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# PREDICTING THE EFFECTS OF PROPOSED MISSISSIPPI RIVER DIVERSIONS ON OYSTER HABITAT QUALITY; APPLICATION OF AN OYSTER HABITAT SUITABILITY INDEX MODEL

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***ABSTRACT*** In an attempt to decelerate the rate of coastal erosion and wetland loss, and protect human communities, the state of Louisiana developed its Comprehensive Master Plan for a Sustainable Coast. The master plan proposes a combination of restoration efforts including shoreline protection, marsh creation, sediment diversions, and ridge, barrier island, and hydrological restoration. Coastal restoration projects, particularly the large-scale diversions of fresh water from the Mississippi River, needed to supply sediment to an eroding coast potentially impact oyster populations and oyster habitat. An oyster habitat suitability index model is presented that evaluates the effects of a proposed sediment and freshwater diversion into Lower Breton Sound. Voluminous freshwater, needed to suspend and broadly distribute river sediment, will push optimal salinities for oysters seaward and beyond many of the existing reefs. Implementation and operation of the Lower Breton Sound diversion structure as proposed would render about 6,173 ha of hard bottom immediately east of the Mississippi River unsuitable for the sustained cultivation of oysters. If historical harvests are to be maintained in this region, a massive and unprecedented effort to relocate private leases and restore oyster bottoms would be required. Habitat suitability index model results indicate that the appropriate location for such efforts are to the east and north of the Mississippi River Gulf Outlet.

***KEY WORDS:*** *Crassostrea virginica,* oysters, freshwater, diversions, coastal erosion, habitat quality, habitat suitability index, modeling, Mississippi River, Louisiana

## INTRODUCTION

During the past 5,000 y, the Mississippi River has switched course numerous times (Roberts 1997) (Fig. 1), resulting in a shift in the distribution of local populations of eastern oysters, *Crassostrea virginica* (Mackin & Hopkins 1961, Coleman & Gagliano 1964). As deltas prograde, the main channel of the river—through an inevitable break in the natural levee—finds a more hydrographically efficient route to the sea (Roberts 1997). Interdistributary bays are formed between old degrading deltas and new advancing ones (Coleman & Gagliano 1964) in which a broad mesohaline zone develops into which oysters expand in number and range (Mackin & Hopkins 1961, Coleman & Gagliano 1964). The natural process of delta switching and delta building has been largely circumvented by the construction of levees and control structures to keep the river within its banks, to divert river flow at dangerous flood stages, and to maintain the river along its current course (Barry 1997). The modern Mississippi River Delta (the Bird-Foot or Balize Delta; Fig. 1), being maintained along its current path, is not accreting; it has advanced to the edge of the continental shelf and transports much of its sediment load to the depths of the Gulf of Mexico (Gagliano et al. 1981). In the natural cycle of delta switching, an abandoned deltaic lobe erodes and gives rise to a new accreting one. The modern coast of southeast Louisiana is, however, deprived of much of the sediment load of the Mississippi River, which bypasses its deltaic system. To counter coastal land loss, large-scale diversions of fresh water and sediment have been proposed (Day et al. 1997, Day et al. 2009, CPRA 2012).

To decelerate the rate of coastal erosion and wetland loss, and to protect human communities, Louisiana's Comprehensive Master Plan for a Sustainable Coast (CPRA 2012) has been developed. The master plan proposes a combination of restoration efforts including shoreline protection, marsh creation, sediment diversions, and ridge, barrier island, and hydrological restoration. Coastal restoration projects, particularly large-scale diversions needed to transport sediment, will affect oyster populations and oyster habitat.

The voluminous fresh water needed to suspend and broadly distribute river sediment pushes optimal salinities required by oysters seaward, potentially beyond existing reefs. Sedimentation covers oyster reefs; land building converts open water to marsh.

Oysters occupy a relatively narrow zone of intermediate salinity (Gunter 1952, Cake 1983, Chatry et al. 1983, Melancon et al. 1998). When salinity patterns shift at a particular location, oyster populations establish a new distributional equilibrium (Gunter 1952). With the extension of levees along the lower Mississippi River, salinity increased and oyster populations shifted inland (Gunter 1952, Mackin & Hopkins 1961, Coleman & Gagliano 1964); proposed diversions portend a seaward shift in optimal oyster habitat. Oyster habitat suitability index (HSI) models are designed to evaluate the suitability of a habitat to support oysters (Cake 1983, Brown & Hartwick 1988, Soniat & Brody 1988, Barnes et al. 2007). Cake (1983) developed the initial eastern oyster HSI model for environmental impact assessment

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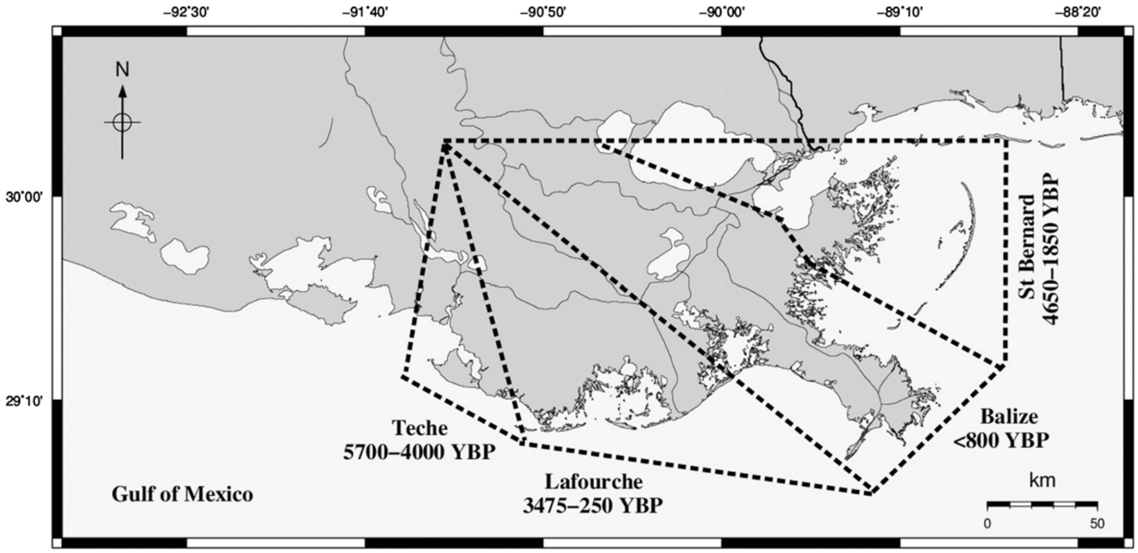

**Figure 1. Approximate location and age (years before present; YBP) of the Teche, St. Bernard, Lafourche, and Balize subdeltas of the Holocene Mississippi River Delta (modified and redrawn from Yuill et al. (2009)).**

and habitat management. Brown and Hartwick (1988) applied a Pacific oyster HSI to the selection and protection of aquaculture sites. The Soniat and Brody (1988) model was intended for the assessment of impacts on habitat quality from canal dredging, spoil bank construction, and other hydrological alterations. Barnes et al. (2007) used their HSI model to simulate habitat response to proposed freshwater inputs.

As part of the master plan an oyster HSI was developed (Soniat 2012). The model was used as a broad-based management tool to determine the consequences of the statewide implementation of the master plan in comparison with a no-action strategy (CPRA 2012, Nyman et al. 2013). In contrast, the purpose of this work is to develop the HSI for the evaluation of the effects of specific restoration projects, using the proposed sediment and freshwater diversion from the Mississippi River into Lower Breton Sound as an initial application.

## MATERIALS AND METHODS

### *Study Site*

Model simulations were conducted to determine the effects of freshwater diversion on oyster habitat quality in Breton Sound and immediately adjacent waters. Breton Sound is

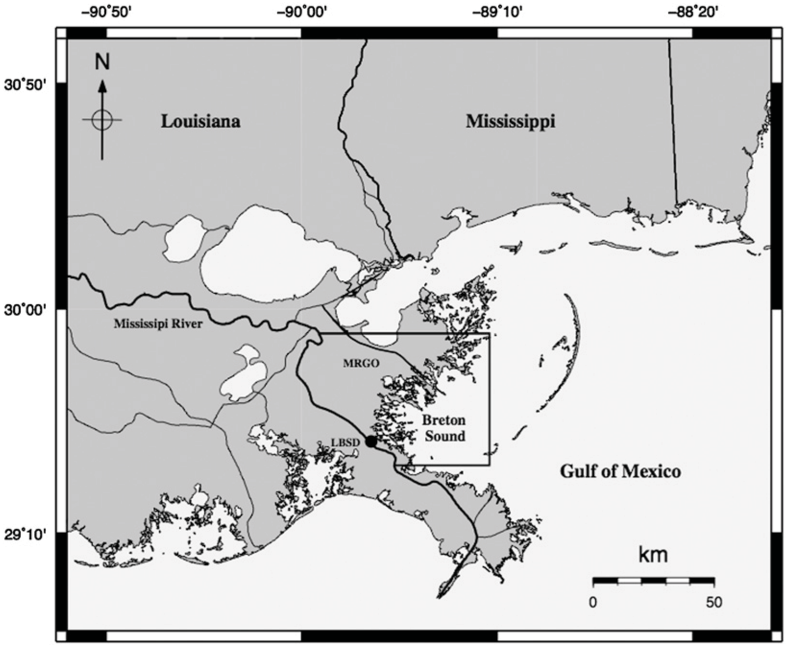

**Figure 2. Study location in the Breton Sound area. The Mississippi River forms the western boundary of the study area; the north, south, and east boundaries are delineated as straight lines. MRGO identifies the location of the Mississippi River Gulf Outlet. LBSD is the location of the proposed Lower Breton Sound Diversion structure.**

a 271,000-ha microtidal estuary located in the Mississippi River deltaic plain of southeast Louisiana; it is bounded to the east by the Mississippi River Gulf Outlet (MRGO) and to the west by the Mississippi River (Fig. 2). It consists of a myriad of lakes, bayous, bays, and canals, with fresh, intermediate, brackish, and saline marsh (Lane et al. 1999, Penland et al. 2002, Piazza & LaPeyre 2012). The model simulation study area was delineated to encompass 362,546 ha east of the Mississippi River (Fig. 2). The study area includes regions where oysters are harvested and where most of the reefs in the Breton Sound basin are found, as well as higher salinity regions beyond the locus of current oyster populations that may be made suitable for oyster cultivation if the diversion is implemented.

### *Model Variables*

The overarching assumption of the oyster HSI model is that oyster habitat quality can be described as suitable salinity over suitable substrate. Suitable salinity is resolved into 3 salinity-based variables, which relate to different aspects of the oyster's dependency on salinity. A higher optimal salinity for spawning and set than for survival of adults is described as mean salinity during the spawning season (Butler 1954, Cake 1983), an annual mean salinity designates an expected range over which oysters exist as well as an optimum range over which they thrive (Gunter 1955, Calabrese & Davis 1970, Castagna & Chanley 1973, Cake 1983, Chatry et al. 1983), and a minimum annual salinity defines the impacts of killing floods (Cake 1983, Soniat & Brody 1988). Suitable cultch is expressed as the percentage of the bottom covered with hard substrate (e.g., oyster shell) (Cake 1983). A percent land variable restricts oysters to aquatic habitats and includes or excludes them from terrestrial ones as land is lost or built (CPRA 2012). The relationship between variable value and suitability index (SI) value is discussed next.

### *Suitability Indices*

The developer-chosen variables with their various units and ranges are converted to a dimensionless SI that varies from 0 (unsuitable) to 1 (optimal). The following is a rationale for and a description of the conversion of variable values to SIs.

Variable 1 ($V_1$) is the percent of bottom covered with suitable cultch (Fig. 3). Oyster larvae require a hard substrate (cultch) on which to settle and metamorphose (Galtsoff 1964). Suitable substrates are hard bottoms such as natural oyster reefs or "shell plants." Shell plants are constructed hard bottoms of natural substrate such as oyster shell or alternative substrate such as limestone. Cake (1983) considered a high-quality bottom to be one in which ≥50% is hard substrate, although no indication was given of the spatial scale over which the variable is to be applied. Soniat and Brody (1988) field tested the Cake model on 0.1-ha sites in Galveston Bay, TX. Although the relationship between $V_1$ and $SI_1$ is somewhat arbitrary, at the extremes the relationship is certain; no substrate is unsuitable and 100% coverage is ideal. It is in the intermediate range of percent cultch (PC) that the uncertainty arises. Cake (1983) considered the relationship between $V_1$ and $SI_1$ to be linear from 0–50% cultch; with PC values of ≥50% assigned an SI of 1.0. In the current construction, SI values for 10%, 20%, 30%, and 40% were assigned explicitly; the resulting relationship yields greater SI values for PC values more than 0% and less than 50% than those of Cake (1983).

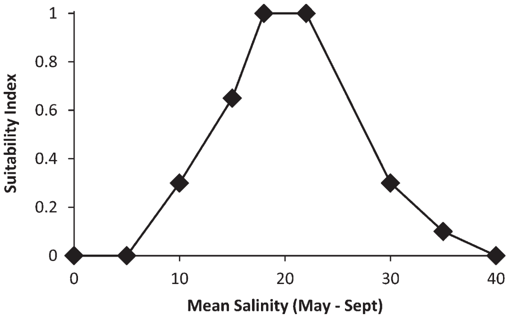

**Figure 4. Conversion of mean salinity during the spawning season (May to September) to suitability index.**

Louisiana has 667,731 ha of public oyster grounds and 155,802 ha of private leases, much of which has not been mapped. To assign a PC value, an approach based on a hierarchy of data quality and surrogates of percent coverage was used. A 500 × 500-m grid overlay of the Louisiana coast was created and populated with PC values. Percent cultch is thus the percentage of the grid that is covered with hard bottom. The highest quality data are from reefs on public grounds mapped using side-scan sonar. Overlays of mapped reefs fall within numerous grids and portions of some grids. The PC values were calculated within a GIS format and assigned to the appropriate grid. The next lower level in the hierarchy is the leases, the boundaries of which are known. If any potion of a lease falls

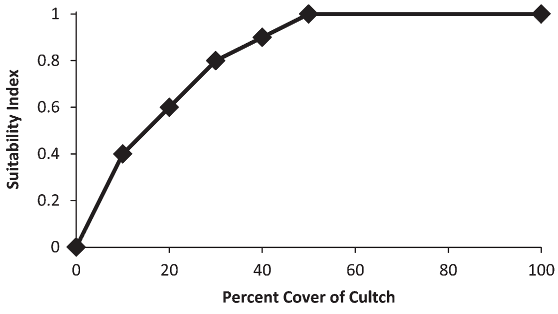

**Figure 3. Conversion of cover of bottom with suitable cultch to suitability index.**

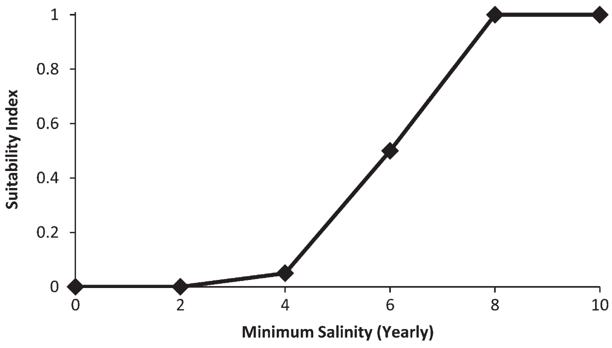

**Figure 5. Conversion of minimal monthly mean salinity within a year to suitability index.**

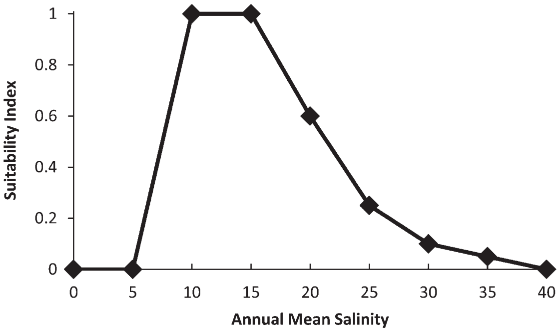

**Figure 6. Conversion of annual mean salinity to suitability index.**

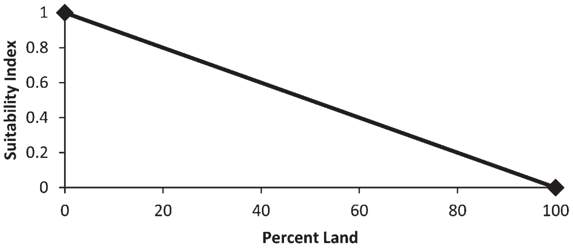

**Figure 7. Conversion of percent coverage with land to suitability index.**

within a grid, a PC value of 10% is assigned to that grid. If the grid is not on a lease but within the north–south and east–west boundaries of leased areas, the grid is assigned a value of 3%. The lowest level in the hierarchy is the public grounds off of a mapped reef. Grids within these areas are assigned a PC value of 3%. Any grid that does not fall in any of these areas is assigned a PC value of 0%.

Salinity values were obtained from master plan ecohydrology models of differing restoration scenarios (CPRA 2012, Meselhe et al. 2012, Meselhe et al. 2013). A single monthly mean salinity was provided for each hydrographic unit (polygon) for each year for 50 y. Polygons provided were considered too large to provide adequate salinity resolution for an oyster HSI. To resolve salinities further, the polygon map was overlaid by a 500 × 500-m grid; linear interpolations were made across salinity gradients, and each grid was populated with a monthly salinity value. The monthly values for each grid were used to derive values of the salinity-based variables ($V_2$, $V_3$, and $V_4$). Variable 2 (mean salinity during the spawning season) was constructed as the mean salinity of May through September means. Variable 3 (minimum salinity) is the minimum value of the 12 monthly mean salinities for each grid. This is an annual representation of a ''sister'' historical variable of Cake (1983)—namely, the frequency of killing floods. Likewise, $V_4$ is an annual representation of Cake's historical mean salinity. The current model does not use historical salinity time series and is an evaluation of habitat quality for 1 y only, based on salinity conditions provided as input from the ecohydrology model (Meselhe et al. 2012, Meselhe et al. 2013).

Variable 2 is the mean salinity during the May to September spawning season (Fig. 4). This variable reflects the higher optimal salinities required for spawning as opposed to the optimum salinity requirements of adults (Butler 1954, Cake 1983).

Variable 3 is the minimum salinity (Fig. 5); in other words, the minimum value of the 12 monthly mean salinities for each grid. This variable is essential to describe impacts of freshwater diversions or hydrological alterations. Low-salinity events, which occur during the summer, have a greater negative impact than those that occur during the winter (Shumway 1996);

**TABLE 1.**

**Monthly and annual flow rates (cfs × 1,000) for the proposed Lower Breton Sound Diversion.**

| Year | January | February | March | April | May | June | July | August | September | October | November | December | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2010 | 32.772 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 | 42.870 | 28.415 | 24.189 | 24.312 | 24.088 | 34.813 | 38.455 |
| 2011 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 | 48.808 | 29.626 | 18.857 | 17.691 | 8.888 | 28.616 | 47.419 | 37.492 |
| 2012 | 47.739 | 34.684 | 48.834 | 42.373 | 36.599 | 32.512 | 31.734 | 38.668 | 23.157 | 19.515 | 27.827 | 49.605 | 36.104 |
| 2013 | 50.000 | 48.831 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 | 50.000 | 42.347 | 45.215 | 37.275 | 49.337 | 47.750 |
| 2014 | 39.006 | 50.000 | 50.000 | 50.000 | 50.000 | 33.931 | 31.179 | 22.970 | 14.968 | 16.614 | 25.699 | 40.266 | 35.386 |
| 2015 | 35.574 | 42.140 | 47.985 | 39.728 | 50.000 | 50.000 | 44.637 | 31.574 | 19.731 | 18.810 | 23.976 | 23.301 | 35.621 |
| 2016 | 29.721 | 45.167 | 42.111 | 46.408 | 50.000 | 50.000 | 37.329 | 31.561 | 21.405 | 26.170 | 41.115 | 50.000 | 39.249 |
| 2017 | 47.066 | 50.000 | 50.000 | 50.000 | 49.455 | 49.701 | 39.409 | 23.360 | 16.867 | 16.524 | 20.381 | 25.636 | 36.533 |
| 2018 | 45.835 | 49.334 | 50.000 | 50.000 | 50.000 | 46.784 | 47.837 | 31.311 | 16.517 | 22.895 | 30.187 | 32.175 | 39.406 |
| 2019 | 40.975 | 50.000 | 49.605 | 50.000 | 50.000 | 45.840 | 41.123 | 22.204 | 2.160 | 0.000 | 0.000 | 16.343 | 30.688 |
| 2020 | 12.088 | 7.454 | 39.334 | 46.427 | 31.554 | 33.744 | 39.401 | 20.183 | 4.461 | 3.786 | 15.275 | 25.915 | 23.302 |
| 2021 | 28.147 | 43.574 | 50.000 | 49.933 | 40.733 | 49.205 | 31.120 | 22.222 | 15.227 | 19.677 | 19.091 | 46.986 | 34.660 |
| 2022 | 38.689 | 48.606 | 40.356 | 50.000 | 50.000 | 49.149 | 27.406 | 18.973 | 13.240 | 25.639 | 28.651 | 31.267 | 35.165 |
| 2023 | 40.575 | 30.383 | 50.000 | 40.688 | 45.383 | 49.429 | 35.406 | 28.103 | 24.768 | 20.297 | 23.469 | 40.552 | 35.755 |
| 2024 | 45.326 | 47.321 | 48.294 | 43.949 | 47.419 | 49.557 | 44.387 | 25.548 | 27.016 | 27.332 | 42.224 | 50.000 | 41.531 |
| 2025 | 50.000 | 50.000 | 45.773 | 47.517 | 34.498 | 29.192 | 23.471 | 4.947 | 15.877 | 8.307 | 4.285 | 15.892 | 27.480 |
| 2026 | 20.797 | 38.777 | 33.915 | 34.200 | 38.498 | 24.080 | 18.426 | 1.613 | 4.792 | 24.526 | 33.392 | 32.036 | 25.421 |
| 2027 | 48.919 | 40.814 | 44.317 | 49.661 | 49.004 | 32.072 | 38.532 | 24.005 | 22.749 | 6.844 | 16.733 | 30.354 | 33.667 |
| 2028 | 38.405 | 42.160 | 50.000 | 50.000 | 50.000 | 50.000 | 47.814 | 33.554 | 36.747 | 26.795 | 18.203 | 26.237 | 39.160 |
| 2029 | 45.773 | 38.246 | 44.854 | 50.000 | 50.000 | 50.000 | 36.934 | 31.835 | 26.293 | 44.299 | 50.000 | 49.861 | 43.175 |

Diversion flow rates are calculated from 1990 to 2009 Mississippi River flow rates and applied to simulation years 2010 to 2029. The diversion structure discharges 50,000 cfs when the river flow is more than 600,000 cfs, 8% of the river flow at river flows between 200,000 and 600,000 cfs, and 0 cfs at a river flow less than 200,000 cfs.

however, the model does not include a temperature effect. Furthermore, the relationship between minimum salinity and $SI_3$ does not describe any potential positive benefits of killing floods, such as reducing predators and disease (Butler 1954, Gunter 1979, Mackin 1962, LaPeyre et al. 2009).

Variable 4 is annual mean salinity (Fig. 6). Annual mean salinity defines the range over which adult oysters survive and thrive (Gunter 1955, Calabrese & Davis 1970, Castagna & Chanley 1973, Cake 1983, Chatry et al. 1983). The relationship between $V_4$ and $SI_4$ follows that of Soniat and Brody (1988), with the exception that the optimum annual mean salinity in the current HSI is a range (10–15) and not a discrete point (12.5).

Variable 5 is percent land (Fig. 7). As land is built with restoration projects, water grids are replaced by land grids; likewise, as land is lost, land grids are replaced by water grids (CPRA 2012, Steyer et al. 2012).

### Habitat Suitability Index

The HSI is determined as the geometric mean of the SI values for the 5 component variables; thus, if any component SI is 0 (unsuitable), HSI is 0 (poor quality habitat).

An annual HSI value is calculated for each 500 × 500-m grid as

$$HSI = (SI_1 \times SI_2 \times SI_3 \times SI_4 \times SI_5)^{1/5}.$$

Note from the previous equation that each variable is given equal weight (unweighted).

### Data Processing

The oyster HSI model was designed to operate against data sets organized in orthogonal grids of 500 × 500-m cells. Percent cultch and percent land data sets were produced for the master plan within the target 500 × 500-m grid (CPRA 2012, Visser et al. 2013). The PC was derived from a number of sources, including oyster leases, public seed grounds, and mapped reefs. Based on their coverage by the source data, a PC value was applied to each of the affected 500 × 500-m cells. As mentioned earlier, however, salinity data were produced within large-scale hydrological units, resulting in data that was spatially too coarse for use in the oyster HSI model. To prepare the salinity data for this model, an interpolation program was developed in the Java programming language as part of the Coastal Louisiana Data Converter suite for the master plan (CPRA 2012). The program down-sampled salinity data from the original hydrographic units into the target 500 × 500-m grid cells by using a spline with a barriers interpolation algorithm found in the ESRI ArcObjects geoprocessing package. This required defining the bounding polygons that would serve as the barriers for the interpolations. The hydrological basin polygons were the logical choice, but after inspection of the initial salinity output the decision was made to combine several of the hydrological basin polygons to allow interpolation across artificial boundaries defined for this modeling effort. The Pontchartrain, Pearl, and Breton Sound basins were merged to create a larger basin for the eastern side of the Mississippi River. The modified hydrological basin file was used as the

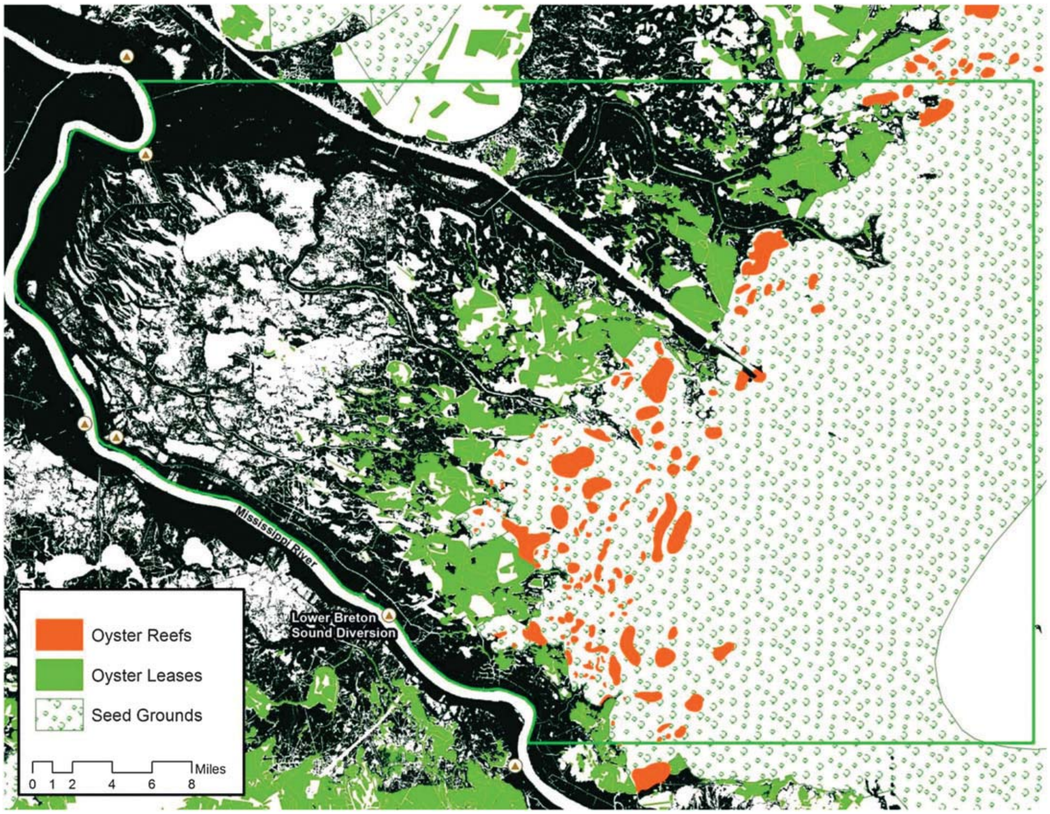

**Figure 8. Locations of private leases, public oyster reefs, and public seed grounds. Location of the proposed Lower Breton Sound Diversion structure is indicated.**

barrier input file by the Coastal Louisiana Data Converter suite to provide the salinity interpolation required for the oyster HSI model.

### Model Software Development

The logic of the oyster HSI model is nested within the Coastal Louisiana Ecological Modeling package produced for the master plan (CPRA 2012). Like the salinity interpolator described earlier, this modeling package was developed in the Java programming language and was informed by earlier ecomodeling efforts performed by the Joint Ecosystem Modeling community of practice (Romañach et al. 2011a, Romañach et al. 2011b). The intuitive user interface allows for quick parameterization and model execution by supplying only the path to a folder containing the 3 required inputs: salinity, cultch, and percent land. Inputs are expected in the network common data form (NetCDF) file format and must adhere to the Comprehensive Everglades Restoration Plan NetCDF metadata conventions defined by Joint Ecosystem Modeling (2011). Output from the oyster HSI model consists of a single NetCDF file containing monthly HSI values for each cell in the target grid.

### Model Application and Simulations

As mentioned earlier, salinity values in small grids were derived from spatially referenced data in large polygons (CPRA 2012, Meselhe et al. 2012, Meselhe et al. 2013). Interpolated monthly salinity values for each grid were used to derive SI values for the salinity-based variables described earlier. Salinities in polygons were generated from hydrographic models using Mississippi River flow rates (USACE Tarbert Landing, MS station; N latitude, 31°00’30", W longitude, 91°37’25"), for years 1990 through 2009 (CPRA 2012). The Tarbert Landing monitoring station is located at river mile 306 just below the Old River Control Structure. There are no major inflows to the river below Tarbert Landing and few major diversions; therefore, flows recorded at Tarbert Landing are a reasonable approximation of the flows of the Lower Mississippi River from there to the mouth of the river. Data years 1990 to 2009 correspond to simulation years 2010 to 2029. Lower Breton Sound Diversion (LBSD) discharge flows are estimated using river flow and appropriate decision rules (Table 1). The diversion structure is to operate at 50,000 cubic feet per second (cfs) when the river

TABLE 2.

**Habitat suitability index summary statistics calculated from 14,444 grids (500 × 500 m) for simulation years 2013 (high-discharge year), 2020 (low-discharge year), and 2023 (average-discharge year).**

| Year | Minimum | Maximum | Mean | SD |
|---|---|---|---|---|
| 2013 | 0.00 | 0.82 | 0.17 | 0.220 |
| 2020 | 0.00 | 0.88 | 0.39 | 0.282 |
| 2023 | 0.00 | 0.90 | 0.28 | 0.274 |

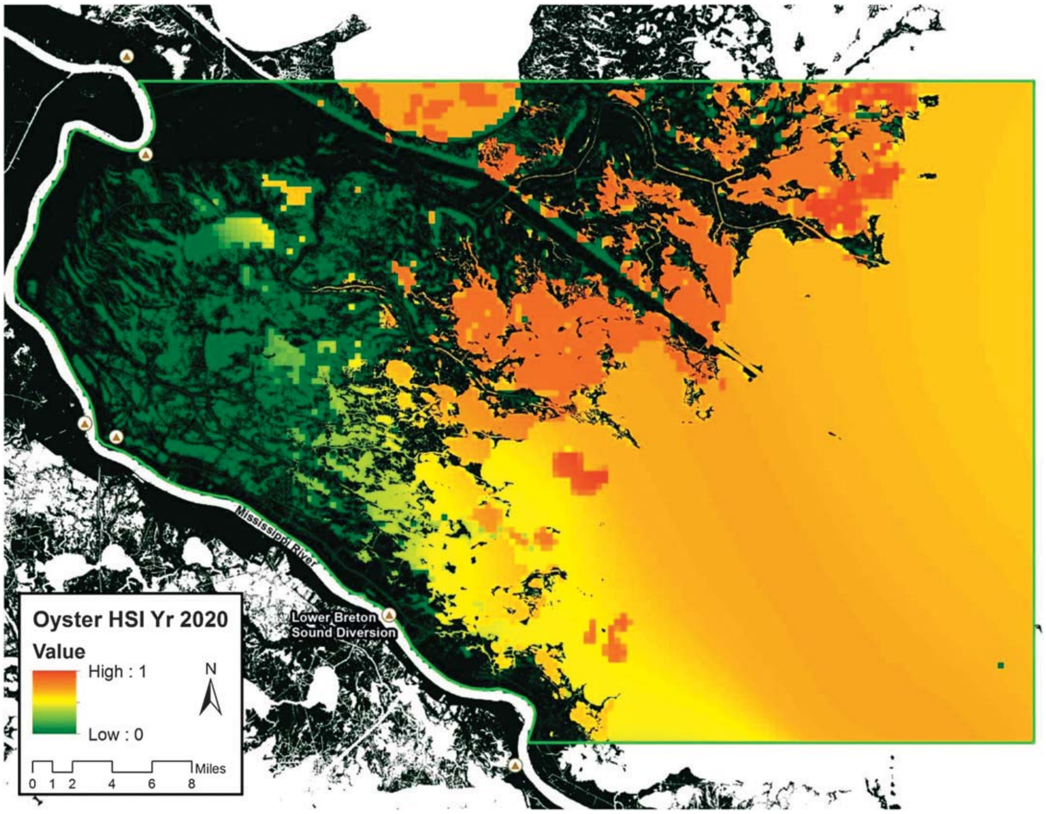

Figure 9. Distribution of habitat suitability index (HSI) in a low-discharge year (2020). Location of the proposed Lower Breton Sound Diversion structure is indicated.

flow rate exceeds 600,000 cfs, 8% of flow when the river flow rate is 200,000–600,000 cfs, and 0 cfs at river flow rates less than 200,000 cfs. The location of the proposed LBSD in relation to private leases and public reefs and seed grounds is shown in Figure 8.

## RESULTS

The model generates an HSI value for each of 14,444 grids for each year (Table 2). Simulation results from the low-discharge year (2020; Table 1) produces the highest mean HSI (0.39; Table 2), whereas simulation results from the high discharge year (2013; Table 1) returns the lowest mean HSI (0.17); the mean discharge year (2023; Table 1) yields an intermediate HSI (0.28; Table 2). The low HSI values and modest range in their means as shown in Table 2 are, in part, a result of the choice of a large study area with many low-quality grids; results are more easily visualized. Figures 9, 10, and 11 show the distribution of HSI and thus the extent of impact of freshwater inflow from the discharge structure (Table 1). A comparison with the distribution of hard bottom (Fig. 8) with low HSI values is an estimate of the reef area made unsuitable for the cultivation of oysters by increased inflow. A grid with an HSI value ≥0.9 is considered optimal for oysters, whereas grids with values of about 0.5 are considered marginal; an HSI value of 0.0 indicates that the habitat is unsuitable (Soniat & Brody 1988).

Under low-discharge conditions (Fig. 9), favorable HSI values are widely dispersed, notably over the area occupied by private leases and public reefs (Fig. 8). Simulation year 2020 (low-discharge conditions) corresponds to river conditions in year 2000. Interestingly, in year 2000, seed oysters (<75 mm) were uncommonly abundant in LDWF Coastal Study Area (CSA) 2, which encompasses our study area. In year 2000, the estimated stock of seed oysters in CSA 2 was about 3.5 million barrels compared with a long-term (1982 to 2010) average of about 1 million barrels (LDWF 2010). The distribution of HSI for a moderate-discharge year (simulation year 2023) is shown in Figure 10. Leases and public grounds from the Mississippi River to mid Breton Sound are affected adversely (Fig. 8). In contrast, under conditions of high discharge (simulation year 2013; Fig. 11), unfavorable HSI values fall over the private leases and public reefs east of the Mississippi River and west of the MRGO (Fig. 8).

A rough upper boundary estimate of the area of public reef made unsuitable for the cultivation of oysters by increased freshwater inflow is derived from an overlay of the distribution of HSI in a heavy-discharge year (Fig. 11) with the distribution of public reefs (Fig. 8), and with reference to the acreage of the reefs affected (LDWF 2010). Under the heavy discharge scenario (Fig. 11), about 4,381 ha of public reef are rendered unsuitable for oyster cultivation. The estimate is based on a total of 7,037 ha of public reef in CSA 2 less the presumably unaffected Lake Fortuna (1,735 ha) and Wreck (921 ha) reefs, north and east of the MRGO, respectively (LDWF 2010). This estimate does not include reefs on private leases. Assuming that all the 17,923 ha of leases in the study area west of the MRGO are affected (Fig. 11), and that about 10% of lease bottoms are

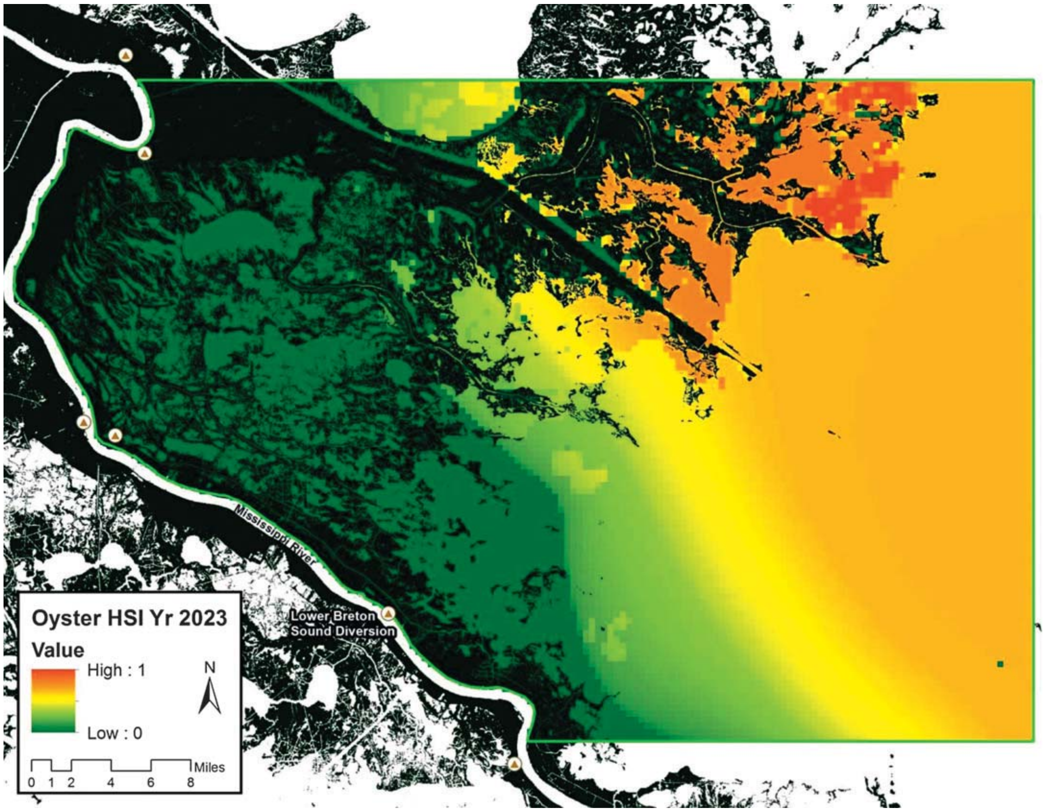

**Figure 10. Distribution of habitat suitability index (HSI) in an average-discharge year (2023). Location of the proposed Lower Breton Sound Diversion structure is indicated.**

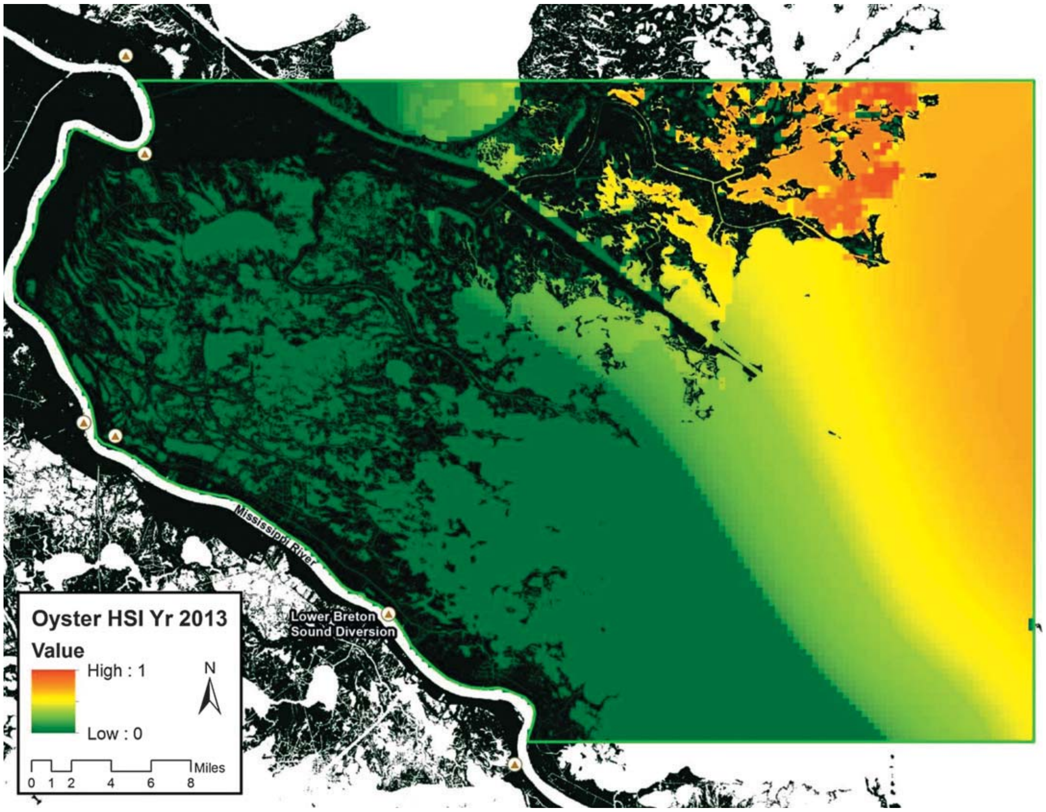

**Figure 11. Distribution of habitat suitability index (HSI) in a high-discharge year (2013). Location of the proposed Lower Breton Sound Diversion structure is indicated.**

hard reef, 1,792 ha of hard bottom on private leases are rendered unsuitable (Fig. 11) by freshwater discharge from the LBSD.

## DISCUSSION

As constructed, the HSI describes the ability of each spatial unit (in this case a 500 × 500-m grid) to support a self-sustaining population of oysters. Thus, the model does not consider metapopulation dynamics whereby, for example, larvae produced from higher salinity environments provide recruits to those in lower salinity ones (Munroe et al. 2012). In the current model, HSI is calculated in a 1-y time step for each spatial unit without the use of historical salinity data. The HSI, therefore, describes the habitat for a particular year for the given annual salinity regime without reference to historical salinity trends, and thus differs from the models of Cake (1983) and Soniat and Brody (1988).

The salinity and habitat requirements of oysters are well known (Galtsoff 1964, Cake 1983, Shumway 1996). Salinity inputs to the HSI model were generated from an ecohydrology model (CPRA 2012, Meselhe et al. 2012, Meselhe et al. 2013) and are subject to any errors inherent in the modeling process (Habib & Reed 2013). Spatially referenced salinity data were provided in polygons of various shapes and sizes. Unfortunately, the polygons were too large for resolution of an oyster HSI; furthermore, the polygons were almost always oriented perpendicular and not parallel to the salinity gradient. The 500 × 500-m grid overlay was used to provide greater spatial resolution of salinity. Each grid was populated with a salinity value by linear interpolation of salinity from the polygons. This procedure, although necessary, introduces an additional uncertainty that can be resolved by finer spatial resolution of salinity output from future hydrographic models. The 500 × 500-m raster was also populated with PC data. As mentioned earlier, these data are of greatly varying quality; however, the raster is a receptacle of all future improvements to the PC map of Louisiana oyster bottoms as existing analog data become digitized, new side-scan surveys are conducted, and new reefs are built.

The goal of large diversions such as LBSD is to deliver from the Mississippi River to the modern delta sufficient suspended sediment to reduce coastal land loss (Day et al. 1997, Day et al. 2009, CPRA 2012). The fresh water required to carry and broadly distribute adequate sediment produces a footprint of salinities unfavorable for oysters (this study) that is much broader than the footprint of the deposited sediment itself (CPRA 2012). The implementation of the LBSD will result in a considerable seaward shift of salinity conditions suitable for the cultivation of oysters. The shift is away from the existing production on the private leases and public reefs into areas with less favorable bottoms. The modeling exercise indicates that the current distribution of leases and public reefs (Fig. 8) is compatible with low (Fig. 9), but not mean (Fig. 10) or high (Fig. 11) discharges. Unfortunately, the fresh water needed to distribute sediment broadly is counter to the maintenance of optimal salinity conditions for oysters given the current distribution of hard bottoms. Although the model's estimation of reef area affected is subject to numerous assumptions, the implementation and operation of the LBSD as proposed would render about 6,173 ha of hard bottom immediately east of the Mississippi River unsuitable for the sustained cultivation of oysters. If historical harvests are to be maintained in this region, a massive and unprecedented effort to relocate private leases and create suitable water bottoms for oyster production is required. The HSI model results indicate that the appropriate locations for such efforts are to the east and north of the MRGO (Figs. 10 and 11).

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