Model Name: Largemouth Bass Habitat Suitability Index

Functional Area: Ecosystem Service / Upper Trophic Level

Model Proponents: Coastal Protection and Restoration Authority

Model Developer(s): Michael D. Kaller, Louisiana State University AgCenter

Please note this is a working-draft document currently undergoing review and revision. The final version will be posted in March 2012 along with the final version of the 2012 Coastal Master Plan.

Table of Contents

1. *Background*

a. Purpose of Model

With many potential actions regarding protection and restoration projects, information on the implications of actions or inaction to the ecosystem and economy of coastal Louisiana is necessary. Coastal land loss threatens the ecological integrity and economic viability of Louisiana; however, understanding the implications to the ecosystem and economy as a whole is complex. One simpler method to understand the implications of action or inaction is to develop a predictive model that will outline responses of desired end states to various action or inaction scenarios. Among the desired end states is a healthy and robust community of animals that are either of direct economic importance or represent a functional ecosystem. Within this community of organisms, largemouth bass represent an economically important organism (Southwick Associates 2008), as well as, indicate a healthy freshwater ecosystem (Meador and Carlisle 2007) as an apex predator. Therefore, the expansion or contraction of largemouth bass habitats in relation to various restoration or protection scenarios offers insights into desired end states of ecosystem integrity and economic viability by outlining the benefits of these projects scenarios through expanded habitat and, therefore, economic activity and ecosystem integrity.

This model will assist CPRA and other water management agencies (e.g., U.S. Army Corps of Engineers) in evaluating the effect of various protection and restoration measures on large mouth bass habitat suitability. Specifically, increases, transitions, and decreases in freshwater will be clearly indicated by this model. Further, this model will indicate the habitat losses from inaction.

b. Model Description and Depiction

The largemouth bass (*Micropterus salmoides*) and Florida bass (*Micropterus floridanus*, formerly *M. salmoides floridanus*) are among the most widely sought after sportfishes in North America and support many popular fisheries in Louisiana. The quality of largemouth bass fisheries, in terms of both fish production and angler harvest, is affected directly and indirectly by factors under the control of fishery managers, such as stocking practices and management regulations, as well as less controllable factors such as system productivity, invasive species, and water quality fluctuations. For management purposes, the two species are more often described in older literature as sub-species and are managed together because these species are nearly impossible to differentiate in field settings. Specific-level identification requires examination of liver proteins or microsatellites. Further, the species are known to hybridize, with many Louisiana waterbodies supporting *M. salmoides*, *M. floridanus*, and *M. salmoidesXfloridanus* (Constant 1990; Fries 2010). Hereafter, both species and their hybrid will be referred to as largemouth bass, and this HSI has been generalized to address both basses and their hybrid.

Coastal Louisiana freshwaters support economically and ecologically important populations of largemouth bass. Although often overshadowed in the minds of coastal anglers by spotted seatrout and redfish, many anglers fish Louisiana coastal freshwaters targeting largemouth bass. The expenditures of these anglers are important income in coastal communities. Further, the largemouth bass is an important aquatic predator, often a keystone predator if alligator gar or alligators are low in number. In turn, shorebirds and other avian predators are the principal non-human predator of bass in these systems.

Published studies of largemouth bass in Louisiana coastal freshwaters are few. In Louisiana, coastal largemouth bass salinity studies have been published by Meador and Kelso (1989, 1990). Additionally, theses by Constant (1990) and Fries (2010) provide data on distributions and field conditions. The Louisiana Department of Wildlife and Fisheries conducts monitoring of fishes, including largemouth bass, in selected coastal waterbodies, and some of these data contributed to the HSI. A portion of these data were withheld from model construction and were used to validate model predictions. To supplement the Louisiana data and construct the HSI, data from nearby states [Alabama (Peer et al. 2006; Hayer and Irwin 2008), Florida (Moxley and Langford 1982; Maciena 1996; Chick et al. 2004; Rehage and Loftus 2007; Rogers and Allen 2009), and Georgia (Sammons et al. 2005)] and territories (Puerto Rico; Ozen and Noble 2002, 2005; Neal and Noble 2006) were included, as well as relevant laboratory and field trials (Garvey et al. 2002; Buisson et al. 2008; Hoyer et al. 2008; Hazler et al. 2009; Rypel 2009). These data were subsequently used to modify the original 22 variable largemouth bass HSI model developed by Stuber (1982) replacing suitability values derived from northern field studies with more recent laboratory or field data from climates more akin to Louisiana.

The HSI was constructed by examining the reported abundance, density, or presence/absence relationships with specific abiotic or biotic factors (e.g., temperature, chlorophyll *a* as a measure of phytoplankton productivity). The optimal ranges of these factors were assigned a 1.0 and less optimal conditions leading toward mortality were assigned decreasing values based on either reported mortality or substantial declines in reported abundance, density, or presence/absence. For example, Fries (2010) reported the lowest catch-per-unit-effort in lakes with low chlorophyll *a*, although all lakes produced fish. Therefore, chlorophyll *a* values associated with the highest catch-per-unit-effort were assigned a 1.0 and the decreasing relationship between declining chlorophyll *a* with catch-per-unit-effort were modeled with logit (logistic) model following comparison of a variety of possible linear and non-linear relationships bounded by 0 and 1.0. The final suitability values for the relationship between chlorophyll *a* with largemouth bass were estimates from this relationship. Similar relationships were constructed for each of the five variables included in the HSI. The final HSI was adjusted relative to the input variables following validation by comparison with distributional data, described above, and input from the Coastal Protection and Restoration Authority (CPRA). In the final HSI, values of 1.0 indicate a very high probability, near certainty, that habitat is suitable for largemouth bass in each displayed map cell or polygon. Values below 1.0 indicate decreasing habitat suitability.

c. Contribution to Planning Effort

Largemouth bass are intolerant of high salinities, specifically salinities in the ranges that would be expected with further coastal land loss. Therefore, expansion of largemouth bass should be indicative of freshening from river diversions or other similar restoration efforts. Additionally, because largemouth bass can tolerate low salinities (< 12 ppt), expansion of largemouth bass also may indicate habitats in transition from river diversions or no action (i.e., continued erosion). Localized extirpations over the course of the modeling period should be inferred as habitat loss from increased salinity and land loss.

d. Description of Input Data

This model requires temperature, salinity, emergent vegetation, submerged aquatic vegetation (SAV), and chlorophyll *a*. Temperature, salinity, and chlorophyll a data are outputs from the

Eco-Hydrology model. Emergent vegetation and submerged aquatic vegetation are outputs from the Vegetation model. The vegetation data also are derived from outputs of the Eco-Hydrology model. All data are yearly averages for a cell or polygon.

e. Description of Output Data

This model will output a habitat suitability index from 1.0 to 0 for each 500 x 500m cell with 1.0 indicating very high suitability of habitat for largemouth bass.

f. Statement on the capabilities and limitations of the model

This model is adequate for assessing habitat suitability in response to changes in salinity. As a species group, largemouth bass are quite temperature tolerant ranging from Mexico and Puerto Rico north into Canada, although individuals may not have wide tolerance ranges. Further, largemouth bass are quite adaptable to a variety of physical habitats, as evidenced by their successful introduction in a wide variety of geomorphological habitats from Japan to Puerto Rico and Mexico. Thus, temperature and habitat are rarely restricting stressors to largemouth bass but may cause mortality through cumulative negative physiological impacts from unsuitable habitat and high or low temperatures. In this model, poor habitat or extremes in temperature as combined stressors result in low probability of habitat use, thus, mathematically representing the physiological impacts from poor habitat and temperature. Because largemouth bass are adapted to the osmoregulatory challenges of freshwater (i.e., retaining ions in an ion-poor solution), these fish experience stress and eventual mortalities at high salinities. This model will predict unsuitable habitat for bass in scenarios where salinity increases and suitable habitat in scenarios where salinities decrease, as well as, identifying poor quality habitat or temperatures through low probabilities of use.

The model has three serious limitations that, given the available data, are impossible to include in the model. First, these fish have strong behavioral tendencies, which result in fish that are highly territorial, actively seeking physical structures (e.g., woody debris, docks, vegetation), and actively avoiding deep water (i.e., most bass are found in less than 3 meters). Modeling this behavioral aspect is not possible, given that depth data are not available and the model only works on presence/absence lacking the density data necessary to determine territorial segregation. Second, largemouth bass do not thrive in habitats with high densities of predators, such as alligator gar or alligators. Although alligator data could be available, the nature of this relationship is more anecdotal than quantitatively described. Lastly, largemouth bass avoid low levels of dissolved oxygen or suffer mortality, if avoidance is impossible. Largemouth bass may tolerate brief excursions below 1 mg/L; however, fish commonly become stressed when dissolved oxygen is consistently below 2 mg/L and will experience mortality if these conditions persist or if dissolved oxygen plummets to near zero. These data are not available as inputs to the model. Consequently, the model may err in prediction based on largemouth bass behavior, predatory pressures, and effects of low dissolved oxygen.

g. Description of model development process including documentation on testing conducted (Alpha and Beta tests)

1. CPRA identified largemouth bass for inclusion as a target species for the ecosystem service modeling.

2. The original HSI for largemouth bass by Stuber (1982) was retrieved. Stuber's (1982) HSI included 22 variables that described four primary habitat selection factors, which were food, cover, water quality, and reproduction. Food was described by a total dissolved solids variable. Cover was described as % area greater than 6 m deep, % bottom cover, and two water level fluctuation variables. Water quality was described by dissolved oxygen, pH, temperature, turbidity, and two salinity variables. Reproduction was described by % area greater than 6 m deep, temperature, salinity, substrate, and water level fluctuation variables. Each variable had a reported non-linear relationship with a suitability index based on literature reports or observational knowledge. Not all 22 variables were available from Eco-Hydrology, Wetland Morphology, or Vegetation models for this modeling effort. Therefore, the author conducted a search of the published literature, theses and dissertation, and agency reports and documents for updated information on largemouth bass relationships with habitat and water quality variables and distributional data, specifically targeting variables, such as temperature and salinity, that would be available from the outputs of the other modules
3. These data were used to update the variable-suitability index relationships reported by Stuber (1982) based on reported values in the literature, theses and dissertations, and agency reports. Additional variables, such as chlorophyll *a* (as a measure of primary production), were added based on more recent Louisiana State University graduate student research (Fries 2010) and studies in other states (e.g., Peer et al. 2006). Some recent fish monitoring data (4 collections between 2008-2010) and associated physicochemical data were withheld for validation.
4. A HSI was constructed from these data such that optimal habitat or water quality variables were set at a suitability of 1.0. Literature values, when reported in the appropriate format, or non-linear models were used to describe the relationship between reported sub-optimal values and reported abundance, density, or presence/absence data. Once constructed, the HSI predictions were compared against the 4 withheld fish sampling efforts. The HSI was successful in this validation.
5. Through an iterative process in cooperation with CPRA, water depth and habitat similarity variables were removed and suitability functions were adjusted to better fit the available data.

2. Technical Quality

a. Theory

The concept of a habitat suitability model for a species has roots in the Hutchinson's (1957) multidimensional niche. Simply put, for each environmental parameter (or stressor), a species has a bell-shaped response peaking in optimal, decreasing over sub-optimal conditions in higher and/or lower values, and eventually reaching zero ability to support organisms in extremes beyond a species' tolerance. Because many environmental parameters may impact an organism, the niche may be conceived as a multi-dimensional volume defined by these multiple individual tolerance relationships. In the central region of this volume, conditions across all environmental parameters are optimal, and organisms experience low stress, high reproductive success, and high somatic growth. As conditions approach the volume's boundaries, one or more environmental parameters exert a stress upon the organisms that decreases reproductive success and/or growth. Beyond the volume's boundaries, conditions are such that organisms will experience mortality. This concept is still widely applied (e.g., Davies and Jackson 2006), forms the foundation of several state aquatic biological monitoring programs (e.g., Ohio and Maine) and is being considered for adoption in other states (e.g., Texas and Florida).

In the case of largemouth bass, despite the fish consisting of two species and a hybrid, the multidimensional niche is readily described by an HSI. In Stuber's (1982) HSI, the largemouth bass niche was defined by 22 environmental parameters, of which only four variables were available in the outputs from other master plan models. However, only a few parameters directly cause mortality, whereas the other parameters stress fishes decreasing growth and/or reproductive success. Specifically, extremes of temperature, salinity, and dissolved oxygen may cause direct mortality. Excessively warm and cold temperatures will cause bass mortality by freezing or by protein breakdown in high temperatures (e.g., upper 30s C). Largemouth bass survive far into the northern United States and southern Canada, and overwinter successfully under ice. Therefore, only extreme temperatures, which are not experienced in coastal Louisiana, are a concern. Salinity only causes mortality at high levels, and salinities near zero are readily tolerated. Largemouth bass are designed to retain and absorb ions at the gills passing excess ions in the urine because their primary habitat is hypotonic (i.e., less ions in the water than their blood). In high salinities, ions enter through the gills at rates greater than may be passed in the urine; therefore, imbalances in internal ionic concentrations may cause acute toxic mortality. Dissolved oxygen values were not available for this model, however, similar to salinity, only extreme values in one direction, very low, are problematic. Therefore, only temperature and salinity factors included suitability values of 0. Other model components would only be considered stressors in relation to growth and reproductive success and did not include 0 values, except aquatic habitat parameter that forced the model to keep the fish in water.

The development of the model then followed that optimal ranges of model inputs were assigned a suitability of 1.0 and sub-optimal to lethal values were either reported directly from the literature or derived from provided data. Suitability curves were fit with polynomial or logit models, if expectations had to be derived, such that optimal values were 1.0, less optimal values were 1.0 > value > 0 with the relative value based on reported abundance, density, or presence/absence data (i.e., habitat variable values associated with higher reported densities or catch-per-unit-effort would be closer to 1.0 and lower values would be scaled closer to 0). Then, the HSI was developed to predict suitability on a 0 – 1.0 scale for each cell per year. Because physicochemical data and catch-per-unit-effort from four fish sampling events were withheld from model development, these data were used to validate the HSI. Subsequent to this validation effort, the HSI was further modified following an iterative process with CPRA to better fit the HSI to available inputs.

V1 - percent emergent vegetation per 500m^2
V2 - average water temperature for April to August
V3 - maximum yearly salinity for June to August
V6 - percent of cell that is SAV per 1km^2
V7 - index value of primary productivity in open waters

HSI = $[(SI_1 \times SI_7)^{1/8} \times (SI_1 \times SI_6)^{1/8} \times (SI_2 \times SI_3 \times SI_7)^{1/12} \times (SI_2)^{1/4}]$

Variables V4 (water depth) and V5 (habitat similarity) were initially proposed for this model; however, through an iterative process in cooperation with CPRA during model output quality review, the variables were removed.

In the equation above, the SIs are weighted following Stuber's (1982) HSI. In Stuber's (1982) HSI, suitability was based on four equally-weighted factors that influence largemouth bass habitat selection, which were food, cover, water quality, and reproductive potential. In the original HSI, 22 variables were used to describe the four factors. To ensure that the product of the geometric mean was bounded by 0 and 1, variables were grouped by the factor that they described and weighted such that each group of variables only contributed 25% to the product. In this HSI, variables were also grouped to address food (SI_1 and SI_7), cover (SI_1 and SI_6), water quality (SI_2, SI_3, and SI_7), and reproduction (SI_2). Even with a ¼ exponent weighting each grouping to 25% contribution, groups with multiple variables would contribute more to the model than groups with only a single variable. Therefore, the exponent was multiplied by 1/(# variables in the group) to ensure that the whole group of variables only contributed 25% to the HSI and was bounded by 0 and 1.

Suitability function for V1 based on % emergent vegetation * 100.

Emergent vegetation, which in this model is included as emergent vegetation of all types per 500 m^2, provides two important functions for largemouth bass. Bass forage on smaller fish and invertebrates that live on the vegetation's submerged surfaces or in the spaces among the vegetation's stalks or roots. Bass also use the shade and physical structures (e.g., roots and submerged stalks) as cover from their predators or to modify their local microhabitat conditions (e.g., seeking shade to cool their body temperatures). The relationship between emergent vegetation with bass suitability was modified from Stuber's (1982) bottom cover variable, because in Louisiana coastal systems, vegetation provides the overwhelming majority of available cover (Fries 2010; Kaller and Kelso 2010), unlike the systems where Stuber's (1982) model was derived that have a diversity of rock, gravel, woody debris, and vegetation as bottom cover. Data from Sammons et al. (2005), Hoyer et al. (2008), Reed and Pereira (2009), and Fries (2010) modified the Stuber (1982) bottom cover – suitability relationship as indicated in Figure 1. Generally, these studies reported that intermediate percent cover values were optimal for largemouth bass because these values afforded suitable cover from predators, allowed microhabitat condition modification, and foraging opportunities without being either too dense for swimming or too sparse. Because lack of cover and reduced foraging opportunities are not directly lethal and operate more as physiological stressors, the suitability function does not reach 0 indicating that unsuitable vegetation will not prevent habitat use but may deter use if other unsuitable conditions co-occur.

$$SI_1 = \begin{cases} 0.01 & \text{for } V1 < 20 \\ 0.0991 * V1 - 1.97 & \text{for } 20 \leq V1 < 30 \\ 1.0 & \text{for } 30 \leq V1 < 50 \\ -0.028 * V1 + 2.4 & \text{for } 50 \leq V1 < 85 \\ 0.01 & \text{for } V1 \geq 85 \end{cases}$$

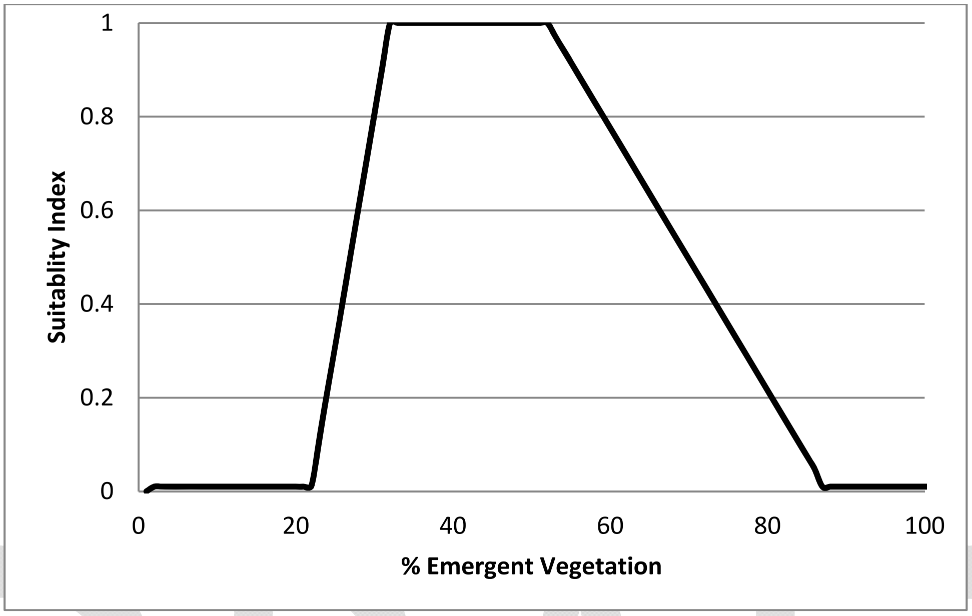

Figure 1. The relationship between % emergent vegetation with the suitability index.

Suitability function for V2 based on temperature in Celsius.

Extreme temperatures are known to be lethal for largemouth bass. In this model, temperature is an interpolated mean of April to August temperatures applied to an individual cell or polygon. Temperatures outside optimal ranges can be physiological stressor through the denaturing of proteins, complications in osmoregulation, and interference with metabolic pathways. Typically, Louisiana coastal waters do not reach temperatures that would elicit direct mortality. However, temperatures do reach stressful values. Stuber (1982) included temperature in the original largemouth bass model, however, the relationship between temperature with the suitability index was largely based on studies in the northern 2/3 of the United States. Since 1982, additional research has occurred in the southern United States and Caribbean that was used to modify Stuber's (1982) relationship between temperature with the suitability index (Neal and Noble 2006, Buisson et al. 2008, Hayer and Irwin 2008, Rogers and Allen 2009, Rypel 2009, Fries 2010). Further, Stuber's (1982) HSI did not distinguish between northern strain or Florida bass that differ in their relationships with temperature. This HSI uses the higher thermal tolerance of Florida bass rather than northern strain bass because of the widespread stocking and occurrence statewide of Florida bass and Florida-northern hybrids (Constant 1990; Fries 2010). The relationship between temperature with the suitability index is indicated in Figure 2. The suitability curve is skewed toward higher temperatures to reflect the genetic contribution of Florida bass. The decision rule below does reach 0 for temperatures reported to be outright lethal to largemouth bass.

$$
SI_2 = \begin{cases} 0 & \text{for } V2 \le 6 \\ 0.061 * V2 + 0.196 & \text{for } 7 \le V2 < 18 \\ 1.0 & \text{for } 18 \le V2 < 30 \\ -0.166 * V2 + 5.9 & \text{for } 30 \le V2 < 36 \\ 0 & \text{for } V2 \ge 36 \end{cases}
$$

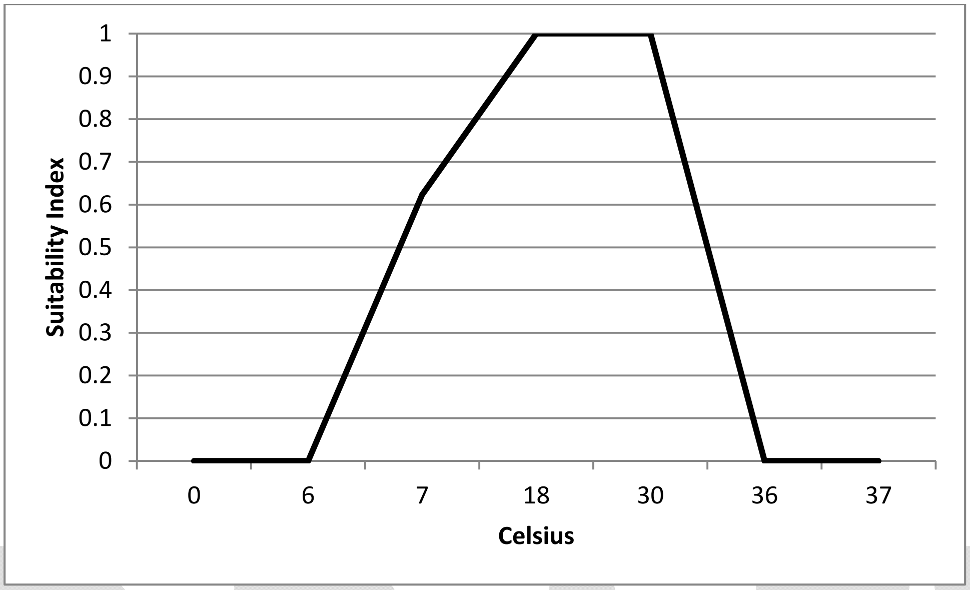

Figure 2. The relationship between temperature with the suitability index.

Suitability function for V3 based on salinity measured in parts per thousand (ppt). Salinity is a very important limiting water quality variable for largemouth bass, which is an interpolated annual mean value applied to an individual cell or polygon. Largemouth bass evolved in a freshwater environment hypotonic to their internal fluids and have developed mechanisms to retain internal ions and capture new ions at the gills and through the gut. However, in saltwater, the environment becomes hypertonic compared to the fish and the osmoregulatory mechanisms that conserve ions in freshwater lead to toxic and often lethal accumulations of ions. Very little research on largemouth bass in coastal and estuarine ecosystems had been completed when Stuber (1982) developed the original largemouth bass HSI and Stuber's (1982) salinity suitability index is zero above 2 ppt. Since 1982, a number of studies in coastal and estuarine environments, as well as, laboratory studies have increased the documented upper salinity tolerance for largemouth bass to 12 ppt (Meador and Kelso 1989, 1990; Peer et al. 2006; Rehage and Loftus 2007). These studies did note physiological impacts between 8 and 12 ppt, and the salinity-suitability index reported in this model reduces suitability between 8 and 12 ppt based on these studies. The upper tolerance at 12 ppt and decreased suitability between 8 and 12 ppt are depicted in Figure 3. Decision rules for the salinity-suitability index are below.

$$SI_3 = \begin{cases} 1 & \text{for } V3 \leq 8 \\ -0.037*V3 + 1.109 & \text{for } 8 < V3 \leq 12 \\ 0 & \text{for } V3 > 12 \end{cases}$$

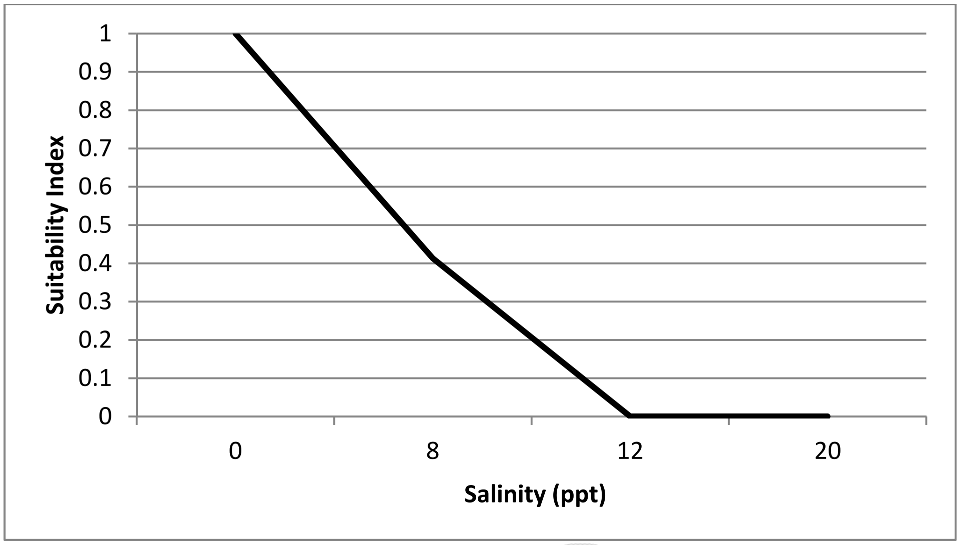

Figure 3. The relationship between salinity with suitability index.

Suitability function for V6, which is the percent of a cell or polygon that is SAV per 1 km^2, restricts largemouth bass to aquatic habitats by excluding terrestrial habitats.
Submersed aquatic vegetation, which in this model is included submersed vegetation of all types per 1 km^2, provides cover and foraging opportunities for largemouth bass, similar to the functions of emergent vegetation. Similar to emergent vegetation, bass forage on smaller fish and invertebrates that live on the vegetation's submerged surfaces or in the spaces among the vegetation's stalks or roots. Bass also use the shade and physical structures (e.g., roots and submerged stalks) as cover from their predators or to modify their local microhabitat conditions (e.g., seeking shade to cool their body temperatures). The relationship between submersed aquatic vegetation with bass suitability was modified from Stuber's (1982) bottom cover variable, because in Louisiana coastal systems, vegetation provides the overwhelming majority of available cover (Fries 2010; Kaller and Kelso 2010), unlike the systems where Stuber's (1982) model was derived that have a diversity of rock, gravel, woody debris, and vegetation as bottom cover. Data from Sammons et al. (2005), Hoyer et al. (2008), Reed and Pereira (2009), and Fries (2010) modified the Stuber (1982) bottom cover – suitability relationship as indicated in Figure 4. Generally, these studies reported that high levels of cover values were optimal for largemouth bass because these values afforded suitable cover from predators, allowed microhabitat condition modification, and foraging opportunities. Because lack of cover and reduced foraging opportunities are not directly lethal and operate more as physiological stressors, the suitability function does not reach 0 indicating that unsuitable vegetation will not prevent habitat use but may deter use if other unsuitable conditions co-occur. This variable also restricts largemouth bass to aquatic habitats because submersed aquatic vegetation is only predicted from the Vegetation module in habitats that are majority aquatic throughout the year.

Values are:
[1 - (% open water + % emergent vegetation)]*100.

$SI_6 = 0$ for V6 = 100
$1-0.01*V6$ for V6 < 100

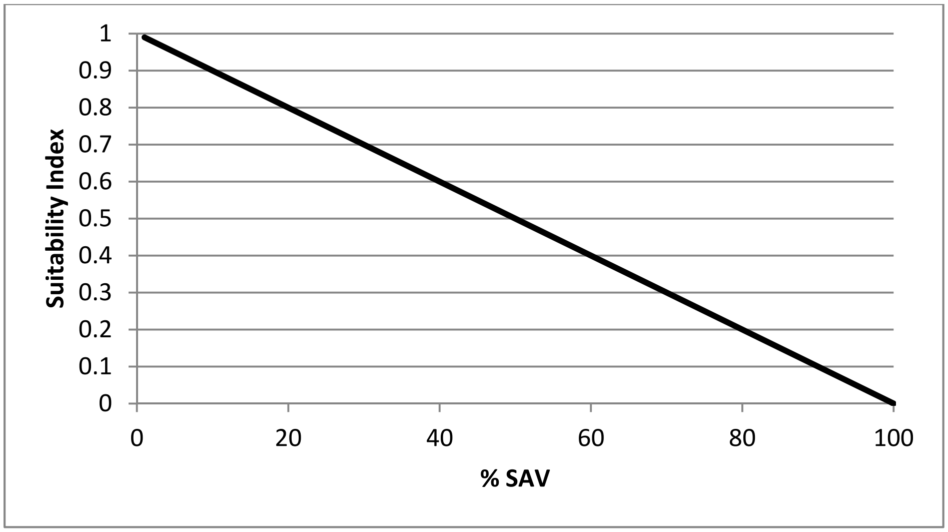

Figure 4. The relationship between % submersed aquatic vegetation with the suitability index.

Suitability Function for V7 based on model predictions of chlorophyll *a* (ug/L).
Primary productivity is a direct predictor of forage availability and water quality. In this model, primary productivity is represented by a surrogate variable, chlorophyll *a*, because primary productivity is difficult to directly measure or model. Chlorophyll *a* is a component of most important phytoplankton and aquatic plants and is readily measured and modeled. Primary productivity was not included in Stuber's (1982) HSI, likely because of difficulty in measurement. However, since 1982, technological advances have eased the measurement of chlorophyll *a*, and several studies have examined the important relationship between primary productivity with largemouth bass (Parkos and Wahl 2002, Fries 2010). The conceptual relationship between primary productivity with largemouth bass is well developed. Primary producers provide forage for zooplankton, small invertebrates, and small fish. Zooplankton and small invertebrates are forage for larval and juvenile bass. Zooplankton, small invertebrates, and small fish are forage for other larger fish and invertebrates that are forage for adult largemouth bass. Highly elevated chlorophyll a is often associated with eutrophication, which may negatively impact largemouth bass through depression of dissolved oxygen. Data reported by Parkos and Wahl (2002) and Fries (2010) did not identify chlorophyll *a* levels where eutrophication was clearly leading to dissolved oxygen depression and bass stress or mortality. Therefore, the relationship between chlorophyll *a* with the suitability index describes a generally positive relationship.

$$SI_7 = \frac{1}{1+ e^{(-1.1835+0.0007973*V7)}}$$

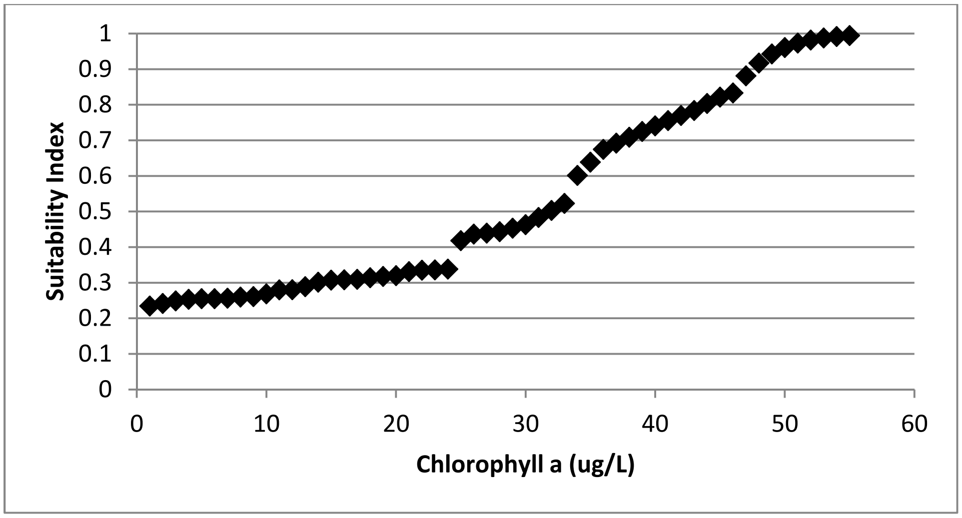

Figure 5. The relationship between chlorophyll *a* with the suitability index.

b. Description of system being represented by the model

This model predicts how suitable the habitat for largemouth bass is in a given cell per year. It does not predict density or abundance. This model addresses aquatic habitat only and primarily reflects the freshening or salinization of aquatic habitats. Although salinity is the principal driver of the model, the influence of salinity is modified by temperature and vegetation variables that reduce habitat suitability when habitat is poor or temperatures are extreme, even if salinity is suitable. As suitability approaches 1, salinity is within tolerable ranges, vegetation and chlorophyll *a*, are appropriate, and temperatures are not extreme. Only salinity may drive suitability to 0 and other variables may only force suitability to very low values.

This model is dependent on temperature, salinity, chlorophyll *a*, and vegetation variables. Any uncertainty in these input variables will be reflected in this model output. Additional discussion of uncertainty and model limitations is included in Sections 5 and 7.

c. Analytical requirements

The largemouth bass HSI has the following analytical requirements: 1) food availability as described by emergent vegetation (SI_1) and chlorophyll a (SI_7); 2) cover as described by emergent vegetation (SI_1) and submersed aquatic vegetation (SI_6); 3) water quality as described by temperature (SI_2), salinity (SI_3), and chlorophyll a (SI_7); and 4) reproduction as described by temperature (SI_2). Because this HSI is based on Stuber's (1982) HSI, 0 to 1 suitability indices derived from the variables are actually incorporated in the HSI. Each 0 to 1 suitability index is derived from the variables following the decision rules associated with Figures 1 through 5 in this document. The suitability index values for each variable are multiplied with the other variables in the groups of food, cover, and water quality, and these products represents the raw suitability of a given cell or polygon with regard to the variables. In the reproduction group, the suitability index is simply the value from temperature. Because food, cover, water quality, and reproduction contribute equally to the HSI, each product of variable multiplication is weighted such that the products are equal. Unequal number of variables in each product unbalance the model, therefore, exponents range from 1/4 for reproduction to 1/12 for water quality so that each product comprises only 25% of the model.

d. Assumptions

During HSI development, several key assumptions were made. First, although the final set of variables all were derived from data collected in Louisiana, supplemental data from neighboring states was included to increase the sample size for deriving the variable-suitability relationships. Because largemouth bass are native, or thriving as an introduced species, across this region, the assumption that data imported from neighboring states and territories was relevant to the HSI development was likely valid. Second, based on comparison of competing functions (e.g., linear and cubic) by chi-square/degree of freedom fit statistic, it was assumed that the polynomial or logit function employed to generate 0 to 1 suitability values were the correct non-linear models. The author has published models selected by this method (e.g., Kaller et al. 2011) and believed this assumption was valid. Finally, the relationship between variables and largemouth bass in the literature were almost always relationships between variables and density or abundance of bass. The HSI operates as a suitability index that predicts presence or absence rather than density or abundance. The author assumed that high predicted density corresponded to high predicted probability of occurrence or habitat suitability and vice versa. Because this assumption may not be true in cases where habitat could be suitable, but fish could not reach these habitats, it is important to acknowledge that high suitability implying presence is an assumption. However, given the natural dispersal capability of largemouth bass and widespread stocking, it is unlikely that barriers are a problem and the assumption of habitat suitability implying presence is likely valid.

e. Identification of formulas used in the model and proof that the computations are appropriate and done correctly

The model decision rules that were coded are provided in section 2.a. above. Quality review was performed by both the model coders and CPRA to ensure formulas and computations were correct.

3. *System Quality*

a. Description and rationale for selection of supporting software tool/programming language and hardware platform

Building upon the ecological modeling application development performed for the Everglades modeling community, Java was used as the programming language inside the Eclipse RCP environment which supports plug-in software development. This approach facilitated the construction of software suites which execute the specific decision rules provided by subject matter experts allowing an end-user to choose which of the ecosystem services models to run.

b. Proof that the programming was done correctly

All software products are the result of multiple programmers working in concert. As part of the code development process, code classes were either developed by teams which ensured multiple individuals were conducting real-time code reviews or when codes were individually written, spot checks were done prior to production builds and exports.

c. Availability of software and hardware required by model

The choice of Java as the development platform ensures the broadest execution platform. These software suites can run on desktops with the following operating systems: Windows XP, 7

(32 and 64 bit), Apple OSX (32 and 64 bit), Linux. Furthermore, these Java executables could be easily re-compiled to run on Windows or Linux Application Servers.

d. Description of process used to test and validate model

Model output validation occurred at two points in the process. As described previously, four data collections were compared to model predictions in a cross-validation type approach. Secondly, visual inspection of the model output by the author and representatives of CPRA compared to known largemouth bass distributions suggested improvements, and following improvements, model success in prediction. The model output also was exhibited to a representative of the U.S. Fish and Wildlife Service, who generally agreed with the output except for the coarse size of some polygons which may yield deceptive distributions near Marsh Island. Because the polygon sizes are set by other working groups, this valid criticism is not actionable.

e. Discussion of the ability to import data into other software analysis tools (interoperability issue)

Being standards compliant with international modeling data standards ensures rather broad interoperability. Unidata actively supports netCDF read/write libraries for C++, Java, C# and Fortran programming languages across multiple operating systems. Additionally, netCDF is natively consumable by commercial software product such as ESRI ArcMAP and MatLab. Furthermore, the Everglades Joint Ecologic Modeling community has backed a USGS software development effort resulting in EverVIEW which brings an open-source visualization platform solution to the complex realm of binary modeling data.

4. *Usability*

a. Availability of input data necessary to support the model

The model requires readily available or predictable temperature, salinity, emergent vegetation, submerged vegetation, and chlorophyll *a* data. The input files required to run this model are available through the CPRA.

b. Formatting of output in an understandable manner

The output data is a suitability index ranging from 0.0 to 1.0 that represents the potential for agriculture/aquaculture of a 500 x 500m model grid cell. The output files are in netCDF format and can be viewed using EverVIEW or ArcGIS.

c. Usefulness of results to support project analysis

Specifically, large changes in the predicted HSI values reflect changes in salinity. Salinity either causes aquatic habitats to become unsuitable by becoming excessively high, which causes direct mortality for largemouth bass, or by altering vegetation such that the vegetation no longer supports cover and forage needs of largemouth bass. If land loss occurs through coastal erosion and/or salinity increases through saltwater intrusion, habitat suitability will decrease and, eventually, reach zero. If aquatic habitats are fresh and remain fresh, suitability will remain moderate to high. If saline habitats freshen below 12 ppt, suitability will increase and will increase more dramatically if salinity falls below 8 ppt. Given these responses to changes in salinity directly and through vegetation, largemouth bass are an ideal organism to evaluate increases and decreases in salinity as a result of various restoration and protection projects.

Diversion, pumps, levee notches or breaches, or other projects that add freshwater to coastal marshes should increase habitat suitability in adjacent cells and polygons and may increase the number of cells and polygons with suitable largemouth bass habitat. Dams, levees, closures, or other actions that prevent freshwater from entering marshes should increase or maintain high salinities and thus decrease habitat suitability. Because no additional coastal action over the next 50 years would likely result in an increase in coastal salinities, decreasing habitat suitability predicted by this model illustrates the consequences of no future protection and restoration action. Finally, because salinity of 12 ppt is a threshold for zero suitability and 8 ppt marks a point where suitability rapidly increases or decreases, the largemouth bass HSI also indicates habitats transitioning through intermediate salinities becoming saltier or fresher.

d. Ability to export results into project reports

The model output is in netCDF format, which provides both a graphical and tabular representation of the model results that can be incorporated into reports. Model outputs can also be imported into ESRI ArcMap.

e. Training availability

Training for model usage would be provided through CPRA.

f. Users documentation availability and whether it is user friendly and complete

There are currently no user's guides or technical manuals to support the model; however, the model does have a help screen that explains how to convert model inputs into the necessary format as well as which files are necessary to run the model.

g. Technical support availability

Access to technical support would be provided through CPRA.

h. Software/hardware platform availability to all or most users

The ecosystem services modeling suite, being coded in Java, will run on most operating systems.

i. Accessibility of the model

Access to model and associated installation and execution files would be provided through CPRA.

j. **Transparency of model and how it allows for easy verification of calculations and outputs**

Model code will be provided for review.

5. Sources of model uncertainty

This model relies on measured and interpolated data, such as temperature and salinity, as well as, modeled inputs, including emergent vegetation and chlorophyll *a*. As with all data, errors occur during measurement, and as with all modeled data, model outputs are estimates with varying levels of confidence. However, validation against withheld data, and visual inspection of model output against known patterns in largemouth bass distribution suggest that these errors are small. Other errors from the omission of important variables, such as dissolved oxygen and behavioral variables may be reduced through interpretation rather than drawing direct conclusions from inspection of the output. For example, the model does appear to predict largemouth bass in open water, which is not likely given their strong behavioral tendencies against open water (i.e., a Type I error of falsely identifying habitat). This may contribute to some uncertainty in the in-shore and off-shore distributions; however, if the outputs are interpreted with insight into behavior, this uncertainty should be minimized.

6. *Suggested model improvements*

Inclusion of water depth and dissolved oxygen data would have greatly improved model predictions. As mentioned in Section 5, the model does predict largemouth bass in open waters that they are unlikely to use. In other words, the model has that potential for Type I errors in incorrectly identifying suitable habitat. However, as mentioned in Section 5, interpretation of model output could address this shortcoming. Further, it is possible that although freshwater diversions lower salinity, the same inputs could lower dissolved oxygen. Potentially, largemouth bass could then be limited by dissolved oxygen, despite adequate conditions in other variables, which would result in Type I model error. This error would be much more difficult to address in the current output. The author suggests inclusion of these variables as inputs in future modeling efforts.

7. *Quality review*

Specific QR procedures for the Largemouth Bass HSI module to support the 2012 Coastal Master Plan included comparison of modeled predictions with expected outcomes given the known inputs. The modeling team used known spatial patterns and temporal patterns in input to predict patterns in habitat quality for each of the species

8. *Uncertainty analysis*

Details regarding the uncertainty analysis for this model is available in Appendix D-27 Model Uncertainty Analysis. This analysis examined the decision rules for each model variable. As well, additional model runs were performed on original and modified decision rules for the variables. Specifically, decision rules for variables SI_1 (emergent vegetation) and SI_6 (submersed aquatic vegetation) were modified during the uncertainty analysis.

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