Nichols 1972).

Juvenile croaker tend to live primarily over muddy substrates (Parker 1971; Chittenden and McEachran 1976; Kobylinski and Sheridan 1979). They use both estuarine open water (predominantly on the Atlantic coast) and estuarine marsh areas (predominantly on the Gulf of Mexico coast). One feature of the substrate that makes it more attractive to croaker on both coasts is organic content. There is a positive correlation between croaker abundance and the amount of organic matter in the surface sediments (Bearden 1964; Sheridan 1979; Weinstein 1979).

HABITAT SUITABILITY INDEX (HSI) MODEL

Model Applicability

Limitations. This model is developed for juvenile croaker. Factors that influence the successful survival and recruitment of larvae from coastal

marine waters are complicated and outside the influence of the estuarine system (Norcross and Austin 1981). Adult croaker are less habitat-specific than juveniles. Any area suitable for juveniles is thought to be suitable for adults. The only exceptions are oligohaline areas, where larger croaker do not usually occur.

The use of this model is not always appropriate, such as where partial or extensive reduction in habitat availability has occurred due to toxic wastes. The unavailability of potential habitat resulting from the presence of environmental contaminants will interfere with proper interpretation of model applications.

Geographic area. The geographic areas covered by this model are the southeast Atlantic coast and Gulf of Mexico coast. There are, however, differences in the areas used as nurseries by the two coastal croaker populations. Gulf of Mexico croaker populations use marshes as their primary nursery area, whereas Atlantic coast croaker use deep creeks or channels and open water areas. Despite this major difference, the basic life requisites of water quality and cover seem to be similar on both coasts. The HSI model attempts to account for nursery habitat differences between the coasts and assumes other variables to be operating similarly between coasts.

Season. The HSI model is designed for spring and summer application. Some of the model variables pertain to environmental conditions that would occur only during these seasons. If applied during other seasons, it would be necessary to adjust variables that are seasonally programmed.

Cover types. Croaker typically use estuarine and nearshore marine habitats. Spawning occurs in the marine habitat and near the transition to the estuarine habitat. The estuarine habitat is used as the nursery grounds. This model is intended for evaluation of only the estuarine habitat.

Minimum habitat area. The minimum habitat area is that area of contiguous suitable habitat that is required for croaker to develop and reproduce successfully. No minimum habitat size requirements for croaker have been identified in the literature.

Verification level. The acceptable output of this HSI model is an index between 0 and 1 which is believed to have a positive relationship to carrying capacity. Hypothetical data sets were used to verify that HSI's determined with the croaker model were reasonable and acceptable. These data sets and their relationship to model verification are discussed later.

Three biological experts outside the U.S. Fish and Wildlife Service were identified to review and evaluate the croaker HSI model throughout its development. Ideas and suggestions from these experts were incorporated into the model-building effort. These experts were Mr. John Lunz, Environmental Laboratory, U.S. Army Corps of Engineers, Vicksburg, Mississippi; Dr. Michael Weinstein, Virginia Commonwealth University, Richmond, Virginia; and Dr. Brenda Norcross, Virginia Institute of Marine Science, Gloucester Point, Virginia.

Model Description-Estuarine

Overview. This HSI model for the juvenile Atlantic croaker considers water quality and cover life requisites in the estuarine habitat. The relationship of habitat variables, life requisites, and life stage to the HSI is illustrated in Figure 1.

The following sections document the logic and assumptions used to interpret the known habitat information for the croaker to explain the relationships among variables and equations used in the HSI model. The two basic life requisites used in the model are not independent. There is a great deal of overlap and correlation between the habitat variables and life requisites. For example, turbidity in estuarine systems is directly related to both the salinity gradient and depth (Nichols 1972). The grouping of habitat variables into water quality, cover, and food is primarily for development of the HSI and is not intended to imply that water quality and cover variables, for example, are mutually exclusive.

Water quality component. Four variables are reported in the literature as influencing the quality of habitat for juvenile croaker. Turbidity, primarily as indication of the suspended solids in the water column, seems positively correlated to croaker abundance. Highly turbid areas are most suitable, but turbidity can be an ephemeral condition in estuaries and should be averaged over at least a tidal cycle. Dissolved oxygen (DO) is important when it drops to limiting concentrations. Although croaker tolerance to low DO is not specifically known, oxygen levels below 3 mg/l are limiting to other fish species (Hoss and Peters 1976). This is possibly the case in deep habitats during the summer when biological and chemical oxygen demand are high, and thermal or salinity stratification prevents the mixing of the water column.

The most suitable habitats for croaker on both the Gulf of Mexico and Atlantic coasts are generally the most turbid (Bearden 1964; Kobylinski and Sheridan 1979; Weinstein 1979). Since turbidity (V_1) in estuarine habitats is mainly suspended solids, it can be categorized by the amount of solids in the water or by Jackson Turbidity Units (JTU). Although it is not a quantitative measure, the turbidity variable may also be defined in four steps from clear to cloudy to light brown or semitransparent to dark brown or opaque.

For the DO variable (V_2), values below 3 mg/l were chosen to identify unsuitable croaker habitat, based on the oxygen tolerance measurements obtained for other fish species (Hoss and Peters 1976). Since low dissolved oxygen is generally a summer phenomenon and usually of short duration, great care must be taken in choosing the time for measurement of oxygen levels. Habitats where oxygen levels do not drop below 4.5 mg/l have the highest suitability, again based on the oxygen tolerances of other species (Hoss and Peters 1976: Doudoroff and Shumway 1970).

Salinity controls the basic distribution of juvenile croaker in the estuary. Highest numbers of individuals are found in salinities from 1 to 12 ppt (Bearden 1964; Parker 1971; Weinstein et al. 1980a). For any location in an estuary, salinity can vary over a tidal cycle and seasonally. Salinity can

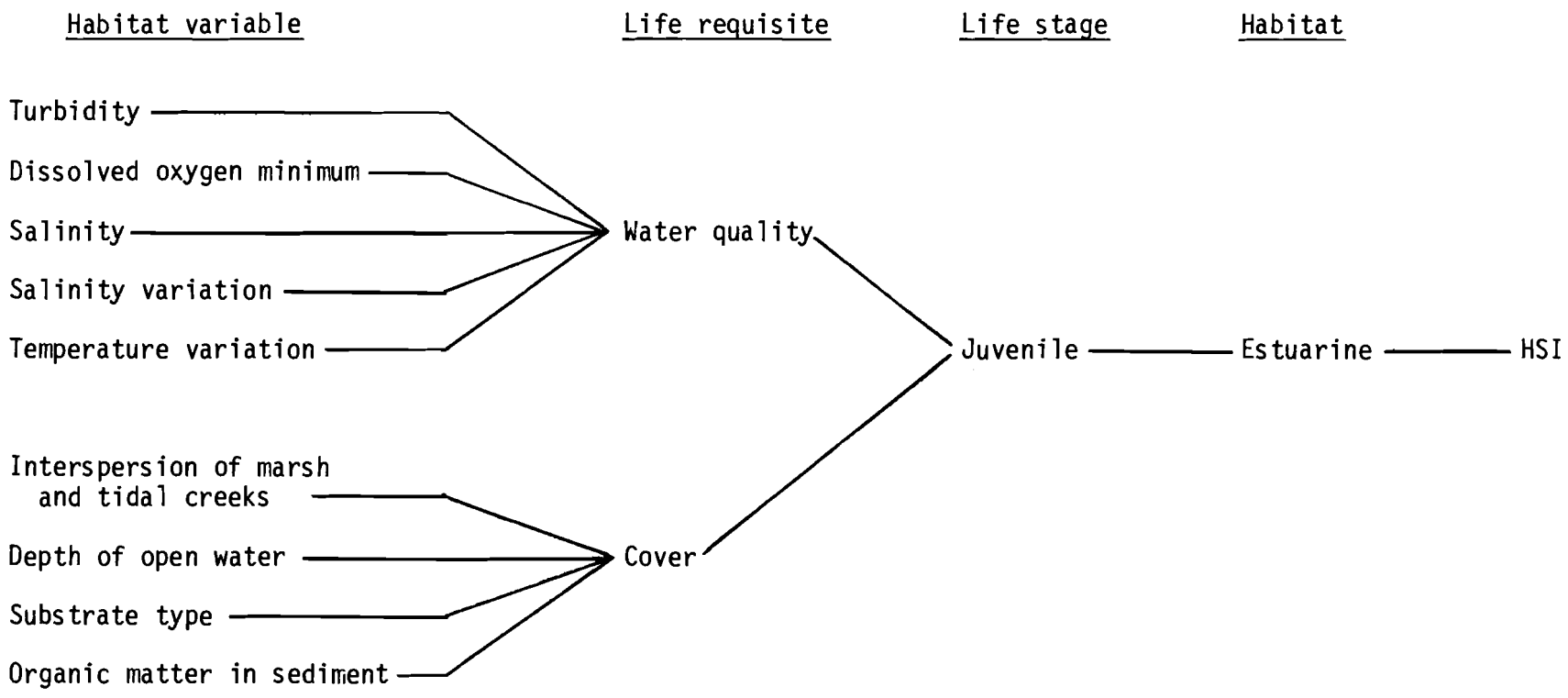


Figure 1. Relationship of habitat variables and life requisites to the HSI for juvenile Atlantic croaker.

also be influenced by storm events or long-term climatic trends; therefore, measured salinity values need to be evaluated in terms of both long- and short-term fluctuations. For example, a drought may temporarily cause salinity to become unsuitably high for croaker, but return of average climatic conditions would result again in favorable salinity levels. The short-term stability of salinity, on the order of a tidal cycle, may be as important as average salinity in determining suitability of a habitat for juvenile croaker. High abundance of juvenile croaker has been correlated with stable salinity (Gerry 1981). Rapid changes in salinity, on the order of 5 ppt/hr, adversely affect juvenile croaker (Perez 1969).

For the HSI model two variables characterize salinity: magnitude (V_3) and short-term stability (V_4). Habitats where the salinity range remains between 2 and 10 ppt are considered optimal. Areas with salinities less than 2 ppt or between 10 and 12 ppt are considered to be suitable but less than optimal for juvenile croaker. Finally, areas where salinities remain 20 ppt or greater are considered to be totally unsuitable (Weinstein 1979). For short-term salinity stability (V_4), optimal habitats are considered to be those in which salinity does not vary by more than 3 ppt/hr (Perez 1969). Areas with salinity variations greater than 9 ppt/hr are assumed to be totally unsuitable for juvenile croaker.

Typical annual variation in temperature poses no problem to croaker over its range (Virginia-Delaware to Texas). Temperature is an important localized habitat variable when considered in terms of the wide variation and duration of temperature extremes. Juvenile croaker will grow over a wide range of temperature (6° to 20°C or 43° to 68°F; Parker 1971), with their tolerance to rapid changes in temperature (thermal shock) limited by their thermal history (Copeland et al. 1974). Temperature increases of 14.4°C caused stress reactions in croaker acclimated to 18°C (64°F), and an increase of 16.6°C above 18°C will physiologically incapacitate croaker (Copeland et al. 1974). At higher acclimation temperatures the thermal shock needed to cause adverse reaction in croaker is smaller. These findings indicate that temperature variations in the spring should not play as great a role in excluding croaker from shallow habitats as would temperature variations in summer when overall temperatures are higher. In both spring and summer, temperature variation in deep water habitats is less than it is in shallow areas. This helps to make the deeper areas, if they are present, preferred habitat; therefore, a measure of the magnitude of temperature variation (V_5) is necessary to determine habitat suitability for croaker. If temperatures vary 10°C or less/day, then the habitat is considered suitable. If variations are as much as 17°C or more then the habitat is considered to be unsuitable. These ranges are based on the work of Copeland et al. (1974).

Cover component. Juvenile croaker, for the most part, are generalists and occupy a variety of cover types. They occur in open water, soft mud bottom, and channel areas as well as in shallow creeks in marshes. Interspersion of marsh and tidal creek is optimal for croaker (Dr. Michael Weinstein, Virginia Commonwealth University, Richmond; personal communication, 1981). When marsh is dissected by tidal creeks, a greater length of shoreline is created. This interspersion of habitats provide better access to food resources through material exchange between the marsh and subtidal habitats. The greater the

interface or edge between these habitats, the greater the value of the overall habitat area to croaker. In marshes and deep open water channels, a combination of water quality and food availability may determine the timing and extent of use of each habitat by croaker.

In general, the primary habitats for juvenile croaker are estuarine marshes on the Gulf of Mexico coast and estuarine open water areas on the Atlantic coast. To apply the HSI model, it may be necessary to use a different variable function for cover (V_6), depending upon which coast is involved. Depending upon local conditions, however, it may also be necessary to switch functions or possibly use both functions in the same area, regardless of which coast is involved.

For the Gulf of Mexico coast or marsh-dominated areas, good croaker habitat is defined as marshes dissected by tidal creeks. Marsh areas undissected by tidal creeks and shallow, open water areas are considered to be less than good habitat. No data are available for quantifying habitat suitability in terms of the ratio of marsh area to tidal creek area. Therefore, optimal habitat is arbitrarily defined to be composed of 50% marsh area and 50% tidal creek area. It is further assumed that, as the proportion of marsh area decreases relative to the area of tidal creeks, the suitability of the habitat drops rapidly; but with a proportional increase of marsh to tidal creek area, the habitat suitability drops slowly.

For the Atlantic coast or open water areas, the cover variable (V_6) is defined as the ratio of area of bottom deeper than 6 ft mean low water (MLW) to total bottom area. Optimal habitat is arbitrarily considered to have 50% or more of its total bottom area deeper than 6 ft. As the proportion of area deeper than 6 ft decreases relative to the total, the habitat suitability is assumed to drop rapidly.

Substrate quality, in terms of dominant substrate type (V_7) and organic content (V_8), plays an important role in determining juvenile croaker distribution. Sand and hard substrates are not suitable at all for juvenile croaker. Mud is most suitable (Chittenden and McEachran 1976; Kobylinski and Sheridan 1979; Weinstein 1979). There is also a positive correlation between occurrence of juvenile croaker and the amount of organic matter in the surface sediments (Bearden 1964; Sheridan 1979; Weinstein et al. 1980a). Weinstein et al. (1980a) found highest abundances of juvenile croaker in areas of high organic content, up to 33%. For relating organic content (V_8) to habitat suitability, it was assumed that areas having a sediment organic content of 10% or more were optimal, whereas areas with sediment organic content of 2% or less were considered to be unsuitable. Table 1 summarizes the assumptions given for each habitat variable.

Suitability Index (SI) Graphs for Model Variables

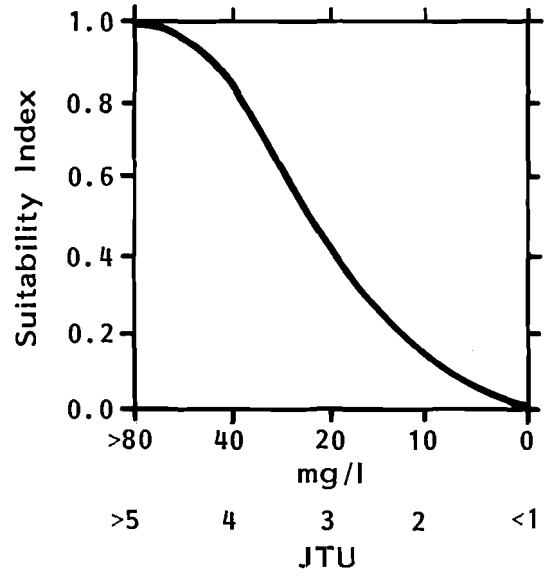
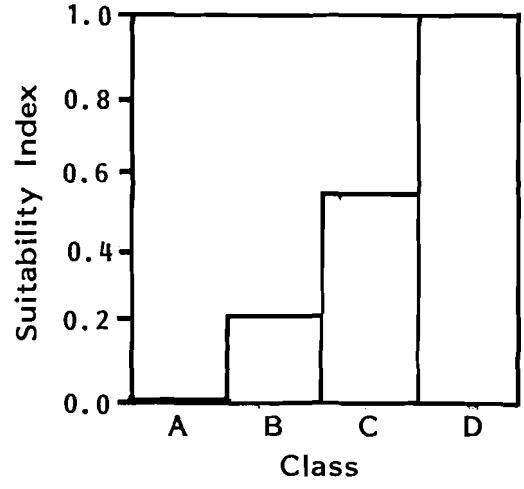
This section provides graphic representations of the relationships between various values of estuarine habitat (E) variables and habitat suitability for juvenile Atlantic croaker. The SI values are read directly off the graph (1.0 = optimum suitability, 0.0 = no suitability) for any variable value.

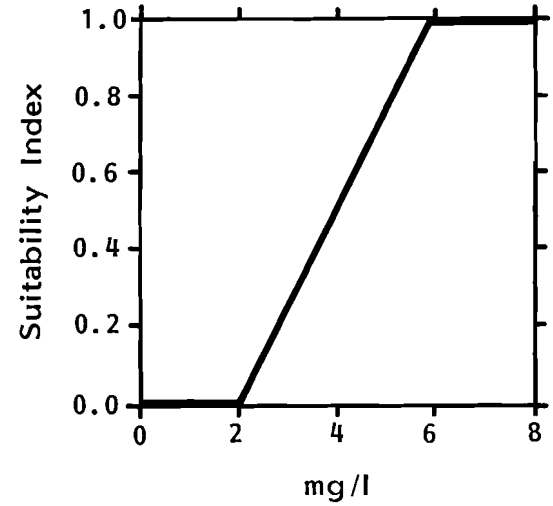
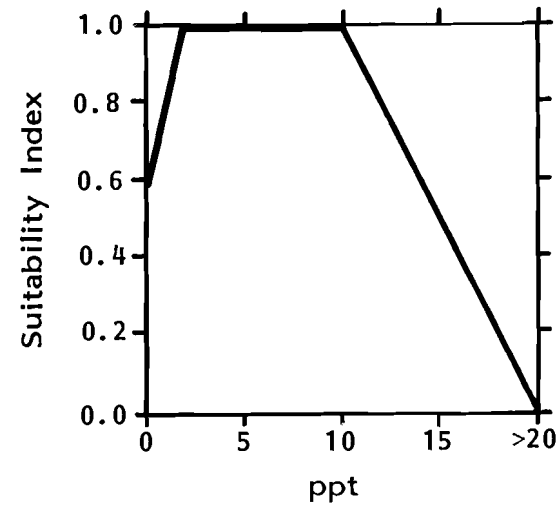
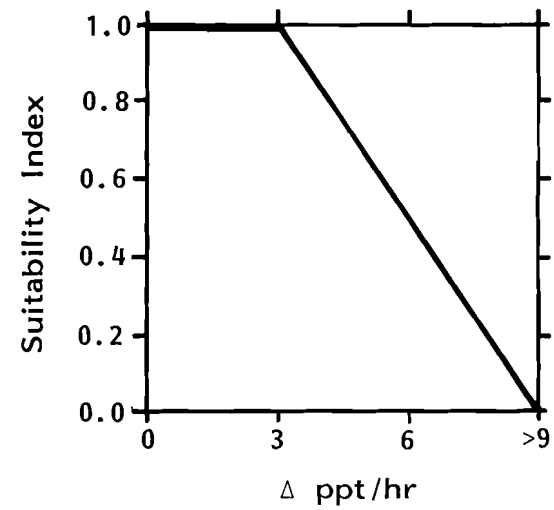
Table 1. Data sources and assumptions for Atlantic croaker suitability indices.

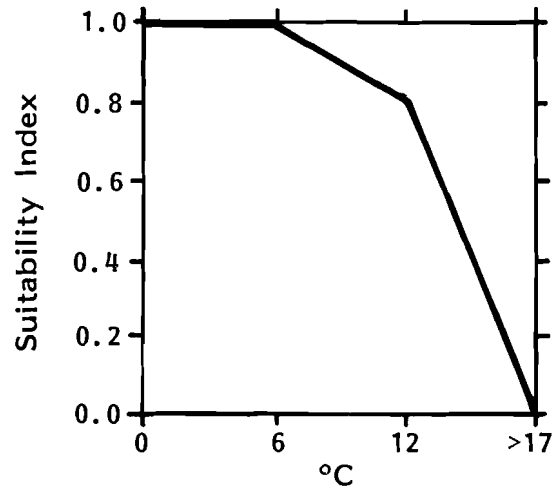
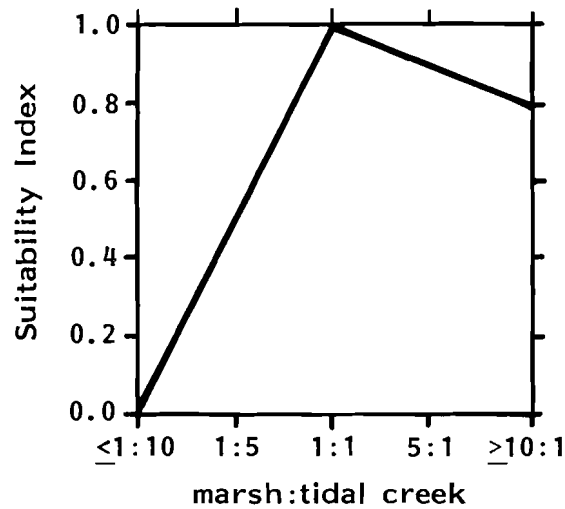
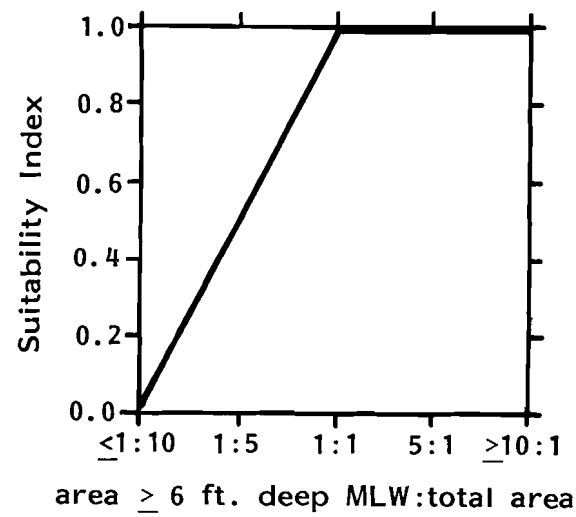
Variable and source		Assumption
V_1	Bearden 1964 Kobylinksi and Sheridan 1979	High turbidity levels are positively related to croaker abundance.
V_2	Doudoroff and Shumway 1970 Hoss and Peters 1976	Low levels of dissolved organic are not suitable.
V_3	Parker 1971 Weinstein 1979 Weinstein et al. 1980b	The range of optimal salinity is much narrower than the maximum range, and oligohaline and lower mesohaline salinities are optimum.
V_4	Perez 1969 Gerry 1981	High salinity stability is optimal. Increasing fluctuations decrease suitability.
V_5	Copeland et al. 1974	High temperature stability is optimal. Increasing fluctuations decrease suitability.
V_6[a]	Option A	Optimal cover diversity of marsh and tidal creek is found when approximately equal amounts of both are present.
V_6[a]	Option B	Optimal cover is found when all bottom is deeper than 6 ft MLW.
V_7	Chittenden and McEachran 1976 Kobylinski and Sheridan 1979 Weinstein 1979	Soft mud is most suitable. Sandy mud is less suitable. Hard and sandy substrates are unsuitable.
V_8	Bearden 1964 Sheridan 1979 Weinstein et al. 1980a	Highly organic muds are optimal.

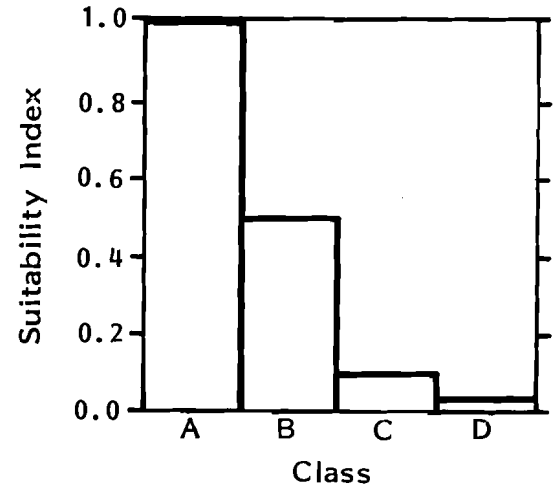
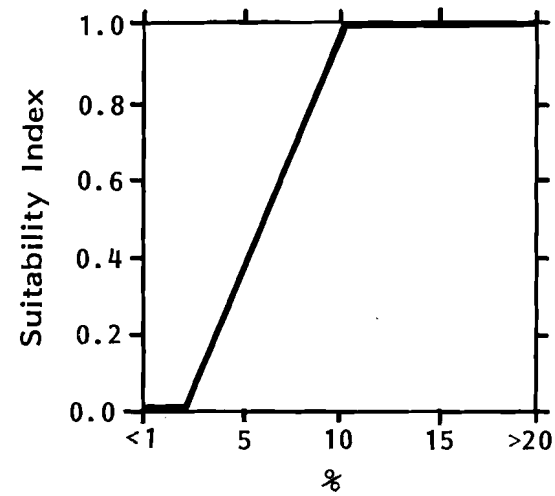
[a] This variable is not discussed in the literature on croaker; it was derived from results of other fish studies.

The SI graphs are based on the assumption that the suitability of a particular variable can be represented by a two-dimensional linear response surface. Even though there are interdependencies and correlations between many habitat variables, it is assumed that each variable operates independently over the range of other variables under consideration. Further, there is no significance to the order in which the suitability curves are presented.

Habitat	Variable		Suitability Graph
E	V_1	Option A: Turbidity 10 to 15 cm above the bottom, measured during spring or summer as either suspended solids or JTU.	
E	V_1	Option B: Turbidity 1 m above the bottom, estimated during spring or summer from water clearness/color. A) Clear B) Cloudy C) Light brown or semitransparent D) Dark brown or opaque	

Habitat	Variable		Suitability Graph
E	V_2	Minimum dissolved oxygen level 10 to 15 cm above the bottom in summer.	
E	V_3	Average salinity 10 to 15 cm above the bottom during spring or summer.	
E	V_4	Rate of salinity change per hour, disregarding the sign of the difference, 10 to 15 cm above the bottom during spring or summer. Collect data at least over half a tidal cycle.	

Habitat	Variable		Suitability Graph
E	V_5	Temperature variance over 24 hr, 10 to 15 cm above the bottom. Subtract the highest temperature from the lowest temperature for 24-hr period, disregarding the sign of the difference.	
E	V_6	Option A: Ratio of marsh area to tidal creek area for Gulf of Mexico coast or marsh-dominated areas.	
E	V_6	Option B: Ratio of bottom area deeper than 6 ft MLW to total bottom area for Atlantic coast or water-dominated areas.	

Habitat	Variable		Suitability Graph
E	V_7	Dominant substrate type A) ≥75% mud or silt, some sand or other materials B) ≥50% sand, some mud, silt or other soft materials C) ≥75% sand, shell, or other hard materials, some mud or silt D) Mostly rock, no soft material	
E	V_8	Percent organic matter or volatile solids in top 5 cm of sediment.	

Component Index Equations

To obtain life requisite scores for juvenile Atlantic croaker, the SI values for the appropriate variables must be combined. A discussion and explanation of assumed relationships between variables was included in the Model Description section. The water quality variables are not all equally important to the croaker. Minimum dissolved oxygen (V_2) at a habitat is generally an ephemeral condition and does not permanently alter habitat suitability so the square root of V_2 is taken to adjust its contribution in the equation. When the SI for V_2 is 1.0 or 0.0, its contribution in the equation is still 1.0 or 0.0. Salinity (V_3) appears to be the most important water quality variable and is doubled to emphasize this fact. Of the cover variables, substrate type (V_7) appears most important and is also doubled. The

suggested equations for obtaining water quality and cover values for juvenile croaker are:

$$\text{Water quality } (CI_{wq}) = \frac{V_1 + \sqrt{V_2} + 2V_3 + V_4 + V_5}{6}$$

$$\text{Cover } (CI_c) = \frac{V_6 + 2V_7 + V_8}{4}$$

HSI Determination

The following steps must be taken to determine an HSI for any application.

1. Review the section on model applicability for validity of the model for the intended application.

2. Identify the boundaries of the evaluation area or areas and obtain data for each model variable used in the model. Using the SI graphs and equation, calculate the component indices.

3. Calculate the HSI:

$$HSI = \frac{C_{wq} + C_c}{2}$$

Four sample data sets, from which suitability indices, component indices, and habitat suitability index values have been generated by using the model equations, are in Table 2. Two hypothetical data sets are shown for the Gulf of Mexico coast and two are also shown for the Atlantic coast. Although the data sets are not actual field measurements, they do represent the kinds of values expected for estuarine habitats used by croaker. The HSI's calculated from these hypothetical data reflect relative abundance for habitats with the characteristics listed in Table 2.

Field Use of the Model

Detailed field sampling of habitat variables through time will provide the most reliable and replicable HSI values. One-time sampling of habitat variables is not considered the best method of collecting representative data. Although it is possible to estimate any of the habitat variables from expert opinion, it is not the best approach unless there are no other options. Collection of field data is best. Average values obtained from scientific data reports are considered acceptable estimates of variables used in the model, assuming the data are from areas close to the evaluation area. The data used to calculate the SI values should be accompanied by appropriate documentation to insure that decisionmakers understand the quality of the data used in

Table 2. Calculation of suitability indices (SI), component indices (CI), and habitat suitability index (HSI) for four sample data sets, using the croaker habitat variables (V) and model equations.

Model component	Gulf of Mexico coast				Atlantic coast			
	Open water		Marsh		Open water		Marsh	
	Data	SI	Data	SI	Data	SI	Data	SI
V_1	60[a]	0.95	110[a]	1.00	2[b]	0.15	4[b]	0.85
V_2	3	0.26	2	0.00	4	0.50	3	0.26
V_3	13	0.66	8	1.00	15	0.50	4	1.00
V_4	4	0.88	2	1.00	3	1.00	1	1.00
V_5	8	0.90	12	0.80	6	1.00	10	0.86
V_6	30	0.60	80	0.91	80	1.00	40	0.90
V_7	C	0.10	A	1.00	A	1.00	A	1.00
V_8	4	0.28	10	1.00	8	0.70	15	1.00
CI_{wq}		0.76		0.80		0.69		0.83
CI_c		0.27		0.98		0.90		0.99
HSI		0.52		0.89		0.80		0.91

[a] Suspended solids mg/1.
[b] JTU's.

developing the HSI. Suggested methods for measuring model variables are given in Table 3. An understanding of field methods is essential to applying the model. Any or all variables can be estimated for preliminary application of the model. Subjective estimates will decrease model reliability and replicability. When subjective estimates are used, they should be made by experienced professionals, if possible, and accompanied by full documentation of the basis on which estimates were made.

Interpreting Model Outputs

A juvenile croaker HSI determined by field application of this model may not reflect the population density of croaker in the study area, since other factors may have significant influence in determining species abundance. In coastal areas where croaker populations are primarily regulated by habitat-based factors, the model should yield HSI values that have positive correlations with long-term abundance. This correlation has not been tested, other than from inferences drawn from the literature to support the model. The proper interpretation of the HSI is one of comparison. If two different areas have different HSI's, then the area with the higher HSI should have the potential to support more croaker than the one with the lower HSI.

In extreme situations where an unusually large, or long-term depletion of oxygen is observed or expected, the dissolved oxygen variable would be used to the exclusion of all others in determining the HSI value.

Table 3. Suggested methods for field measurements of variables used in the croaker HSI model.[a]

Variable	Methods
V_1	Since most turbidity in estuaries is from suspended solids, either direct measurement of suspended solids or a Jackson turbidity meter can be employed. Turbidity may be qualitatively estimated by taking a water sample 1 m above the bottom and noting whether water clearness/color is clear, cloudy, light brown, or opaque.
V_2	Dissolved oxygen can be measured using Winkler titration or oxygen meter.
V_3	Salinity can be measured by titration, refractometer, or salinity meter.
V_4	Same methods as for V_3.
V_5	Temperature can be measured by thermometer or temperature probe.
V_6	Define evaluation area on topographic maps or navigation charts. Option A. For marsh-dominated areas, determine the area of marsh and tidal creek. Option B. For open water areas, determine the area shallower than and the area deeper than 6 ft MLW. Use either a planimeter or cut and weigh method. For cut and weigh, take a copy of the evaluation area and cut out the marshes and tidal creeks or shallow and deep areas, and then weigh all the cut outs for each habitat type. The ratio of the weights will also be the ratio of these areas.
V_7	Substrate type is defined as the amount of coarse or fine sediment. Substrate may be qualitatively measured by sieving a known weight of substrate through a 63-μ sieve (Tyler series No. 250). The material retained on the sieve is the sand or coarser fraction from which the percentage of sand or coarser material can be calculated. What goes through the sieve is mud (silts and clays). The percentage of mud is 100% minus the weight of coarser material retained on the sieve.
V_8	Organic matter content in the sediment may be determined by using methods for volatile solids.

[a]Details for water quality methods can be found in Standard Methods for Examination of Water and Waste Water (Anonymous 1981).

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A review and synthesis of existing information were used to develop an estuarine habitat model for juvenile Atlantic croaker (*Micropogonias undulatus*). The model is scaled to produce an index of habitat suitability between 0 (unsuitable habitat) and 1 (optionally suitable habitat) for estuarine areas of the Atlantic and Gulf of Mexico coasts. Habitat suitability indices are designed for use with Habitat Evaluation Procedures previously developed by the U.S. Fish and Wildlife Service. Guidelines for juvenile Atlantic croaker model applications and techniques for estimating model variables are described.

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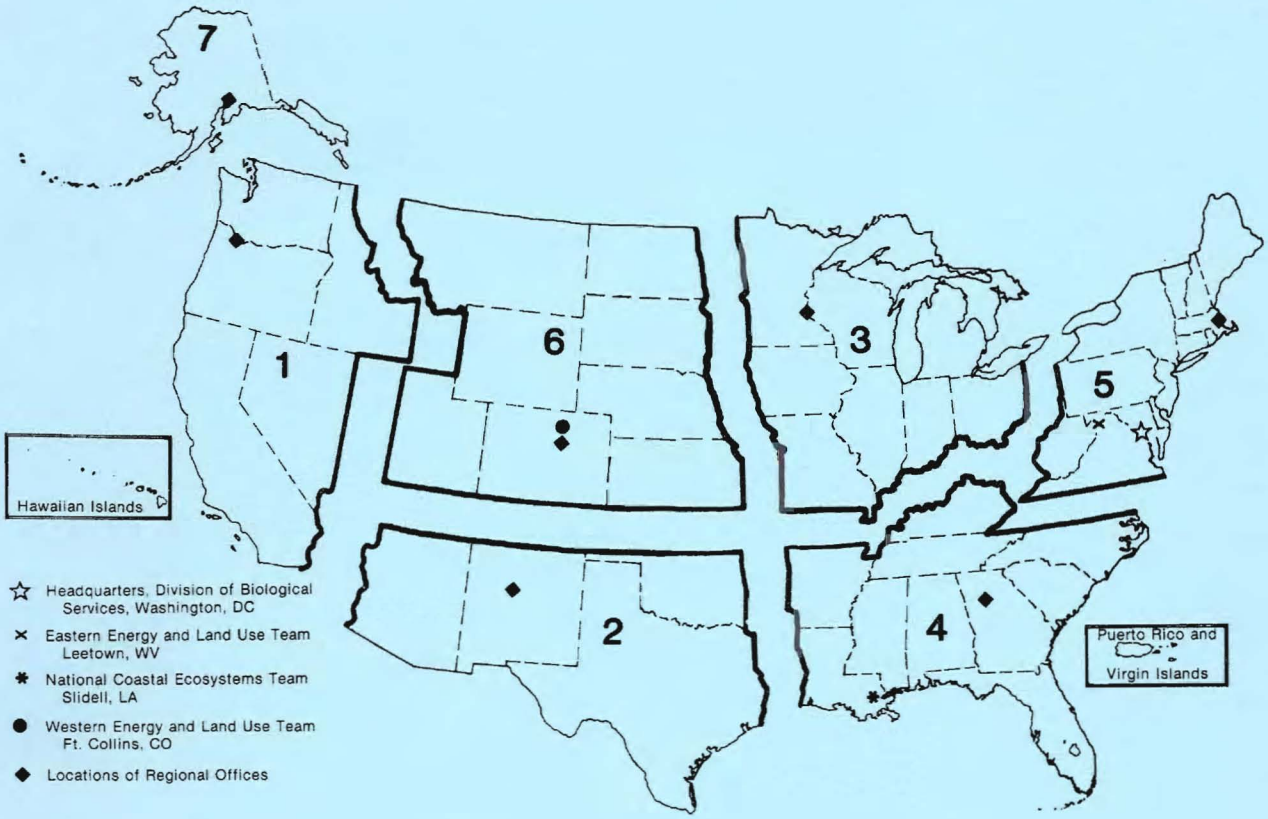

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