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A HABITAT SUITABILITY INDEX MODEL FOR THE EASTERN OYSTER (*CRASSOSTREA VIRGINICA*), A TOOL FOR RESTORATION OF THE CALOOSAHATCHEE ESTUARY, FLORIDA

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ABSTRACT A tool in the form of a habitat suitability index model (HSI) for the eastern oyster, *Crassostrea virginica*, was adapted to evaluate and compare the effects of alternative restoration plans in southwest Florida. A component of a large forecasting model, this tool simulates system response by examining the impact of freshwater inputs into the system. The eastern oyster is a good indicator species for modeling because of its sedentary nature and its susceptibility to natural and artificial changes. In addition, oysters form a complex three-dimensional reef structure, which provides habitat and food for numerous species of fish and invertebrates. The model focuses on salinity, temperature, depth, substrate, and high flow frequency as the particular requirements to determine habitat suitability for the eastern oyster. A geographic information system (GIS) incorporates the oyster HSI model, which includes larval and adult components, to determine responses spatially and temporally to facilitate the decision making process. This paper evaluates four hydrologic and land use scenarios for the C-43 West Basin Reservoir Project. Model results indicate that the Preferred Flow scenario and the future conditions with the Comprehensive Everglades Restoration Plan have higher HSI values then either the existing conditions or the future without the Comprehensive Everglades Plan.

KEY WORDS: eastern oyster, Habitat Suitability Index, *Crassostrea virginica*, Caloosahatchee, restoration, alternative evaluation, Freshwater impacts

INTRODUCTION

Florida's Everglades was once an expansive, ecologically productive system (Davis & Ogden 1994). Water flowed through the Kissimmee River into Lake Okeechobee, spilling over the southern rim of the lake during high precipitation events and into an extensive Everglades system flowing as a sheet of water until it reached the southern estuaries. Fragmentation and hydrologic alterations (Light & Dineen 1994, Ogden et al. 2005a, Ogden et al. 2005b) have led to the loss of this sheet-flow across the system (Science Coordination Team 2003) and into estuaries (McIvor et al. 1994).

The Caloosahatchee Estuary is located on the southwest coast of Florida between the cities of Cape Coral and Fort Myers (Fig. 1). Most of the freshwater flowing into the estuary comes from the Caloosahatchee River. Historically, the Caloosahatchee River was a meandering system with numerous oxbows, flowing from its headwaters at the marshlands of Lake Flirt, west of Lake Okeechobee, to the Gulf of Mexico. Activities that led to its degradation began in the late 1800s, with Hamilton Disston's dredging and channelization project, which included a connection to Lake Okeechobee and construction of an extensive canal network associated with agricultural development in the watershed. The channelization and canal building process (C-43) has changed the timing, quantity, quality, and direction of runoff within the watershed; and it led to abnormal salinity fluctuations. The operation of three water control structures allowing large periodic regulatory releases from Lake Okeechobee has reduced the tidally influenced portion of the estuary.

Two seasonal trends influence Southwest Florida estuaries, including the Caloosahatchee estuary: seasonal variation in air and water temperature and seasonal variation in rainfall and water releases (Tolley & Volety 2005). During dry, cooler months (November to May) little or no rainfall is present and very little freshwater flows from Lake Okeechobee into the Caloosahatchee estuary, resulting in estuarine salinities ranging from 28–38 ppt. In warmer, wet months (June to October), the Caloosahatchee estuary experiences heavy rainfall as well as significant freshwater releases from Lake Okeechobee for flood control (~1,000–20,000 cubic feet per second), resulting in physical flushing of the estuary as well as depressed estuarine salinities (~0–10 ppt, Volety et al. 2003). Thus, the key stressor in the Caloosahatchee estuary is an altered hydrology, which includes unnatural high and low water deliveries to the estuary.

Prior to these impacts, the Caloosahatchee estuary was a highly productive system with an abundance of aquatic plants and animals. Today, abundance, health, and functionality of these species have been greatly reduced (Harris et al. 1983, Chamberlain & Doering 1998a, Doering & Chamberlain 1999).

The Comprehensive Everglades Restoration Plan (CERP), developed by the United States Army Corps of Engineers (USACE) and the South Florida Water Management District (SFWMD), provides a framework and guide to improve quality, quantity, timing, and distribution of water in the Everglades ecosystem (United States Army Corps of Engineers and South Florida Water Management District 1999). A series of eight expedited projects, together called Acceler8, implement the initial phase of Everglades restoration for the State of Florida. The C-43 West Basin Reservoir (an Acceler8 project and a component of a larger restoration effort for the Caloosahatchee River and estuary) focuses on storing regulatory releases from Lake Okeechobee and storm water runoff. Removing this surplus water will reduce excess water flow to the Caloosahatchee estuary during the wet season and provide essential flow during the dry season. The C-43 project will

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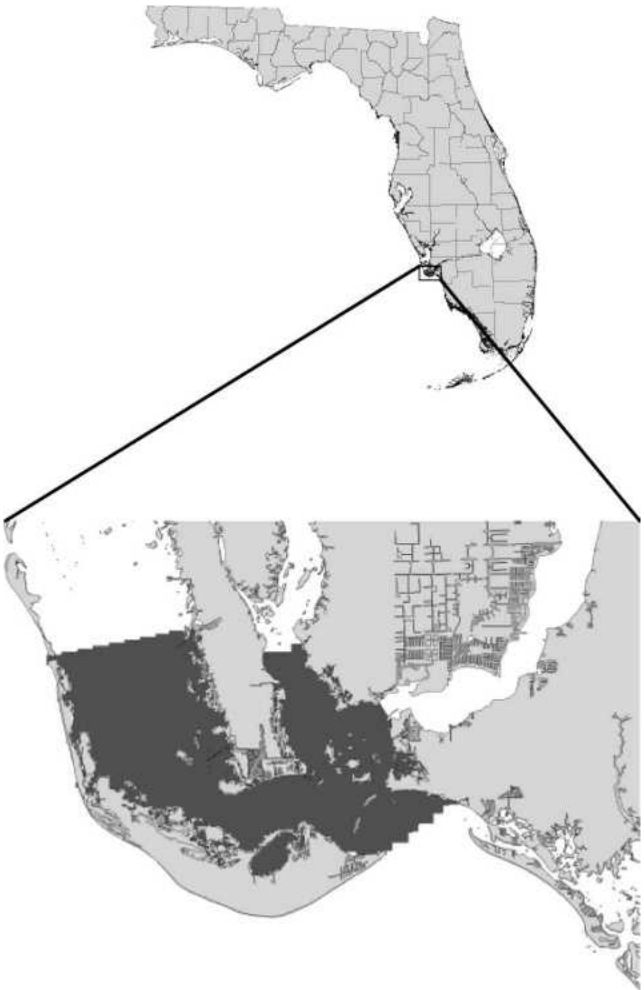

Figure 1. The Caloosahatchee estuary, Lee County Florida.

consist of an above-ground reservoir located along the Caloosahatchee River, Florida with a storage capacity of ~200 million cubic meters.

To arrive at a final plan design, a series of steps must be taken (Yoe & Orth 1996). Two critical steps of this process are the design and evaluation of alternative restoration plans and comparison of effects of each alternative. Through an evaluation process, each individual restoration alternative is assessed and its effects are quantified and evaluated. For the C-43 West Reservoir Project, the evaluation tool is a forecasting model. This forecasting model is a set of habitat suitability index (HSI) models for individual or multiple species, or both, which relate selected environmental metrics to habitat of each organism. The forecasting model applies each HSI to restoration alternatives with the assumption that as changes for each alternative occur, so will extent and quality of suitable habitat. Another assumption is that habitat suitability is related to distribution and abundance of the species (or life stage) modeled (Klopatek & Kitchens 1985).

This paper selected the species used in this evaluation process because of a combination of ecological, recreational, and economic importance. Additionally, they must have an established link to stressors of management interest (Barnes 2005). The eastern oyster, *Crassostrea virginica*, one species chosen for this process, is important commercially and recreationally in fisheries along the Atlantic Ocean and Gulf of Mexico coasts of North America. Whereas this role of oysters as a fishery is well known, their ecological significance remains under appreciated and under studied (Coen et al. 1999a). Individual oysters filter 4–34 L of water per hour, removing phytoplankton, particulate organic carbon, sediments, pollutants, and microorganisms from the water column (Newell 1988, Newell & Langdon 1996). This filtration results in greater light penetration immediately downstream promoting growth of submerged aquatic vegetation. Although oysters assimilate most of the organic matter that they filter, they deposit the remainder on the bottom where it provides food for benthic organisms. Furthermore, the oyster's ability to form large biogenic reefs (Coen et al. 1999b) qualifies it as a keystone species.

Oysters and the complex, three-dimensional, reef structure they form attract numerous species of invertebrates and fishes (Ingle & Smith 1956, Woodburn 1965, McDonald 1982, Peters 1981, Meyer 1994). To date, over 300 species have been identified as depending, either directly or indirectly, on oyster reefs (Wells 1961, Tolley et al. 2006). Many of these organisms in turn serve as forage for important fishery species (Marshall 1958, Tabb & Manning 1961, Fore & Schmidt 1973, Gilmore et al. 1983, Peters & McMichael 1987, McMichael & Peters 1989).

Because of its sedentary nature, the eastern oyster is susceptible to natural and artificial ecosystem changes, making it a good indicator species for this restoration effort. Environmental disruptions are responsible for reducing oyster populations and their traditional habitats (Cake 1983). Although not currently harvested in the Caloosahatchee estuary, oysters have been identified in this area as a valued ecosystem component (VEC) (Chamberlain & Doering 1998a, Chamberlain & Doering 1998b). Historical records indicate that oyster reefs were once significant features of the Caloosahatchee estuary and adjacent San Carlos Bay. However, populations have declined significantly to less than 7.5 ha^2 (18 acres) (Volety et al. unpublished results).

Adult oysters can temporarily tolerate a wide range of salinities ranging from 0–42.5 ppt. Normal species distribution occurs between 5 and 40 ppt (Ingle & Dawson 1953, Loosanoff 1953a, Wells 1961, Galtsoff 1964, Menzel et al. 1966) with optimal salinities in Southwest Florida ranging between 14 and 28 ppt (Volety et al. 2003), but varying by latitude and geography. They can survive at salinities 4–5 ppt indefinitely (Loosanoff 1932, Volety et al. 2003) and can occur at salinities as low as 0.2–3.5 ppt for up to five consecutive months (Butler 1952), including those in the upstream Caloosahatchee estuary where they can encounter zero salinities for several months when regulatory freshwater releases are made (Volety & Savarese 2001, Savarese et al. 2003, Volety et al. 2003). Reefs located near the head of an estuary, where salinities range from 0–15 ppt, are characterized by oyster populations that are small, rounded, and sparse because of frequent flooding and high mortality rates (Butler 1954, Volety & Savarese 2001, Savarese et al. 2003). Spat recruitment and growth rates are also low in this region. Where salinities are between 15 and 20 ppt, populations are dense, reproductive activity high, predator numbers low, and spat recruitment and growth rates high. Near the mouth of a typical Gulf Coast estuary with a salinity of 25 ppt, growth and reproductive rates are typically high;

however, predation and competition are also high. Where the estuary opens into the high-salinity Gulf waters, oyster reefs are sparse, spat recruitment and growth are low, diseases and predators are high, and suitable substrate is lacking. Volety et al. (2003), Volety and Savarese (2001), and Savarese et al. (2003) observed similar conditions in Florida estuaries.

Juvenile oysters less than one year old can survive at salinities of 5 ppt (Chanley 1958, Volety et al. 2003); however, very little growth is observed below 5 ppt, slow growth observed at 12 ppt, and normal growth occurs between 12 and 27 ppt (Chanley 1958). Under laboratory conditions, Volety et al. (2003) observed high mortality (40% to 75%) of juvenile oysters exposed to <5 ppt and >35 ppt salinities for 2 wk, whereas very little mortality (5%) was seen at salinities of 15–25 ppt.

Salinity also affects gametogenesis, condition index, and spawning in oysters (Shumway 1996). Low salinities impair gametogenesis at <5 ppt, whereas normal gametogenesis occurred above 7.5 ppt (Loosanoff 1953a, Loosanoff 1953b). Oysters from Texas showed suppressed gonadal activity at salinities <6 ppt (Butler 1949). Similar trends were observed in the Caloosahatchee river oysters in 2003 when the estuary water was significantly fresh because of regulatory freshwater releases (Volety, unpublished results).

The protozoan parasite, *Perkinsus marinus*, has devastated oyster populations in the Atlantic (Burreson & Ragone-Calvo 1996), as well as in the Gulf of Mexico (Soniat 1996), where it is currently the primary pathogen of oysters. Andrews (1988) estimates that *P. marinus* can kill ~80% of the oysters on a reef. Temperature and salinity influence the distribution and prevalence of *P. marinus* with higher values favoring the parasite (Burreson & Ragone-Calvo 1996, Soniat 1996, Chu & Volety 1997, La Peyre et al. 2003). Laboratory studies by Volety (1995) and Chu and Volety (1997) suggest salinity to be the most important factor influencing the disease susceptibility and disease progression of *P. marinus* in oysters. High salinities also invite various predators such as crabs, starfish, boring sponges, oyster drills, and diseases (Butler 1954, Hopkins 1962, Galtsoff 1964, Livingston et al. 2000, Menzel et al. 1966, MacKenzie 1970, Manzi 1970, Shumway 1996). Other species that are tolerant of low salinities but pose serious threat to oysters include starfish *Asteria forbesi*, whelks *Fasciolaria hunteria* (Loosanoff 1945, Wells 1961), flatworms *Stylocus ellipticus* (Loosanoff 1956), and blue crabs *Callinectes sapidus* (Menzel et al. 1966). Field studies by Wilbur (1992) in Apalachicola Bay, Florida, and by Wilbur and Bass (1998) in Matagorda Bay, Texas showed reduced oyster landings two years after low freshwater flow periods, possibly because of higher estuarine salinities and resulting predation of oyster spat by marine predators. Similarly, higher predation rates caused by oyster drills were observed in the Apalachicola Bay by Livingston et al. (2000).

In the Caloosahatchee estuary there is a seasonal cycle of water temperature with temperatures around 24°C to 34°C during the late spring through fall (April to October) and between 14°C and 23°C from late fall through early spring (November to March). Oysters in the Caloosahatchee estuary reproduce continuously between April and October. The combination of shallow environments, warm water temperature, and food availability may account for the long spawning period, which also coincides with low salinities and high flows in the estuary. This paper presents the process that was used to adapt a habitat suitability model for the eastern oyster and demonstrate its use for the assessment of restoration alternatives in the Caloosahatchee Estuary, Florida.

MATERIALS AND METHODS

Model Development and Application

The HSI for the eastern oyster was developed using adult and larval components to capture highest sensitivities of oysters to environmental changes resulting from restoration activities. The HSI model assesses habitat quality and suitability with a monthly or yearly numerical output ranging from 0 (least suitability) to 1 (most suitability) (Cake 1983, Soniat & Brody 1988). The models calculate habitat suitability, where component indices are the weighted geometric mean of the metrics. The geometric mean is derived from the product of the metrics rather than the sum (as in the arithmetic mean) and has the appropriate property that, if any of the individual metrics are unsuitable for species success (i.e., the value of the metric is zero), then the entire index goes to zero. The final HSI is the minimum score of the larval and adult component indices. Each metric can be weighted (w) with regard to importance; however, the sum of the weights is constrained to be one.

Livingston et al. (2000) previously modeled the relationship between freshwater inputs using a hydrodynamic model and various life history stages in the Apalachicola Bay, Florida. Their model used salinities and flows from the hydrodynamic model to predict oyster mortality in the bay. Percent of bottom covered with suitable cultch, mean summer water salinity, abundance of living oysters, historic mean water salinity, frequency of killing floods, and substrate firmness were chosen as variables in the previous models (Cake 1983, Soniat & Brody 1988). As previously mentioned, water flows within the Caloosahatchee estuary are managed for flood control. High temperatures and low salinities in the summer time alternate with high salinities and low temperatures in the winter time and contrast with other natural systems in the Gulf of Mexico, as well as in the Chesapeake Bay, where higher temperatures and salinities coincide within a given season. Because salinity, temperature, flow, and distribution of oysters serve as proxies for most of the variables in previous models (suitable cultch, mean water salinity, historic mean salinity, frequency of killing flood, and substrate availability), salinity, temperature, substrate, and high flow frequency have been chosen as the particular requirements for determining habitat suitability for the eastern oyster in the Caloosahatchee estuary. Table 1 lists scientific literature indicating specific requirements and data from local monitoring programs, along with their source, for both adults and larval oysters. For the purpose of alternative selection for the C43 West Basin Reservoir Project, substrate has been turned off, or removed from the model. This is because depth within model boundaries does not exceed 3 m, except for within navigation channels, which are not available areas for oyster settlement or growth and because including substrate in the model application limits restoration benefits to areas where oysters are already present, as that is the only hard substrate data available to the model. The addition of hard substrate to areas with high habitat suitability will be included as part of the restoration plan. Specific temperature, salinity, and flow values used for generating HSI results are presented in Figure 2.

HSI Formula

Below is the formula used to calculate the HSI for the eastern oyster in the Caloosahatchee estuary:

Eastern Oyster LarvalComponentIndex = (Salinity^{w1} * Temperature^{w2} * Flow^{w3})

Eastern Oyster AdultComponentIndex = (Salinity^{w4} * Temperature^{w5} * Substrate^{w6})

HSI$_{\text{May–November}}$ = MIN (LarvaeComponentIndex, AdultComponentIndex)

HSI$_{\text{December–April}}$ = (AdultComponentIndex)

where w is a weight between 0 and 1 assigned to each variable and the substrate component can be turned on or off in the model depending on the users need.

The oyster model was programmed in Microsoft Visual Basic using ESRI ArcObjects geographic information system (GIS) libraries to model habitat response spatially within a grid system that encompasses the spatial extent of the estuary. Each modeled grid cell is ~45 m^2. As a result, the model describes a response surface of habitat suitability values that vary spatially according to environmental conditions at specific locations (grid cells) in the estuary, and temporally according to patterns in environmental variables. Additionally, the GIS provides the ability to create visual aids to facilitate the decision making process.

Input data for the model came from multiple sources. The South Florida Water Management Model (SFWMM) coupled with an estuary-salinity regression model provided salinity data. The SFWMM simulates major components of the hydrologic cycle and estimates regional scale hydrologic responses (MacVicar et al. 1984, Hydrologic Realities, Inc. 2005), supplying flow from the S-79 water control structure. The regression model uses this flow data to produce grids of salinity values for different flow alternatives. Previous projects (Avineon 2003, Hansen & Perry 2003, Tetra Tech Inc. 2004) provided substrate, bathymetry, and temperature data.

Modeling Scenarios

Four hydrologic scenarios have been evaluated for the C-43 West Reservoir Project: (1) a preferred flow frequency for the

TABLE 1.

Habitat requirements for the eastern oyster.

Variable	Value	Source
Oyster Larvae: Salinity	Limits: 5‰ and 35‰ Optimal: 10‰ to 30‰ Peak: 20‰ to 22‰ Settlement peak: 25‰ to 29‰. In Caloosahatchee most favorable: 15‰ to 25‰	Calabrese and Davis (1970). Carriker (1951). Castagna and Chanley (1973). Chatry et al. (1983). Davis (1958). Hopkins (1931). Menzel et al. (1966). Savarese et al. (2004). Savarese et al. (2003). Volety et al. (2003).
Oyster Larvae: Temperature	Optimal: 20°C to 30°C With peaks at the higher end	Loosanoff and Davis (1963). Stanley and Sellers (1986).
Oyster Adult: Temperature	Optimal: 20°C to 30°C Can tolerate: 1°C to 49°C Stop feeding: 6°C to 7°C Physiological functions cease: 42°C	Cake (1983). Copeland and Hoese (1966). Galtsoff (1964). Stanley and Sellers (1986). Stenzel (1971).
Oyster Adult: Salinity	Optimal: 10°C to 20°C Normal range: 10°C to 30°C Can tolerate: 5°C to 40°C	Butler (1954). Eleuterius (1977). Galtsoff (1964). Gunter and Geyer (1955). Stenzel (1971).
Oyster Larvae and Adult: Depth	Optimal: 0.5–3 m	Volety et al. (2003).
Oyster Larvae and Adult: Substrate	Oyster shells, calcareous remains of other molluscs, wooden material, rocks, gravel, and solid refuse	Butler (1954). Galtsoff (1964). Hedgepeth (1953). Lunz (1958). MacKenzie (1977). MacKenzie (1981). MacKenzie (1983).
Oyster Larvae: Flow	Optimal: 500–2500 cfs (14.15–70.79 cm) in the Caloosahatchee River resulting in salinities above 5–10 ppt. Flows >4,000 cfs (113.26 cm) will restrict larval settlement	Shumway (1996). Wilson et al. (2005) Volety et al. (2003). Volety (2003 et al.).Wilson et al. (2005)

Caloosahatchee estuary based on a hydrologic target set to provide an optimum inflow range that includes natural variation in salinity to insure a diverse composition of estuarine biota (Table 2) (Chamberlain & Doering 1998a, Chamberlain & Doering 1998b, Doering & Chamberlain 1999, Doering & Chamberlain 2000, Doering et al. 1999, Doering et al. 2001, Doering et al. 2002, Chamberlain et al. 2003); (2) an existing conditions scenario based on hydrology, water demands and land use in the year 2000; (3) a future conditions without the implementation of any Comprehensive Everglades Restoration Plan projects, using predicted 2050 hydrology, water demands, and land use; and (4) a future conditions (year 2050) with the Comprehensive Everglades Restoration fully implemented (United States Army Corps of Engineers and South Florida Water Management District 1999).

In addition, running simulations for a normal rainfall year (1996) illustrates the role of substrate limitation for oysters in the Caloosahatchee estuary. Runs were made with and without the substrate component of the model turned on. Under the with-substrate scenario, the model utilizes the existing substrate, where the removal of substrate as a metric in the model assumes no substrate limitation.

RESULTS

Figures 3, 4, 5, and 6 show the HSI results for various scenarios described earlier. Models display results as an average

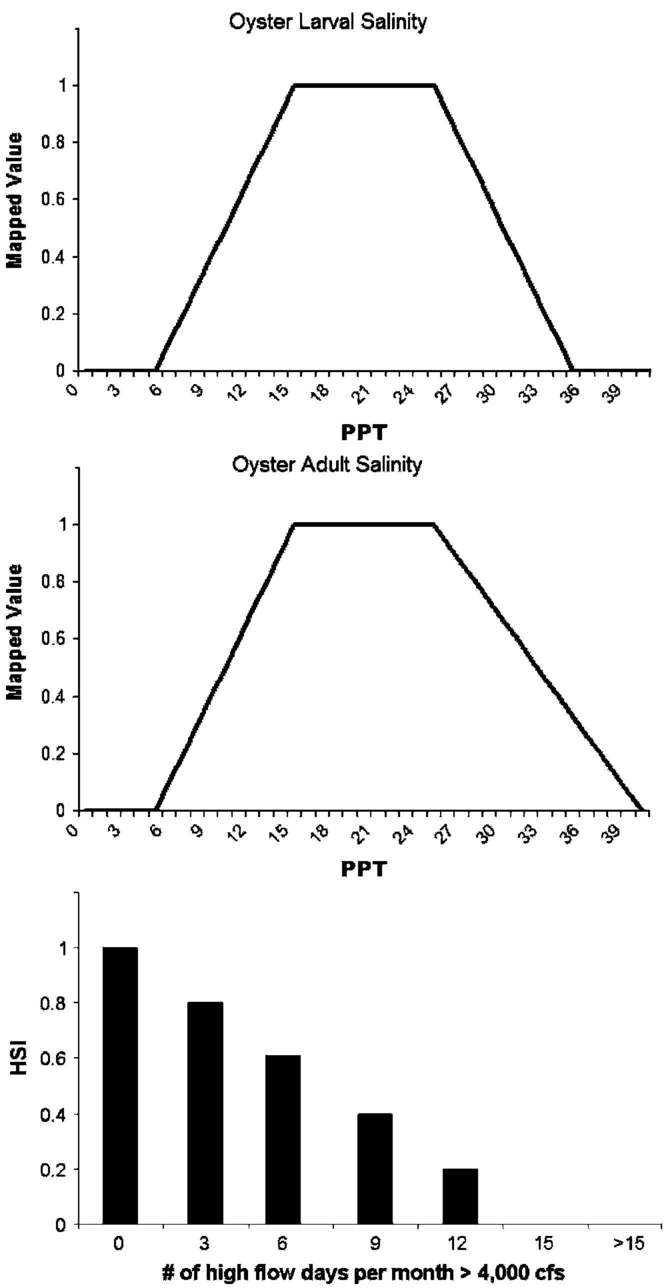

Figure 2. Suitability index diagrams created for the eastern oyster using data from Table 1 (adjusted for local conditions by expert opinion and recent research).

TABLE 2.

Preferred flow regimen for the Caloosahatchee estuary based on a hydrologic target based on an optimum inflow range that includes natural variation in salinity to insure a diverse composition of estuarine biota (Chamberlain & Doering 1998a, 1998b, Doering & Chamberlain 1999, 2000, Doering et al. 1999, 2001, 2002, Chamberlain et al. 2003). The frequency distribution of flows from Lake Okeechobee (S-79 lock and dam) is without tidal basin contribution.

Discharge Range in cubic meters per second (cms) from S-79	Percent Distribution of Flows from S-79
0–12.75	0.0%
12.75–14.16	42.8%
14.16–22.65	31.7%
22.65–42.48	19.2%
42.48–79.29	5.6%
79.29–127.43	0.7%
>127.43	0.0%

yearly HSI computed from monthly HSI values. Models also have capability of displaying results as average yearly habitat units (results not shown). For the purpose of this paper, we used average HSI values for the year.

Preferred Flow

The model predicts that establishment of preferred flows (Table 2) will result in HSI values of 0.5–1 in the majority of the study area (Fig. 3). This is especially favorable during wet years when high regulatory releases as well as watershed runoff is likely to occur, resulting in favorable salinities in the estuary.

Current Conditions

The model predicts that, in wet years, HSI values are between 0–0.5 in most of the study area (Fig. 3). Under current conditions, high regulatory discharges occur during May to October in the Caloosahatchee River, reducing the salinities as well as flushing the larvae downstream. However, in normal to dry years, conditions are favorable with HSI values between 0.5–1 in the study area.

2050 without CERP

The model predicts that HSI values and habitat suitability in the Caloosahatchee estuary without implementation of CERP (and resulting water management practices) are similar to those of current conditions (see earlier) with poor HSI values during the wet years and relatively favorable HSI values during dry and normal years (Fig. 4).

2050 with CERP

The model predicts that HSI values in the Caloosahatchee estuary with CERP implementation (and resulting flow patterns) mimic those of preferred flow regimen during normal and dry years (HSI values between 0.5–1), but with lower values (0.25–0.75) during a wet year compared with those of preferred flow regimen under similar conditions (Fig.3). Figure 6 compares the HSI values for year 2050 with and without the CERP for a six-year period of rainfall (1995–2000).

Role of Substrate

When simulations were run to examine the yearly HSI values for oysters in the Caloosahatchee Estuary under normal rain conditions, with existing substrate as a parameter, HSI values were extremely low (0–0.25) in most areas, with limited areas showing HSI values between 0.5–0.75. When substrate was removed as a factor (implying that substrate was not a limiting factor), most of the HSI values in the estuarine portion of the Caloosahatchee River ranged between 0.5–1 (Fig. 5).

Results from the HSI model indicate that preferred flow frequency distribution and future conditions with implementation of the Comprehensive Everglades Restoration Plan have higher HSI values than existing conditions or the future without the Comprehensive Everglades Restoration Plan.

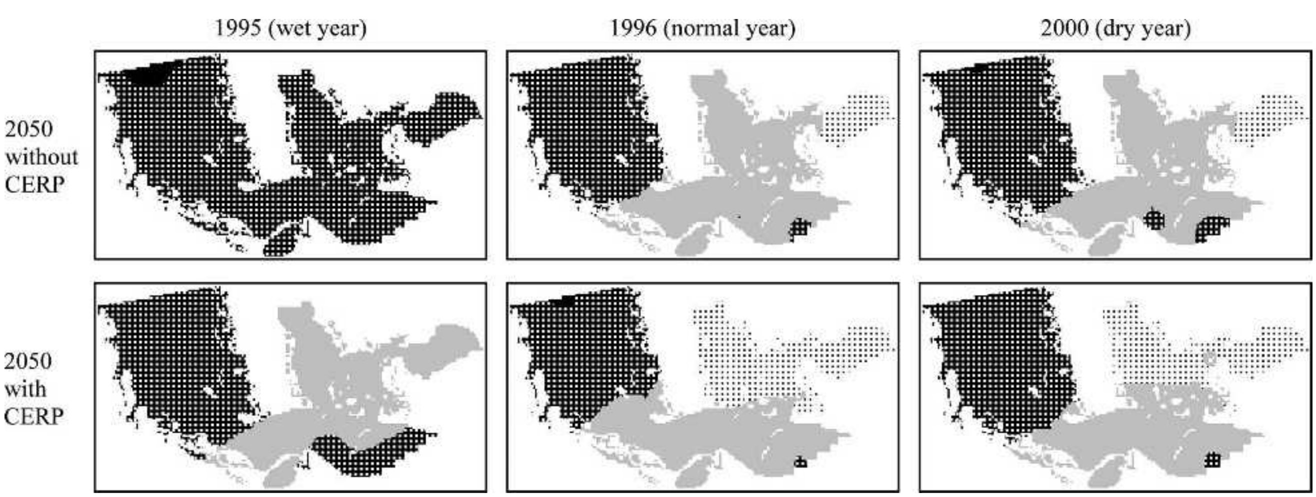

Figure 3. HSI values for the eastern oyster in the Caloosahatchee estuary under current conditions of flow (based on 2000 hydrology and land use) compared with preferred flow frequency (Table 2) for wet (1995), dry (2000), and normal (1996) rain fall years.
0.00–0.25, 0.25–0.50, 0.50–0.75, 0.75–1.00.

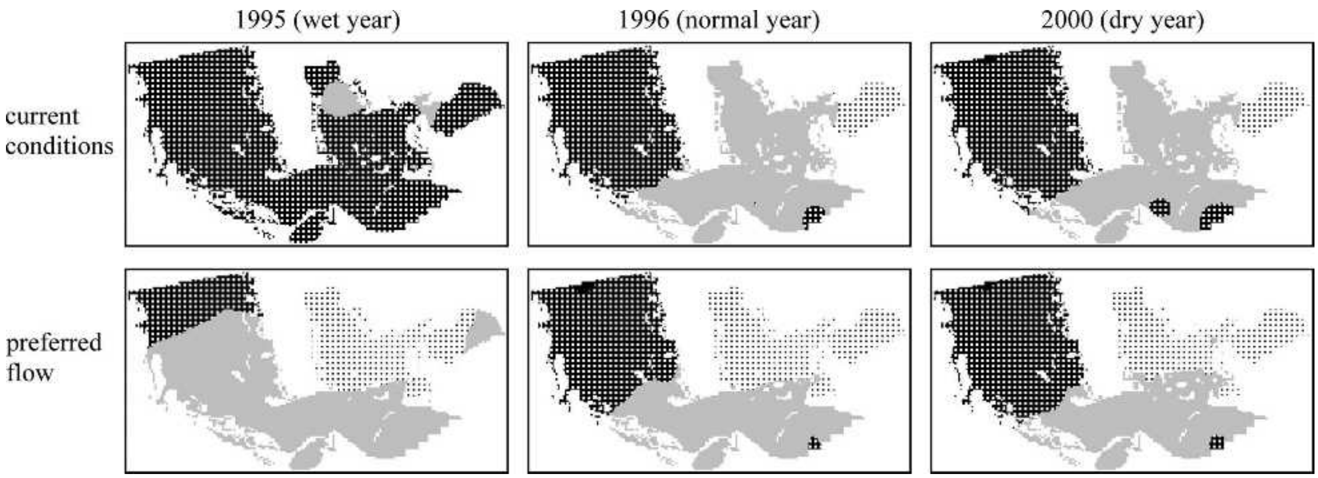

Figure 4. HSI values for the eastern oyster in the Caloosahatchee Estuary using 2050 without the Comprehensive Everglades Restoration hydrology and land use conditions compared with 2050 with complete implementation of the Comprehensive Everglades Restoration hydrology and land use conditions. 0.00–0.25, 0.25–0.50, 0.50–0.75, 0.75–1.00.

DISCUSSION

The United States Fish and Wildlife Service (USFWS) originally developed species-specific HSI models to evaluate environmental impact and project planning studies (Schamberger & Farmer 1978, United States Fish & Wildlife Service 1981), including one for the eastern oyster (Cake 1983). This HSI was later modified and adapted for use in the Galveston Bay by simplifying the model structure and better accounting for local stressors of importance (high salinity, disease, and parasitism on oysters) (Soniat & Brody 1988).

HSIs and other habitat assessment models have become common tools to examine effects of habitat changes on specific species resulting from land use changes, watershed alteration, mitigation, and restoration (USFWS 1981, Soniat & Brody 1988, Turner et al. 1995, Mladenoff et al. 1997, Elliott et al. 1999, Curnutt et al. 2000, Livingston et al. 2000, Larson et al. 2003, Tarboton et al. 2004). As a component of a larger forecasting model, the current study developed a HSI for the eastern oyster to examine the ecological effects of a series of restoration alternatives proposed for the C43 West Basin Reservoir project. The model takes into account primary environmental conditions (salinity, flow, and substrate) in the Caloosahatchee estuary and simulates effects of these on oysters. Because oysters are physiologically adapted to local conditions and their responses vary geographically with variations in seasonal temperature, food availability, seasonal salinity patterns, disease, and predation; it is not easy to adapt existing HSI models to estuaries in Southwest Florida. For example, high salinity conditions prevail in the estuary during summer and early fall in the western Gulf of Mexico estuaries, whereas low salinity conditions are experienced by oysters inhabiting estuaries along the eastern Gulf of Mexico (Volety et al. 2003). In addition, temperature for spawning and duration of spawning varies geographically in oysters. Therefore, suitable ranges for environmental metrics should be specific to the study area to optimize model sensitivity and accuracy (e.g., Layher & Maughan 1985).

Because of the nature of the Caloosahatchee estuary, flow is an essential criterion for identifying and delineating habitat suitability. During the wet season, high flow events resulting from excess rainfall and regulatory releases from Lake Okeechobee can flush larvae from the estuary to the high salinity downstream locations (Volety et al. 2003) and/or into the Gulf of Mexico where substrate is limited, preventing larval settlement. This flushing can be more detrimental to oyster population than lower salinities resulting from excess freshwater entering the estuary. Whereas the previous models considered frequency of killing floods (salinity), flow is not considered in other existing HSI models for the eastern oyster (Cake 1983, Soniat & Brody 1988).

Model results show that under the four different hydrology and land use scenarios examined, the preferred flow frequency

Figure 5. HSI values for the Caloosahatchee Estuary under the preferred flow regimen for model runs with and without substrate. 0.00–0.25, 0.25–0.50, 0.50–0.75, 0.75–1.00.

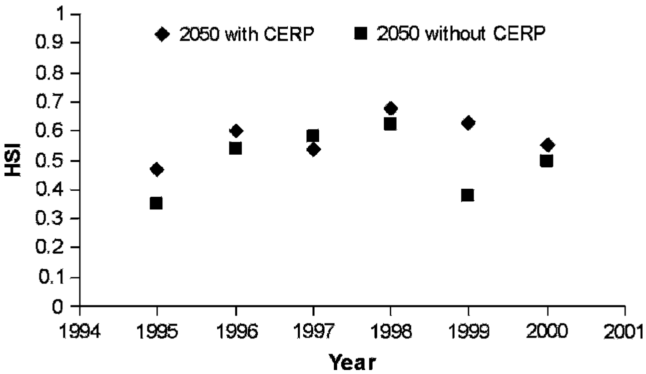

Figure 6. Average yearly HSI scores for year 2050 with and without the implementation of the Comprehensive Everglades Restoration Plan. For this model run, substrate is not limiting.

and the 2050 with restoration (CERP) conditions produce higher HSI values than existing conditions (2000) and 2050 without restoration. The preferred flow frequency and the 2050 with restoration (CERP) conditions produce similar results during a normal and dry year and the existing conditions (2000) and 2050 without restoration produce similar results in all three rainfall years (wet, dry, and normal). The C43 West Basin Reservoir project, the most substantial project currently scheduled to occur in the study area, will capture high flows in the wet season and store water to provide a minimum flow to the estuary during the dry season. By capturing flow, number and magnitude of detrimental high flow events to the estuary will be greatly reduced. This is especially important during spawning season. By holding the water and making it available for a minimum flow in the dry season, the extent of high salinity areas in the estuary will also be reduced, reducing oyster predation and disease. In addition, results show that during a wet year, even with the proposed restoration (CERP) fully implemented, habitat suitability is suboptimal when compared with the preferred flow conditions (Figs. 3 and 5). This suggests that the current restoration plan (CERP) is not enough to achieve wet season flows into the estuary that will result in optimal habitat quality for oysters. The Southwest Florida Feasibility Study (SWFFS), initiated by CERP, will address additional water resource needs in Southwest Florida, including additional water storage in the Caloosahatchee Basin. It should be strongly noted that the preferred flow regimen (Table 2) into the estuary cannot be accomplished without full implementation of CERP, including the SWFFS.

Modeling results also indicate that under the current flow regimen and existing conditions in the Caloosahatchee estuary, the estuary is severely substrate-limited in areas otherwise optimal for oysters, resulting in poor HSI values (0–0.25) in those areas (Fig. 6). An additional value of the model is that it can be used to identify areas where substrate should be restored to achieve maximum colonization by oyster larvae, thus reducing uncertainty associated with restoration of oyster reefs.

The forecasting model for the C43 West Basin Reservoir Project incorporates the oyster HSI model with habitat suitability models for other species. There are several advantages of this type of forecasting tool. The HSI models are easily developed using scientific literature, local knowledge, and field data. This tailors the models to local conditions allowing them to depict results that are more accurate by accounting for physiological adaptations to local environments. Incorporation of the HSIs into a GIS interface makes overall interpretation of results easier for managers by providing visual aids and allowing them to display details for any specific location within the estuary. Additionally, HSI results easily feed into a multi-criteria decision analysis model, the final step in the forecasting process.

When using forecasting models, it is important to remember that output provided by HSIs depends on the quality of data put into the HSI model. In the current HSI model, geographic range specific, peer-reviewed scientific data, in concert with data from local monitoring programs that use published procedures and have QA/QC procedures, minimized uncertainty (Volety et al. 2003). Whereas the current simplified HSI model has several advantages stated earlier, the model is not comprehensive and has certain limitations. For example, whereas temperature, salinity, flow, and substrate are included in the model, and serve to estimate indirectly, effects of disease, predation, and reproduction, their specific role and contribution to habitat suitability are not examined. However, when such information becomes available, it can be incorporated into the model provided their input is deemed critical to decision making. Substrate availability was examined by using existing oyster reefs and mangrove roots that support visible growth of oyster clusters and that provide hard substrate for spat settlement. Because other hard substrate such as boat docks and rip-rap are not examined, the substrate availability may be slightly under-estimated in this model. However, given the size of the estuarine portion of the Caloosahatchee River, contribution of these structures towards suitable substrate is negligible. In addition, HSIs only provide information about quality of their habitat at a fixed time point and not take into account population dynamics of organisms modeled, nor do they take into account the spatial and temporal changes of species-habitat relations (Turner et al. 1995). For example, in the case of the oyster HSI model, the model does not predict if oyster larval settlement is actually occurring; it only examines suitability of the habitat for settlement and at any given point in time. Whether settlement is actually occurring is beyond the scope of this model. Additionally, actual oyster population densities are dependent on what has happened in the estuary in previous years, if settlement conditions are poor one year, the following year there may be a decrease in the population of spawning females and in turn a decrease in larvae for settlement. This may not be apparent in the model results, which strictly looks at average monthly and yearly habitat conditions and is where scientific opinion becomes necessary in model interpretation (Barnes et al. 2006).

Also, it should be cautioned that resource managers should not depend on HSI models alone for selection of restoration or management alternatives, but should also incorporate HSIs with monitoring and research plans. This should be accompanied by efforts to verify the model and calibrate it as new data become available (Barnes & Mazzotti 2005).

In summary, previously developed oyster HSI models (Cake 1983, Soniat & Brody 1988) were optimized for use in the Caloosahatchee estuary and augmented by incorporating GIS for visual display. Modeling efforts by Livingston et al. (2000) plotted the results of freshwater input on the mortality of oysters using GIS. In the current study, whereas the model is optimized for use in the Caloosahatchee estuary, it can be applied to other estuaries by adjusting variable values to mimic local conditions. This model will enhance decision making by resource managers by providing a tool that is based on real scientific data rather than using informal judgments or professional opinion and is easily exportable for use in other estuaries in Florida and other Gulf States with minor modifications.

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