

Predicting the Effects of Proposed Mississippi River Diversions on Oyster Habitat Quality; Application of an Oyster Habitat Suitability Index Model

Authors: Soniat, Thomas M., Conzelmann, Craig P., Byrd, Jason D., Roszell, Dustin P., Bridevaux, Joshua L., et al.

Source: Journal of Shellfish Research, 32(3) : 629-638

Published By: National Shellfisheries Association

URL: <https://doi.org/10.2983/035.032.0302>

The BioOne Digital Library (<https://bioone.org/>) provides worldwide distribution for more than 580 journals and eBooks from BioOne's community of over 150 nonprofit societies, research institutions, and university presses in the biological, ecological, and environmental sciences. The BioOne Digital Library encompasses the flagship aggregation BioOne Complete (<https://bioone.org/subscribe>), the BioOne Complete Archive (<https://bioone.org/archive>), and the BioOne eBooks program offerings ESA eBook Collection (<https://bioone.org/esa-ebooks>) and CSIRO Publishing BioSelect Collection (<https://bioone.org/csiro-ebooks>).

Your use of this PDF, the BioOne Digital Library, and all posted and associated content indicates your acceptance of BioOne's Terms of Use, available at www.bioone.org/terms-of-use.

Usage of BioOne Digital Library content is strictly limited to personal, educational, and non-commercial use. Commercial inquiries or rights and permissions requests should be directed to the individual publisher as copyright holder.

BioOne is an innovative nonprofit that sees sustainable scholarly publishing as an inherently collaborative enterprise connecting authors, nonprofit publishers, academic institutions, research libraries, and research funders in the common goal of maximizing access to critical research.

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

THOMAS M. SONIAT,^{1,2*} CRAIG P. CONZELMANN,³ JASON D. BYRD,⁴
DUSTIN P. ROSZELL,⁵ JOSHUA L. BRIDEVAUX,⁴ KEVIN J. SUIR³
AND SUSAN B. COLLEY¹

¹Department of Biological Science, University of New Orleans, 2000 Lakeshore Drive, New Orleans, LA 70148; ²Pontchartrain Institute for Environmental Sciences, University of New Orleans, 2000 Lakeshore Drive, New Orleans, LA 70148; ³U.S. Geological Survey, National Wetlands Research Center, 700 Cajundome Boulevard, Lafayette, LA 70506; ⁴Five Rivers Services, LLC, 10807 New Allegiance Drive, Colorado Springs, CO 80921; ⁵IAP World Services, National Wetlands Research Center, 700 Cajundome Boulevard, Lafayette, LA 70506

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

*Corresponding author. E-mail: tsoniat@uno.edu
DOI: 10.2983/035.032.0302

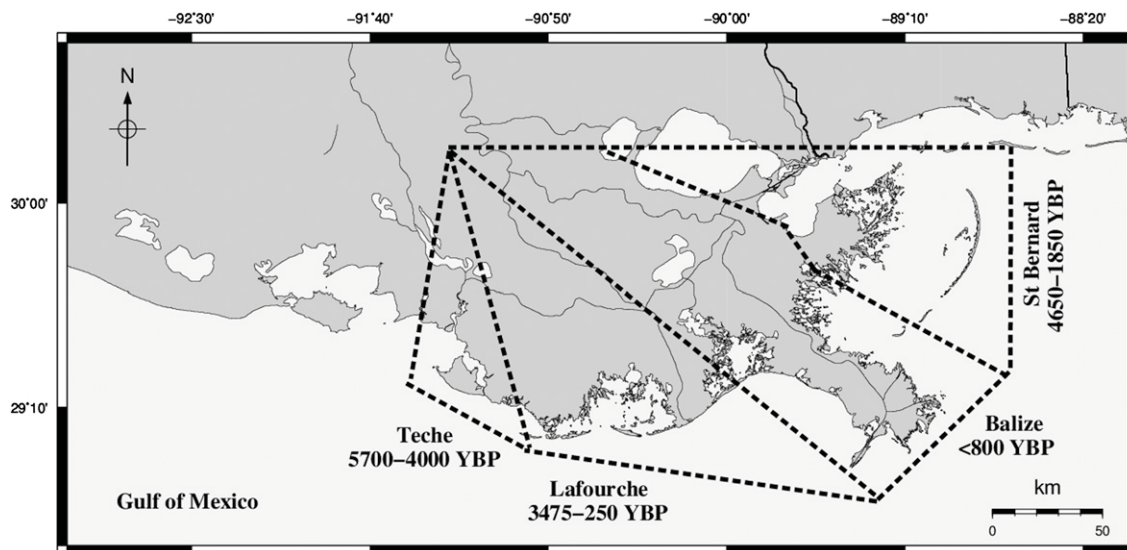


Figure 1. Approximate location and age (years before present; YBP) of the Teche, St. Bernard, Lafourche, and Balize subdeltas of the Holocene Mississippi River Delta (modified and redrawn from Yuill et al. (2009)).

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

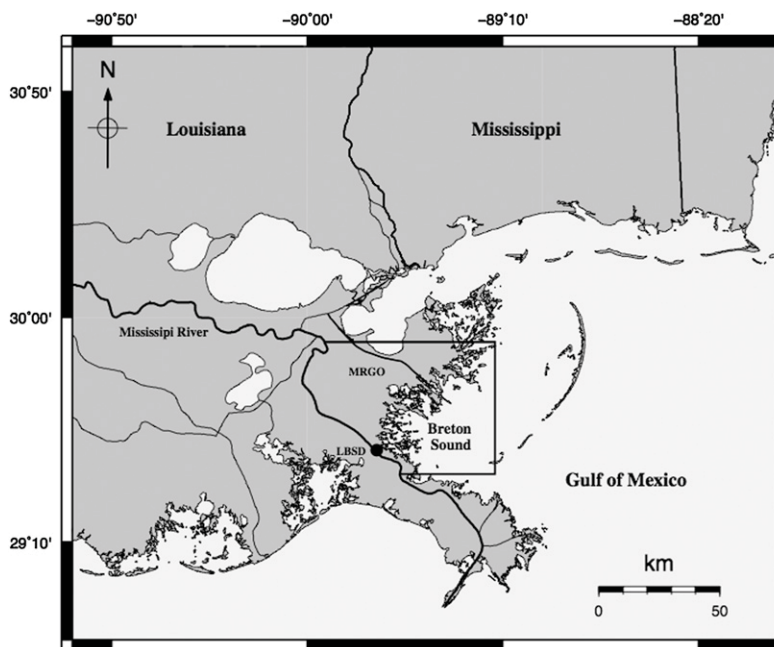


Figure 2. Study location in the Breton Sound area. The Mississippi River forms the western boundary of the study area; the north, south, and east boundaries are delineated as straight lines. MRGO identifies the location of the Mississippi River Gulf Outlet. LBSD is the location of the proposed Lower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

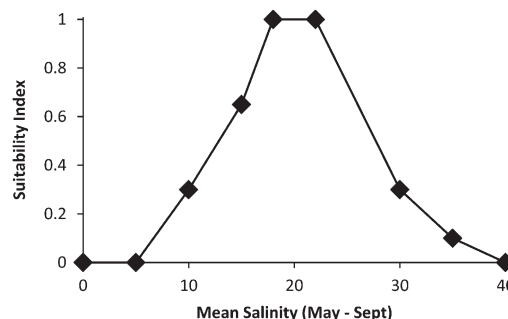


Figure 4. Conversion of mean salinity during the spawning season (May to September) to suitability index.

“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 $\geq 50\%$ 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 $\geq 50\%$ 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).

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 portion of a lease falls

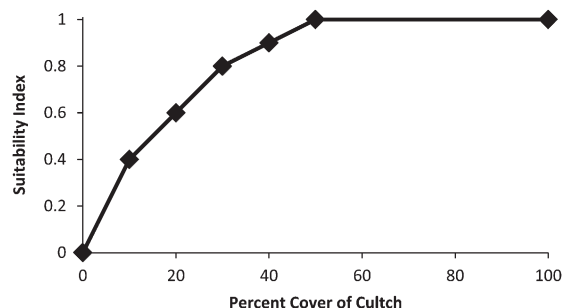


Figure 3. Conversion of cover of bottom with suitable cultch to suitability index.

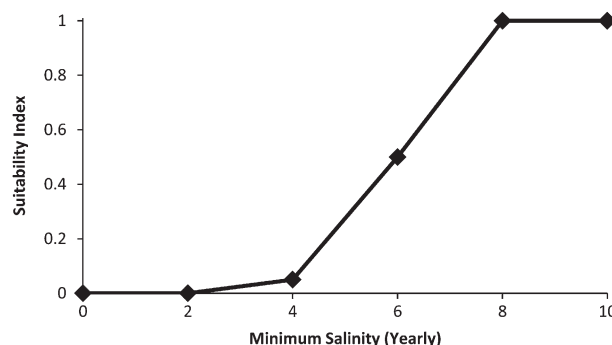


Figure 5. Conversion of minimal monthly mean salinity within a year to suitability index.

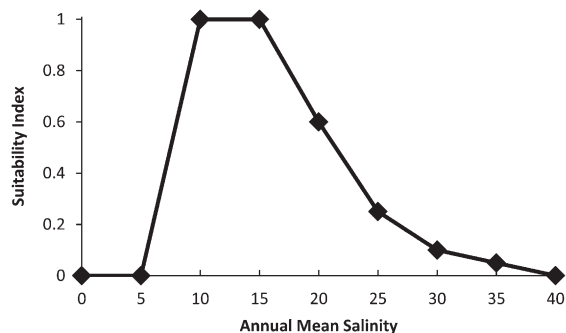


Figure 6. Conversion of annual mean salinity to suitability index.

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

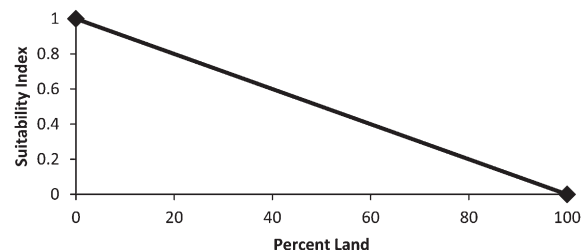


Figure 7. Conversion of percent coverage with land to suitability index.

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

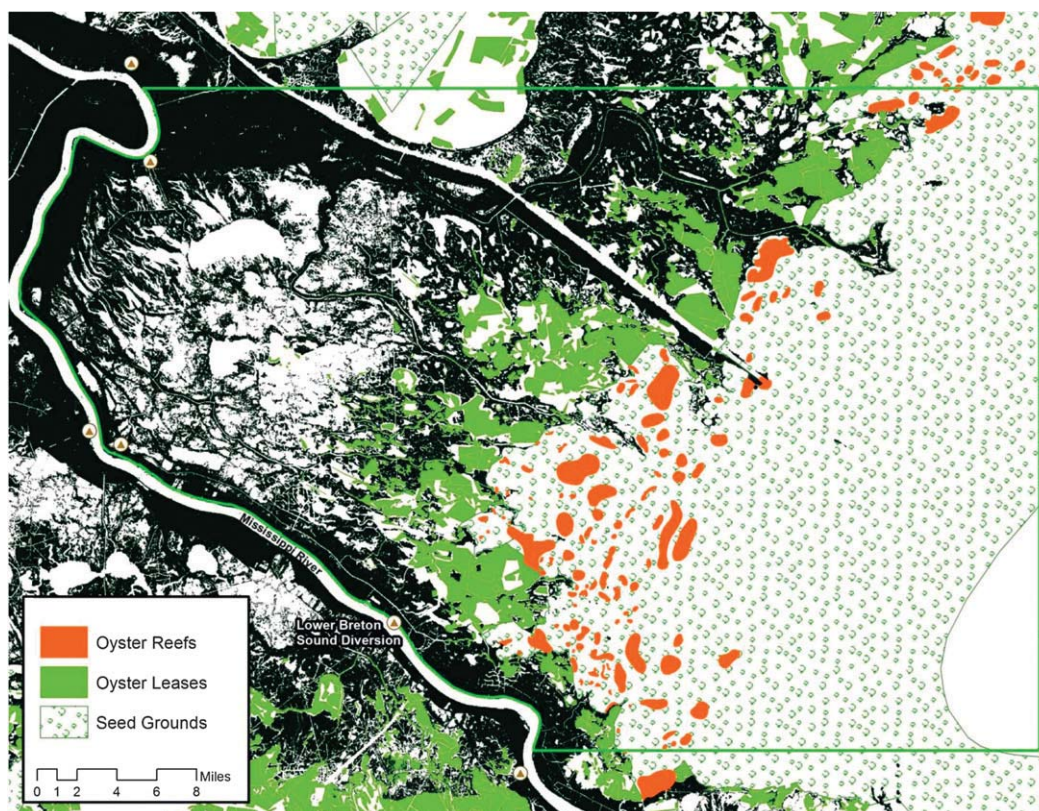


Figure 8. Locations of private leases, public oyster reefs, and public seed grounds. Location of the proposed Lower Breton Sound Diversion structure is indicated.

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

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

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

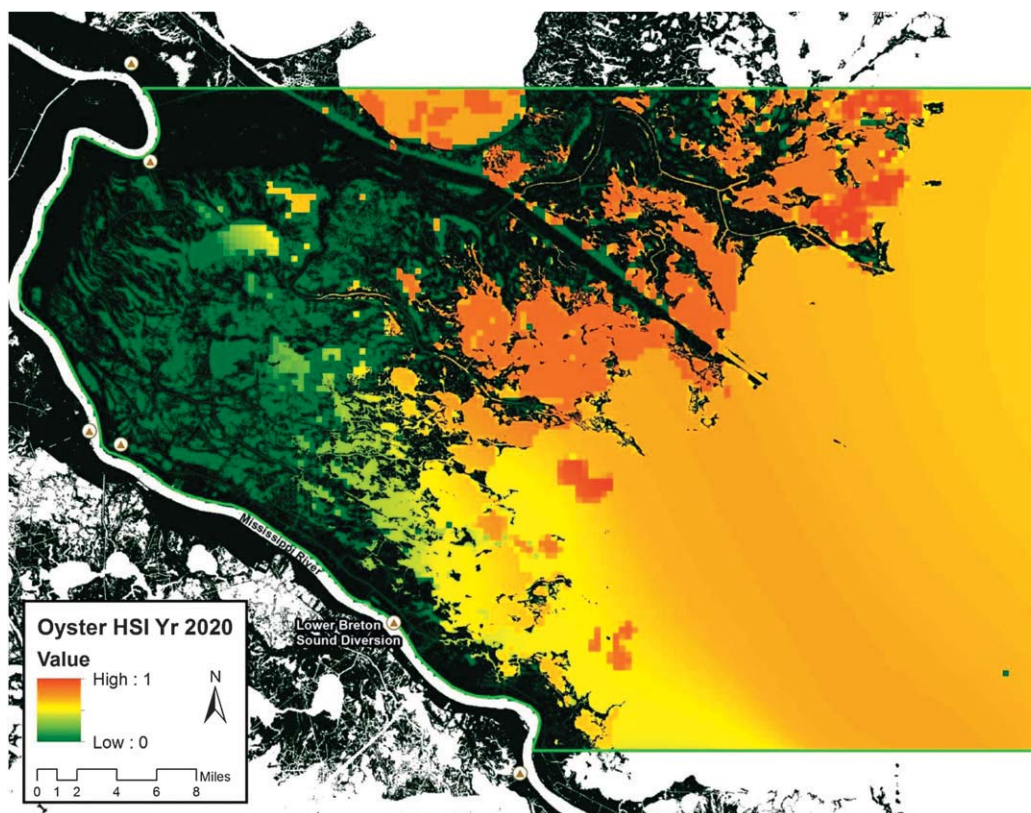


Figure 9. Distribution of habitat suitability index (HSI) in a low-discharge year (2020). Location of the proposed Lower Breton Sound Diversion structure is indicated.

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

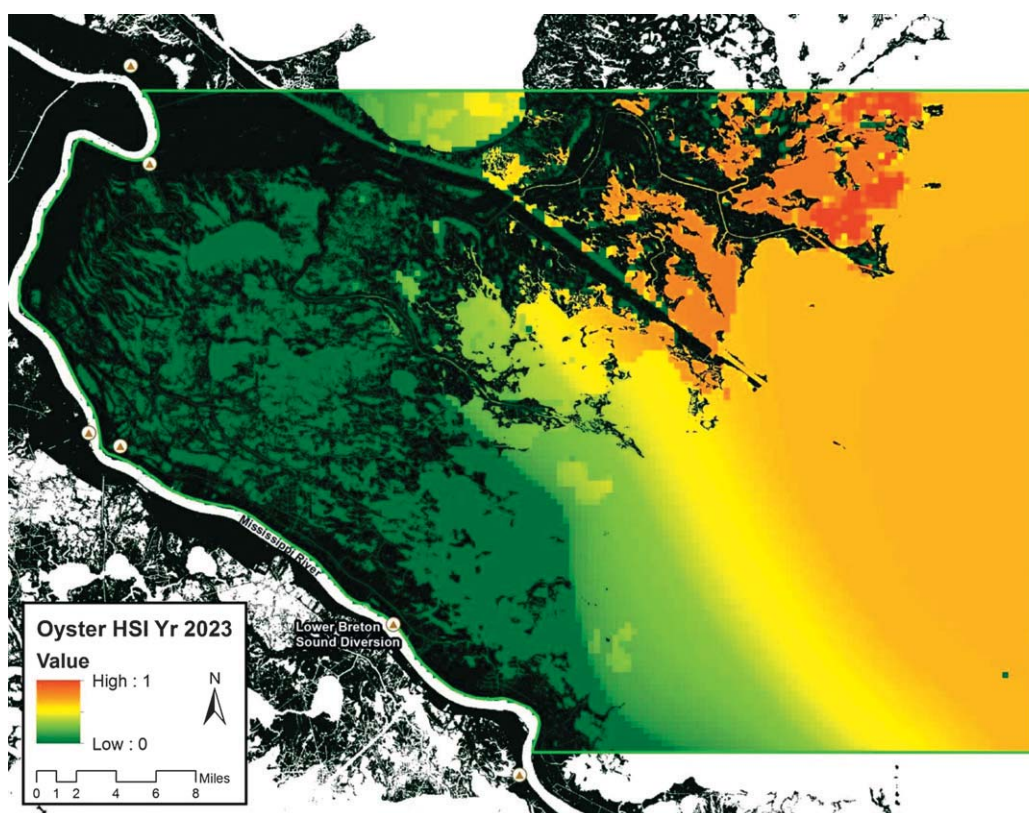


Figure 10. Distribution of habitat suitability index (HSI) in an average-discharge year (2023). Location of the proposed Lower Breton Sound Diversion structure is indicated.

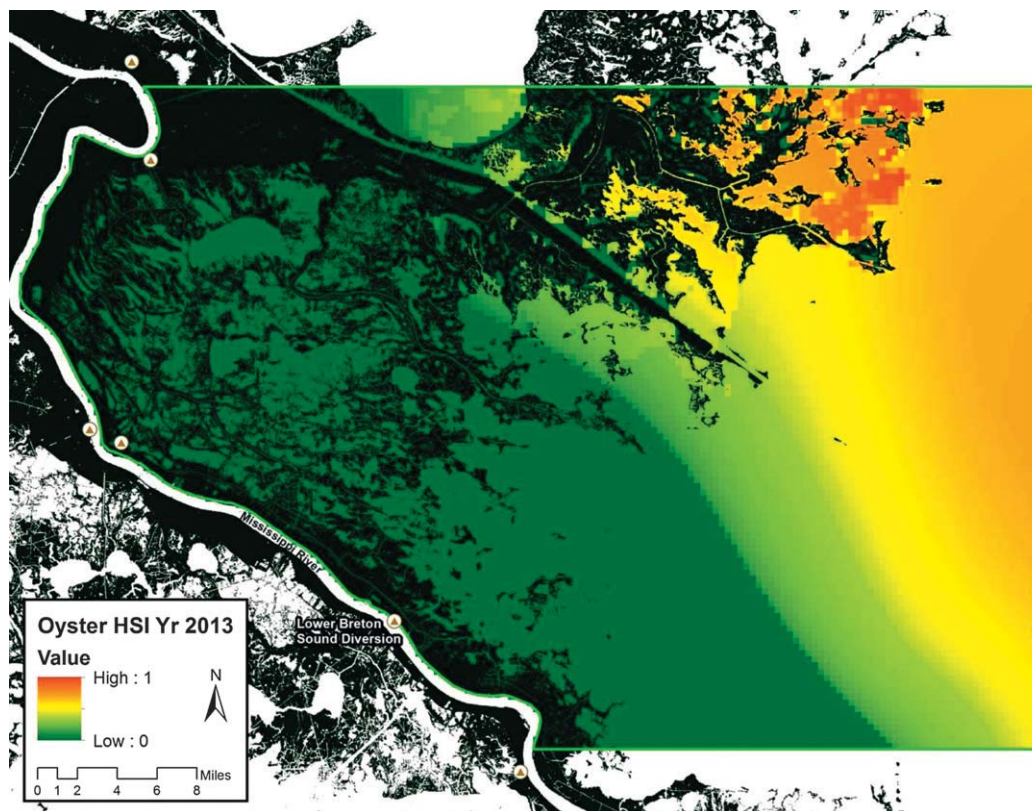


Figure 11. Distribution of habitat suitability index (HSI) in a high-discharge year (2013). Location of the proposed Lower Breton Sound Diversion structure is indicated.

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).

ACKNOWLEDGMENTS

Denise Reed, Natalie Peyronnin, and Alex McCorquodale assisted in obtaining diversion discharge data. Patrick Banks, Michael Kirby, Natalie Peyronnin, Todd Swannack, Molly Reif, and Hongqing Wang provided helpful reviews and comments to an early draft of the manuscript. Nathan Cooper and Josh Gallegos assisted with graphics. We appreciate this assistance.

LITERATURE CITED

- Barnes, T. K., A. K. Volety, K. Chartier, F. J. Mazzotti & L. Pearlstine. 2007. A habitat suitability index model for the eastern oyster (*Crassostrea virginica*), a tool for the restoration of the Caloosahatchee estuary, Florida. *J. Shellfish Res.* 26:949–959.
- Barry, J. M. 1997. Rising tide: the great Mississippi flood of 1927 and how it changed America. New York: Simon and Schuster. 528 pp.
- Brown, J. R. & E. B. Hartwick. 1988. A habitat suitability index model for suspended tray culture of the Pacific oyster, *Crassostrea gigas* Thunberg. *Aquacult. Fish. Manage.* 19:109–126.
- Butler, P. A. 1954. Summary of our knowledge of the oyster in the Gulf of Mexico. *U.S. Fish Wildl. Serv. Fish. Bull.* 55:479–489.
- Cake, E. W. 1983. Habitat suitability index models: Gulf of Mexico American oyster. FWS/OBS-82/10.57. U.S. Dept. of Interior, Fish and Wildlife Service. 37 pp.
- Calabrese, A. & H. C. Davis. 1970. Tolerances and requirements of embryos and larvae of bivalve molluscs. *Helgoland Wiss. Meer* 20:553–564.
- Castagna, M. & P. Chanley. 1973. Salinity tolerance of some marine bivalves from inshore estuarine environments in Virginia waters on the western mid-Atlantic coast. *Malacologia* 12:47–96.
- Chatry, M. R., R. J. Dugas & K. A. Easley. 1983. Optimum salinity regime for oyster production on Louisiana's state seed grounds. *Contrib. Mar. Sci.* 26:81–94.
- Coleman, J. M. & S. M. Gagliano. 1964. Cyclic sedimentation in the Mississippi River deltaic plain. *Trans. Gulf Coast Assoc. Geol. Soc.* 14:67–80.
- CPRA. 2012. Louisiana's comprehensive plan for a sustainable coast. Baton Rouge, LA: Coastal Protection and Restoration Authority of Louisiana. 189 pp.
- Day, J. W., J. E. Cable, J. H. Cowan, R. DeLaune, K. de Mutsert, B. Fry, H. Mashriqui, D. Justic, P. Kemp, R. R. Lane, J. Rick, S. Rick, L. P. Rozas, G. Snedden, E. Swenson, R. R. Twilley & B. Wissel. 2009. The impact of pulsed reintroduction of river water on a Mississippi Delta coastal basin. *J. Coast. Res.* 54:225–243.
- Day, J. W., J. F. Martin, L. Cardoch & P. H. Templet. 1997. System functioning as a basis for sustainable management of deltaic ecosystems. *Coast. Manage.* 25:115–153.
- Gagliano, S. M., K. J. Meyer-Arendt & K. M. Wicker. 1981. Land loss in the Mississippi River deltaic plain. *Trans. Gulf Coast Assoc. Geol. Soc.* 31:295–300.
- Galtsoff, P. S. 1964. The American oyster *Crassostrea virginica* (Gmelin). *U.S. Fish Wildl. Serv. Fish. Bull.* 64:1–480.
- Gunter, G. 1952. Historical changes in the Mississippi River and the adjacent marine environment. *Publ. Inst. Mar. Sci.* 2:120–139.
- Gunter, G. 1955. Mortality of oysters and abundance of certain associates as related to salinity. *Ecology* 36:601–605.
- Gunter, G. 1979. Studies of the southern oyster borer, *Thais haemostoma*. *Gulf Res. Rep.* 6:249–260.
- Habib, E. & D. Reed. 2013. Parametric uncertainty analysis of predictive models in Louisiana's 2012 coastal master plan. *J. Coast. Res.* 67:127–146.
- Joint Ecosystem Modeling. 2011. CERP NetCDF metadata conventions. 5 pp. Available at: http://www.jem.gov/downloads/CERP%20NetCDF%20standard/Cerp_Conventions_v1.1.pdf.
- Lane, R. R., J. W. Day & B. Thibodeaux. 1999. Water quality analysis of a freshwater diversion at Caernarvon, Louisiana. *Estuaries* 22:327–336.
- LaPeyre, M. K., B. Gossman & J. F. LaPeyre. 2009. Defining optimal freshwater flow for oyster production: effects of freshet rate and magnitude of change and duration on eastern oysters and *Perkinsus marinus* infection. *Estuaries Coasts* 32:522–534.
- LDWF. 2010. Oyster stock assessment report of the public oyster areas in Louisiana seed grounds and seed reservations. Oyster data report series. Baton Rouge, LA: Louisiana Department of Wildlife and Fisheries. 93 pp.
- Mackin, J. G. 1962. Oyster disease caused by *Dermocystidium marinus* and other microorganisms in Louisiana. *Publ. Inst. Mar. Sci.* 7:132–229.
- Mackin, J. G. & S. H. Hopkins. 1961. Studies on oyster mortality in relation to natural environments and to oil fields in Louisiana. *Publ. Inst. Mar. Sci.* 7:33–131.
- Melancon, E., T. Soniat, V. Cheramie, R. Dugas, J. Barras & M. Lagarde. 1998. Oyster resource zones of the Barataria and Terrebonne estuaries of Louisiana. *J. Shellfish Res.* 17:1143–1148.
- Meselhe, E., J. A. McCorquodale, J. Shelden, M. Dortch, S. Brown, M. Davis, Z. Wang, P. Elkan & J. Schindler. 2012. Eco-hydrology model technical report (appendix D-1). In: Coastal Protection and Restoration Authority: Louisiana's comprehensive master plan for a sustainable coast. Baton Rouge, LA. 490 pp. Available at: www.coastalmasterplan.louisiana.gov/2012-master-plan/master-plan-appendices/.
- Meselhe, E., J. A. McCorquodale, J. Shelden, M. Dortch, T. S. Brown, P. Elkan, M. D. Rodrigue, J. Schindler & Z. Wang. 2013. Ecohydrology component of Louisiana's 2012 coastal master plan: mass balance compartmental model. *J. Coast. Res.* 67:16–28.
- Munroe, D. M., J. M. Klinck, E. E. Hofmann & E. N. Powell. 2012. The role of larval dispersal in metapopulation gene flow: local population dynamics matter. *J. Mar. Res.* 70:441–467.
- Nyman, J. A., D. M. Baltz, M. D. Kaller, P. L. Leberg, C. P. Richards, R. P. Romaine & T. M. Soniat. 2013. Likely changes in habitat quality for fish and wildlife in coastal Louisiana during the next 50 years. *J. Coast. Res.* 67:60–74.
- Penland, S., A. Beall & J. Kindinger. 2002. Environmental atlas of the Lake Pontchartrain Basin. New Orleans, LA: Lake Pontchartrain Basin Foundation. 185 pp.
- Piazza, B. P. & M. K. La Peyre. 2012. Measuring changes in consumer resource availability to riverine pulsing in Breton Sound, Louisiana, USA. *PLoS One* 7:37536.
- Roberts, H. H. 1997. Dynamic changes in the Holocene Mississippi River delta plain: the delta cycle. *J. Coast. Res.* 13:605–627.
- Romañach, S. S., C. Conzelmann, A. Daugherty, J. L. Lorenz, C. Hunnicutt & F. J. Mazzotti. 2011a. Joint ecosystem modeling (JEM) ecological model documentation 1: estuarine prey fish biomass availability. 1.0.0: U.S. Geological Survey Open-File Report 2011–1272. 20 pp. Available at: <http://pubs.usgs.gov/of/2011/1272/>.

- Romañach, S. S., C. Conzelmann, A. Daugherty, J. L. Lorenz, C. Hunnicutt & F. J. Mazzotti. 2011b. Joint ecosystem modeling (JEM) ecological model documentation 2: roseate spoonbill (*Platalea ajaja*) landscape habitat suitability index. 1.0.0: U.S. Geological Survey Open-File Report 2011–1273. 23 pp. Available at: <http://pubs.usgs.gov/of/2011/1273/>.
- Shumway, S. 1996. Natural environmental factors. In: V. S. Kennedy, R. I. E. Newell, & A. F. Eble, editors. The eastern oyster: *Crassostrea virginica*. College Park, MD: Maryland Sea Grant College, University of Maryland. pp. 467–513.
- Soniat, T. M. 2012. Eastern oyster habitat suitability index (appendix D-13). In: Louisiana's comprehensive master plan for a sustainable coast. Baton Rouge, LA: Coastal Protection and Restoration Authority. 18 pp. Available at : www.coastalmasterplan.louisiana.gov/2012-master-plan/master-plan-appendices/.
- Soniat, T. M. & M. S. Brody. 1988. Field validation of a habitat suitability index model for the American oyster. *Estuaries* 11:87–95.
- Steyer, G., B. Couvillion, H. Wang, B. Sleavin, J. Rybczyk, N. Trahan, H. Beck, C. Fischenich, R. Boustany & Y. Allen. 2012. Wetland morphology model technical report (appendix D-2). In: Louisiana's comprehensive master plan for a sustainable coast. Baton Rouge, LA: Coastal Protection and Restoration Authority. 104 pp. Available at: www.coastalmasterplan.louisiana.gov/2012-master-plan/master-plan-appendices/.
- Visser, J. M., S. M. Duke-Sylvester, J. Carter & W. Broussard. 2013. A computer model to forecast wetland vegetation changes resulting from restoration and protection in coastal Louisiana. *J. Coast. Res.* 67:52–59.
- Yuill, B., D. Lavoie & D. J. Reed. 2009. Understanding subsidence processes in coastal Louisiana. *J. Coast. Res.* 54:23–36.