F I N A L   R E P O R T

DISTRIBUTION OF OYSTERS AND SUBMERGED AQUATIC VEGETATION IN THE ST. LUCIE ESTUARY

CONTRACT NO.: C-7779

Prepared for

South Florida Water Management District
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May 1999

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This report has been prepared for the South Florida Water Management District (SFWMD) as the final report under Contract C-7779 for the Distribution of Oysters and Submerged Aquatic Vegetation (SAV) in the St. Lucie Estuary (SLE). The objectives of this study have been to:

- Document the relevant ecological requirements of American oysters and potentially occurring SAV species based on literature review
- Develop information concerning past conditions and historical distributions of oysters and SAV in the SLE
- Establish baseline oyster and SAV distribution and occurrence in the SLE as of 1997 based on field surveys
- Provide field survey data on substrate and shoreline conditions to aid in evaluating potential distribution of oysters and SAV in the SLE under differing conditions of salinity and other environmental factors
- Develop Geographic Information System (GIS) coverages of this data
- Develop a user-friendly GIS interface to aid planners and decision makers in evaluating the SLE data and in inputting bathymetric data and salinity model results to evaluate the impact of various management options on oyster and SAV distribution in the SLE

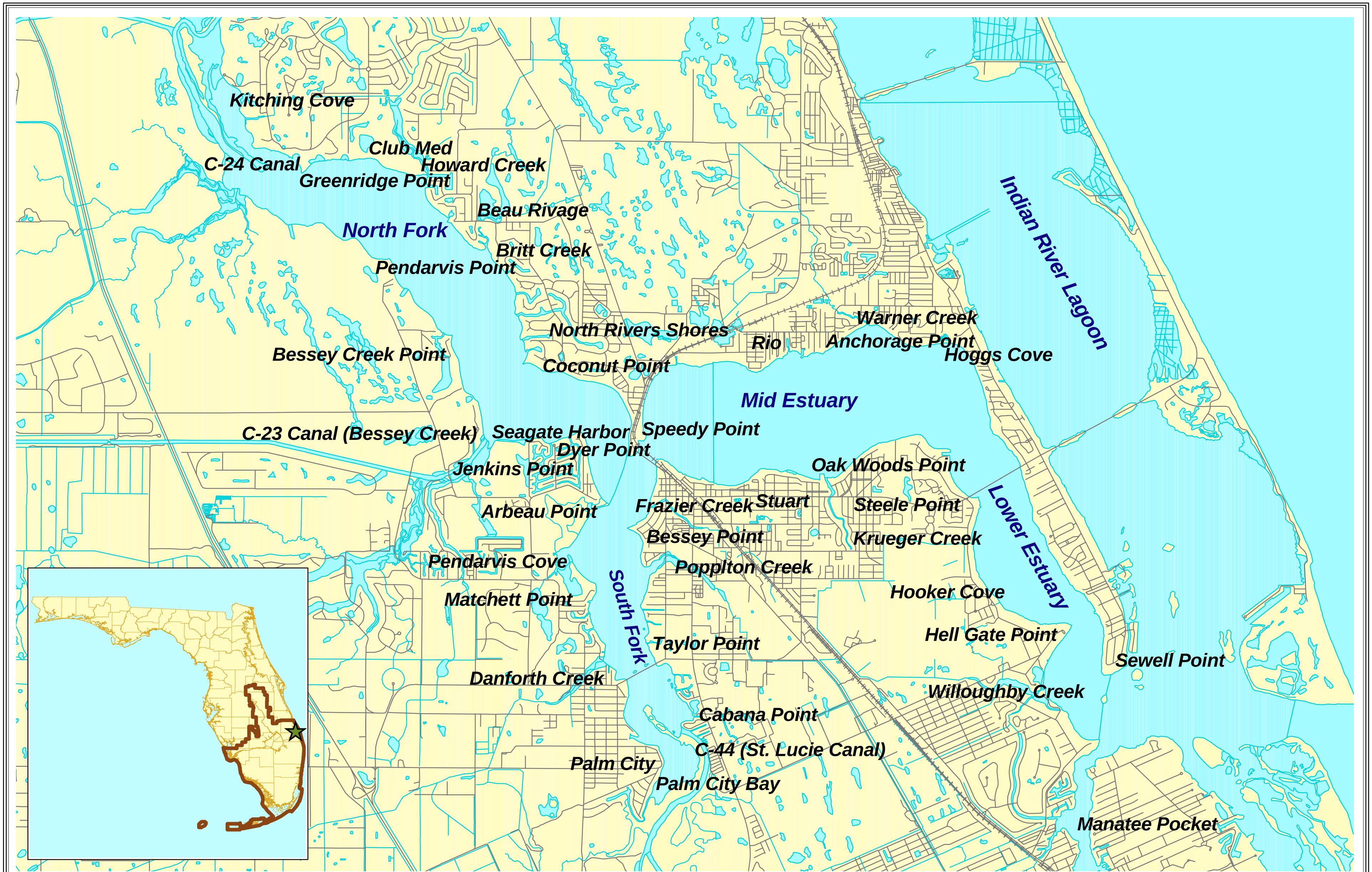
The first intent of this report (Chapter 2) is to describe the methods and sources used for literature and historical reviews, field surveys, and development of a Geographic Information System (GIS) and user interface system. The second objective (Chapters 3 and 4) is to summarize the literature review and historical information review concerning historical conditions in the SLE, including historic populations of oysters and SAV and ecological requirements of oysters and SAV. This information has been discussed in greater detail in *St. Lucie Estuary Historical, SAV, and American Oyster Literature Review* (Woodward-Clyde International-Americas, 1998).

Chapters 3 and 4 include relevant information from the published literature concerning the salinity and habitat requirements (primarily substrates) of SAV species as it may relate to efforts to re-establish populations within the SLE. This summary covers the true seagrass species of the region, as well as fresh water or brackish submerged species that may be able to tolerate low salinity conditions that may be present in certain parts of the upper estuary. The literature review report also covers in greater detail the species and their life cycles, as well as other physico-chemical requirements which may affect colonization success in the SLE.

The third objective is to summarize the results of field surveys conducted in summer and fall of 1997 (Chapter 5) including data on oyster and SAV distribution, water depth, substrate conditions, shoreline type and condition, and piers present throughout the SLE. The study area for this project includes the SLE from Hell Gate Point in the lower estuary to Cabana Point in the South Fork and Kitching Cove in the North Fork of the St. Lucie River. Figure 1-1 shows the location of landmarks referenced in this report.

Chapter 6 deals with the GIS data base and the development of the SLE User Application Interface. The intent of this report is to summarize the coverages and describe the user interface and its capabilities. More detailed information on the coverages is included in the metadata associated with the data base and more details on the user interface are included in it's accompanying Design Document.

Chapters 7 and 8 discuss potentially suitable regions of the SLE for SAV and oysters based on a synthesis of field and literature information, as well as providing recommendations for further study and areas of management concentration. Finally, a summary and conclusions section is included in Chapter 9.



Study Area
St. Lucie Estuary, Florida

Figure 1-1

2.1 HISTORICAL LITERATURE AND ST. LUCIE ESTUARY BACKGROUND INFORMATION

Background material for the St. Lucie Estuary historical review consisted of five primary types:

- Published scientific literature
- Government agency technical reports and unpublished studies
- Non-scientific historical accounts of the region
- Historical photographs and maps
- Personal contact with scientific and lay experts on the St. Lucie and long-time residents of the area

The most important technical reports and studies included several reports produced by or for the SFWMD (e.g., Haunert and Startzman, 1980, 1985; Davis and Schrader, 1984; Schrader, 1984; Morris, 1986; Haunert, 1988; Mote Marine Laboratory, 1995; Chamberlain and Hayward, 1996), and several technical reports and impact assessments by the U.S. Army Corps of Engineers produced as part of the Central and Southern Florida Flood Control Project (Murdock, 1954a, 1954b, 1954c; U.S. Army Engineer District, Jacksonville, 1954, 1959). Other key scientific sources included Phillips (1960a), Gunter and Hall (1963), and Graves and Strom (1992).

Copies of maps and information concerning bathymetric and soundings maps from the 1800s were obtained from the Corps of Engineers reports and other historical accounts. Several accounts of Florida originally published prior to 1930 were also examined at the Stuart/ Martin County Public Library, Palm Beach County Public Library Main Branch, and the SFWMD library. Key historical sources included Romans, 1775; Forbes, 1821; Henshall, 1884; Gregg, 1902; Packard, 1910; and J. Hutchinson, 1975. Several newspaper accounts from the Stuart News and Stuart Times were also reviewed at the Stuart/Martin County Public Library.

A contact list of 44 people and organizations was prepared as possible historical information sources for the SLE. This list included contacts at various water management districts; Florida Department of Environmental Protection (Port St. Lucie District Office, Shellfish Assessment Section, Florida Marine Resources Laboratory); federal agencies such as Natural Resource Conservation Service (NRCS), U.S. Fish and Wildlife Service (USFWS), and Corps of Engineers (COE); research facilities, universities, and local environmental organizations such as Harbor Branch, the University of South Florida, and the Environmental Studies Center; local environmental and historical groups (St. Lucie Initiative, Conservation Alliance of Martin County, Stuart Heritage Museum, St. Lucie County Historical Museum), and recreational and professional fishermen and local experts. At least two attempts were made to contact each person or organization. Only 15 of these were reached or responded in the time available for input to the literature report. Information from these sources is included in the literature report as personal communications.

2.2 LITERATURE REVIEW

Preliminary information regarding the range and habitat requirements of approximately 35 seagrass and fresh water SAV species was obtained from a number of published summaries, floras, and taxonomic references, including Muenscher (1944); Hotchkiss (1967); Radford *et al.,* (1968); Long and Lakala (1971); J. Hutchinson (1975); Godfrey and Wooten (1979); Muhlberg (1981); Wunderlin, 1982; and Livingston (1990). Eighteen species were eliminated from further consideration based on information from these sources that indicated either that the ranges did not include the St. Lucie Estuary region, or that the species had no tolerance for brackish water. The remaining 17 species were retained for further consideration and a review of pertinent literature with more detailed data on habitat requirements.

A computer search of scientific literature from 1991 to the current period was made using the Cambridge Scientific Abstracts (CSA) Biological Sciences and Living Resources data base, using CSA's WAIS Server. Searches were run using the common and scientific names for the eastern oyster and the 17 SAV species considered for this report. Searches were also made using the key words "seagrasses", "seagrass", "SAV", and "St. Lucie River". This search supplemented a previous search made in 1992 for literature prior to 1992 in conjunction with the Indian River Lagoon National Estuary Program Characterization Report.

In addition, several review articles, species summaries, and habitat requirement syntheses were reviewed for content and as a source for literature references, which were subsequently reviewed. Some of these key summary sources included *Summary of Our Knowledge of the Oyster in the Gulf of Mexico* (Butler, 1954b), *The Ecology of the Seagrasses of South Florida* (Zieman, 1982), *A partial bibliography of oysters with annotations* (Joyce, 1972), and *Habitat Requirements for Chesapeake Bay Living Resources* (Hurley *et al.*, 1991).

An intensive review of the sources from the updated computer search, file articles, and references from the summary documents was made. Libraries utilized included the University of South Florida libraries in Tampa and St. Petersburg, Florida; the Florida State University Library in Tallahassee, Florida; the Louisiana State University Library in Baton Rouge, Louisiana; and the South Florida Water Management District (West Palm Beach) and the Florida Department of Environmental Protection Florida Marine Research Laboratory libraries (St. Petersburg).

2.3 FIELD SURVEYS

2.3.1 Study Design

Field surveys were designed around an ability to link GPS and GIS technology in the field, with direct data input to a laptop computer. A differential GPS unit was mounted on the survey boat and connected to a laptop computer via a serial cable interface. Dynamo GPS, a software program for entering GPS data and field data was used as the base of the data collection module. This program integrates real-time download GPS data with data entered into a Trimble compatible data directory.

In the Dynamo GPS system, the computer interface controlled the GPS receiver and functioned as the data logger. Clicking a button on the computer screen toolbar captured a GPS position point and created a data point. Opening the data point simultaneously activated pre-defined data dictionaries for that point. A series of pull down menus was then used to enter data for each study parameter. Separate data dictionaries were created for substrate, oysters, SAV, shorelines, and piers. Shoreline and pier surveys were conducted separately from the other surveys. In general, substrate, oyster, and SAV surveys were conducted concurrently with data for each entered at each data point. After the first few points, because SAV was present only in a very limited area, data was recorded only if SAV was present.

2.3.2 Data Dictionaries and GIS Data Base

For each of the surveys, data dictionaries were created to enter data. A complete listing of field definitions and descriptions are provided in the metadata file of each GIS coverage.

The GIS coverages generated as part of the study were stored within a structured data base. A full description of the GIS data base is presented in a separate report "GIS Documentation Booklet: Geographic Information System (GIS) Design Documentation".

2.3.3 Survey Design

A grid was built with ArcInfo GIS to overlay the NOAA chart on the computer screen. This grid was created by establishing transects at 1,000-foot intervals largely perpendicular to the shore for each reach of the estuary (lower estuary, middle estuary, confluence area, South Fork, and North Fork). Perpendicular lines were created at 700-foot intervals to create a grid such that each intersection point represented a regularly spaced sampling point at 700-foot intervals on transects spaced 1,000-feet apart. In the first stage of field surveys, each sampling point was sampled for substrate and oyster and SAV presence. A total of 305 points were included in this grid-based sampling. The grid sampling thus provided a detailed reconnaissance and ensured some degree of coverage of the entire study area.

Since the grid-based survey found no evidence of oyster or SAV presence in mid-channel areas greater than about 8-feet deep, no additional sampling was done in this area. However, additional sampling was conducted in more shallow areas to give higher data resolution and locate features between transects. Additional sampling was also done near areas where suitable substrate and depth were found, where evidence of potential oyster or SAV presence was found, and in areas where the literature review or historical conditions survey indicated possible presence in the past. By the end of the survey, 305 points had been sampled for substrate based on the grid and additional 214 points had been sampled away from the grid points.

When oyster or SAV presence was found, the sampling point also was logged into the oyster or SAV data dictionary. The boat was moved around the point to evaluate the density and extent of coverage, which was recorded. Where coverage extended beyond a 5-m radius, additional data points were added. Whenever density appeared to be sufficient to indicate a potential bed, the boat was maneuvered to the edge of the bed and a GPS record was identified as a polygon boundary point. The boat was then moved back toward the center of the bed and proceeded outward at another point until the boundary was identified and logged. This process was then repeated along the entire perimeter of the bed.

2.3.4 Duration and Staffing

A preliminary reconnaissance was conducted on July 15 and 16, 1997 to evaluate the performance of the Global Positioning System (GPS) and survey methods. Although originally intended to begin in March, 1997, field surveys were not initiated until August, 1997 due to delays prior to contract development. An initial set of surveys occurred between August 25 and October 10, in which all pre-selected points were surveyed. Additional surveys between November 4 and November 18 filled in gaps and provided additional resolution of beds identified in the earlier surveys. Field surveys of the SLE were conducted from a 17-foot Boston Whaler outboard boat with a field crew of three to four people for resource surveys and two people for shoreline and pier surveys. Personnel included staff from Woodward-Clyde International-Americas and CZR, Inc. of Jupiter, Florida.

2.3.5 Geo-Positioning

Location in the field was determined with a Trimble Pro XR differential GPS receiver, utilizing the U.S. Coast Guard Cape Canaveral GPS beacon at 289 kHz for real-time differential conversions. The beacon is at 28^{o} 27’35” N and 80^{o} 32’35” W, approximately 175 km north of the study area.

Settings used for the GPS were:

- PDOP (Position Dilution of Precision) < 6
- Number of Satellites Used > 4
- SNR (Signal to Noise Ratio) > 6
- Satellite Elevation Mask > 15^{o}

PDOP is a measure of the current satellite geometry, with lower numbers indicating greater accuracy. A PDOP of 6 or lower is needed for accurate measurements. SNR is a measure of signal strength to background noise, with 6 or more recommended, although the SNR mask can be set as low as 3 if there are interferences such as tree canopy. The Satellite Elevation Mask allows logging to only those satellites that are at least 15^{o} degrees above the horizon to minimize signal distortion.

The method determined in the field to be most efficient was to slowly motor along a transect, throwing a buoy out as each sample point was crossed. After several points were marked, the boat returned to a buoy and the computer was used to zoom in at a high resolution sufficient to determine whether the location in the field was within the geo-referenced 5-m radius of accuracy around the sampling point. The boat was then maneuvered into position and held stationary by anchoring, idling the motor, or driving poles into the substrate while sampling occurred. Overall accuracy and replicability of positioning was checked each day by logging the location of known fixed points such as channel markers. In all cases noted, the logged location was within 5-m of the location as shown on the scanned NOAA chart, and all subsequent iterations at each marker were within 5-m of each other. In fact, relative precision was 2 meters.

2.3.6 Substrate Sampling Methods

At each sampling point, substrate was observed and placed into one of the following categories, in approximate decreasing order of firmness:

- Rocks/Gravel
- Oyster Bar/Dense Shell
- Coarse/Medium Firm Sand
- Well Sorted Fine Sand
- Mucky/Muddy Fine Sand
- Muck/Organics/Detritus
- Firm Mud/Clay/Silt
- Muck
- Ooze

Samples were obtained in a number of methods depending on water depth and characteristics of the substrate. Where possible, samples were obtained with a petite Ponar dredge, dropping the dredge in at least three spots within a 5-m radius of the designated sampling point.

In locations where shells, debris, or other features prevented the dredge from closing properly, a modified oyster tong apparatus was used to obtain sediment samples. This equipment consisted of two ordinary garden rakes connected about one-third of the way up the handles by a bolt which allowed the two rakes to be opened and closed like tongs. The tines of the rakes faced each other. When the two sides of the rake were held closed, most substrates types were held sufficiently to be raised to the surface. PVC tubes were place over the upper handles and bolted into place to extend the reach of the rake. These also made the handles more rigid, allowing increased closing and holding force. This rake could be used effectively in depths to 8 feet in all substrates except soft muck or ooze and unconsolidated sands.

In deep waters where substrates were too soft for the modified rake method to be used and in which the dredge failed to penetrate or to hold a sample, a 1-inch diameter PVC pipe was used as a sampling cylinder. This pipe was pushed into the substrate to a depth of about 8 inches in most cases. The open top of the pipe was then held shut with the palm of the hand creating a suction, allowing the substrate in the tube to be pulled from the bottom. The pipe was then tipped to the horizontal and the lower end brought to the opposite end of the boat where a bucket was placed under the opening as suction was released. This method worked well in soft sands, mud, partially decomposed organics, and most muck consistencies. In very soft muck, there was usually enough muck clinging to the side of the pipe to characterize the bottom. In cases where sediment was too soft to be obtained with any method, it was assumed to consist of ooze. Substrate characterization in this study was limited to the upper 6 inches of sediments, and each sampling point was characterized on the basis of the topmost 6 inches of substrate. In a few cases, a change in substrate consistency with depth was noted. Notes on such changes are included in the comments field of the data base.

Water depth at each sampling station was measured in one of two ways. Depth intervals were marked with indelible markers on the PVC poles and depth was read directly from the poles. A Hondex digital depth sounder was also used, primarily in deeper water or in cases where the bottom was of such soft consistency that a water/substrate interface could not be identified with the pipe method. Except in the areas with soft ooze bottom and possible flocculent layers, all depth measurements are considered to be accurate to within at least 0.5 feet. Accuracy in shallow areas is probably higher. Accuracy is dependent upon effects of tide, water level, and wave height at the time of measurement. Date and time were also recorded, so depth data could be adjusted if accurate water level gage and tide data were available.

Data were entered into the data dictionary associated with the GPS. The substrate data dictionary included the following data fields:

- *Data Point Type* - all entered as points
- *Date* - year/month/day
- *Sample Point ID Number* - individual identification number for each point
- *Water Depth* - feet
- *Secchi Depth* - feet
- *Primary Substrate* - choice of nine types
- *Secondary Substrate* - choice of nine types
- *Secondary Substrate Modifier* - % of total substrate represented by this class, based on the following cover classes: 0-19%, 20-39%, 40-59%, 60-79%, 80-100%
- *Comments*

The secondary substrate was used where there was a mix of types, for example when shells or shell hash was mixed with muck. Substrate data was collected at 519 points.

2.3.7 Oyster Sampling Methods

The modified oyster rake described above was the primary method for identifying and characterizing oyster distribution. At each sampling point at least five samples were collected with the rake. For a sample, the rake was opened to a distance of about 24 inches, placed on the substrate, and closed. With a rake width of about 18 inches, this yielded a sample area of approximately 3 ft^2 per grab, or 15 ft^2 per station. Oysters brought up in the grab would be counted, characterized for condition and live/dead composition, and shell length measured. The estimated average surface area per shell was multiplied by the number of shells in the sample to estimate total cover per sample. This was divided by the sample area to yield an estimate of total surface coverage, done for both live and dead shells. Each sampling station was then characterized in terms of approximate density, size and condition categories. After measurements, live oysters and dead shells were returned in the estuary while at the sampling point.

When moving between sampling stations or over areas where oysters were believed to potentially be present, a steel rod 0.5 inches in diameter or the 1-inch PVC pipe was pulled across the bottom. These pipes would bounce upon hitting shells or rocks on the bottom. When such “hits” were recorded, the oyster rake was utilized to sample for oysters and a sampling point was logged. With practice, differences in feel and sound could be readily identified for oyster shells, clams, and rocks. In shallow areas, direct observation was also used to identify oyster presence and estimate densities.

The data dictionary for oyster resources included the following fields:

- *Data Point Type* - point or polygon
- *Polygon Boundary Marker* - yes or no
- *Date* - year/month/day
- *Time* - 24 hr clock basis
- *Sample Point ID Number* - individual identification number for each point
- *Transect Number*
- *Transect Type* - regular (on our defined grid), nearby bed (additional points taken after oyster beds were located to characterize bed), historical (points take where historical data or other sources indicated beds may occur)
- *Water Depth* - feet
- *Oyster Presence* - yes or no
- *Density of Live Oysters* - based on cover percent classes: 0%, 1-5%, 6-20%, 21-40%, 41-70%, 71-100%. Determined on the basis of the area of live oysters per sample, as described above
- *Density of dead oysters* - same as for live oysters
- *Size Distribution of Live Oyster Shells* - 0-Not applicable, 1-All < 5 cm, 2-Mostly < 5 cm, some larger, 3-Mostly 5-10 cm, 4-Mostly >10 cm, 5-Mixed all sizes
- *Size Distribution of Dead Oyster Shells* - same as for live oyster shells
- *Condition of Live Oysters* - 0-Not applicable, 1-Good/no stress, 2- Good/predation, 3-Moderate/discolored or algal growth, 4-Moderate/other stresses, 5-Poor/discolored or algal growth, 6-Poor/other stresses
- *Comments*

In the original data dictionary, several other condition classes were defined, but were not encountered in the field, so the above classes include only those actually encountered. Some data fields, such as time and water depth were entered only at random points.

A total of 665 data points were entered in the oyster data dictionary. Many of these were used to mark the edge of well-defined oyster bars or aggregations. At these points, only data on presence or absence was consistently collected. These points, which were identified as Polygon Boundary Markers, were later put into a separate data base and used to construct polygons marking well-defined oyster bars or aggregations. Notes placed in the comments field were used to reconstruct the perimeters of the beds from the data points. The newly created oyster bar polygon data base contains the following fields:

- *Data Point Type* - Polygon
- *Area of Polygon* - scale can be set in GIS
- *Perimeter of Polygon* - Scale can be set in GPS
- *Species* - Crassatrea virginica

Other data concerning the density, condition, etc. of oysters in and near the bars, is contained in the original oyster point data base.

2.3.8 SAV Sampling Methods

Where possible, SAV surveys consisted of visual observations made from the boat or while wading in shallow water. A 26” Aqua Scope underwater viewing tube was used to augment visibility and viewing. However, visibility was limited to less than 3 feet in most of the estuary and in many cases was less than 1 foot, limiting the suitability of these observations to very shallow (<2 feet) depths and to the lower estuary where visibility was increased on incoming tides.

Substrate samples obtained in the petite ponar dredge and the modified oyster rake were closely examined for signs of SAV stems, leaves, or rhizomes/roots in all samples. It quickly became obvious that no SAV was present in depths of more than 5 feet anywhere in the middle estuary and the North and South Forks, so more detailed examination of the deep zones was not continued. In shallower areas where there was historical or recent accounts of possible presence, where suitable substrate occurred, or where substrate or other samples indicated possible presence, additional surveys were made using snorkel gear. At such sites, investigators would swim through the area, observing bottom conditions through masks. Usually an area of about 100-foot radius would be checked at a time. Often, observations had to be made within 1 foot of the bottom due to low visibility.

SAV was identified by species and condition, canopy height, and % aboveground cover. Cover was estimated by species and by total cover of all species based on a 5-foot radius around the sample point. Polygon boundaries were not established for SAV resources because of the extreme sparseness and sporadic occurrence. The only true “bed” areas were along very narrow bands near the shores of the lower estuary. In these cases, the “beds” were generally less than 3 meters in width, less than our target level of GPS position accuracy. Thus they were mapped as a series of point data only. In all other cases, SAV observations consisted of only a few small plants with less than 1 % cover even within our sample point.

The SAV data dictionary was originally set up to allow identification of the following species: *Thalassia testudinum, Syringodium filiforme, Halodule wrightii, Halophila johnsonii, H. englemannii, H. decipiens, Ruppia maritima, Najas guadalupensis, and Vallisneria americana*. Only *Halodule wrightii, Halophila johnsonii, Ruppia maritima, Najas guadalupensis,* and *Vallisneria americana* were actually found during the field surveys, and the data base was subsequently streamlined by deleting the other species.

A total of 95 points defining SAV occurrence were entered in the data base. SAV data dictionary fields were:

- *Data Point Type* - point
- *Date* - year/month/day
- *Time* - 24 hr clock basis
- *Sample Point ID Number* - individual identification number for each point
- *Transect Number*
- *Transect Type* - regular, nearby bed, historical
- *Water Depth* - feet
- *Dominant Species Present* - species as listed above
- *Secondary Species Present* - species as listed above
- *Dominant Species Canopy Cover* - None, <1%, 1-9%, 10-39%, 40-69%, 70-100%
- *Secondary Species Canopy Cover* - same as for dominant species
- *Total Canopy Cover* - same as for dominant species
- *Canopy Height* - Average height (length) of shoots and leaves - cm
- *Vegetative Condition* - 1-Normal/good, 2-Moderate/stressed or low vitality, 3-Very Poor/extremely stressed or dying
- *Community Type* - 1- Not Present, 2-Present as single shoots only, 3-Present in small clusters of shoots, 4-Present in small patches or distinct groups (sparse beds), 5- Present as colonies or mats, relatively dense (dense beds)
- *Comments*

2.3.9 Shoreline Surveys

Shorelines were characterized based on the type and condition of the land/water interface, and also on the type of land use or cover present immediately adjacent to the shoreline. The following shoreline categories were used:

Shoreline Type

- *Mangroves* - any mangrove species rooted at the edge of water line
- *Brackish/Saline Emergent Marsh* - well-defined band of emergent herbaceous plant species capable of surviving in brackish or saline conditions
- *Freshwater Emergent Marsh* - well-defined band of emergent herbaceous plant species not readily capable of surviving in saline conditions
- *Native Hammock/Upland Forest* - stands of native forest vegetation extending to water edge
- *Exotic Species* - exotic or weedy species dominating at water edge; generally Brazilian pepper or Australian pine
- *Grassed Unarmored Slope* - grassed lawns and similar areas extending to water edge with no seawall or other shoreline stabilization
- *Sandy Slope/Beach* - flat beach or sloping unvegetated sand surfaces adjacent to water edge
- *Vertical Seawall* - artificial vertical shoreline protection, usually of concrete or wood; some areas have rip rap or other material in front of wall, which is noted in comments
- *Rip Rap* - various sized rock pieces placed adjacent to shoreline, usually sloped; occasionally interlocking blocks included if in a sloping surface
- *Tributary Channel* - any tributary channel or canal greater than 10 feet wide, connected to main estuary
- *Culvert/Outfall* - spillway or large culvert greater than 36" and associated outfall structure in which outfall structure dominates shoreline use
- *Dock/Boardwalk/Marina* - areas in which shoreline is partially obscured by marina or boat related facility requiring access channel, or in which a boardwalk extends parallel to and abutting the shoreline
- *Bridge/Other Structure* - landward extend of road or rail bridge, cement breakwater, cable crossing or other man-made structure not in other categories
- *Mixed Uses < 50 Feet* - area in which several shoreline types may be interspersed, but no single type extends for more than 50 consecutive feet

Shoreline Condition

Several categories of modifiers were developed to used as applicable for the above shoreline types to describe condition. These are:

- *Good/Normal Condition* - could describe any type
- *Healthy Condition* - for vegetated types
- *Damaged* - could describe any type in less than good, normal, or healthy condition

- *Dead* - dead vegetation
- *Debris/Trash Present* - extensive presence of trash or other debris
- *Exotic Species Present* - extensive presence of exotic plant species
- *Steep, >30 Degree Slope* - unarmored areas with steep slopes
- *Eroded* - signs of bank erosion present
- *Highly Eroded* - signs of extensive bank erosion such as erosion gullies or collapsing banks present
- *Sediment Accumulation* - noticeable shoaling in front of bank due to accumulation of eroded materials from adjacent shore
- *Dredge Spoil* - area in which spoil has been deposited on bank or shore around dredge spoil disposal areas
- *On-going Construction* - area in which shoreline is being disturbed during construction on shore edge or adjacent property

Land Use

Land use was also noted for the parcel immediately landward of the shoreline. Both land use and the relevant Florida Land Use and Cover Classification System (FLUCCS) codes were included. Categories include the following:

- *Mangrove Forest (FLUCCS 610)*
- *Marsh (FLUCCS 640)* - includes saline, brackish, and freshwater
- *Upland Forest/Native Hammock (FLUCCS 400)* - includes all kinds of native upland forest or tree cover
- *Exotic Species (no specific FLUCCS code)* - weedy areas dominated by exotic plant species
- *Low Density Residential (FLUCCS 110)* - residential areas with density no higher than approximately 4 units per acre
- *Mid to High Density Residential (FLUCCS 120,130)* - residential areas with density higher than approximately 4 units per acre; generally consists of apartment, condominium, townhouse, and manufactured home complexes
- *Commercial/Industrial/Institutional (FLUCCS 140, 150, 170)* - includes transportation areas such as roads and recreational areas
- *Marina/Dock (FLUCCS 180)* - land uses associated with commercial boat servicing; includes associated channels
- *Vacant/Undeveloped (FLUCCS 190)* - land cleared of natural vegetation cover in transitional stage prior to development
- *Other (no specific FLUCCS code)* - area not readily falling into one of the above categories

In addition, the shoreline data dictionary included the following fields:

- *Data Point Type* - Polyline
- *Date* - year/month/day
- *Size* - width of band of appropriate shoreline type extending from shore(for instance, width of marsh vegetation) in feet
- *Density/Cover* - density of vegetation as applicable as % cover
- *Comment*

Surveys were conducted from the boat. At each point where shoreline or land use type changed significantly, a GPS coordinate was entered on the data system, thus opening the shoreline data entry fields. The shoreline and land use type and condition were entered into the computer data base at this time. The GPS logging system was set as a line feature, with way points manually entered as the boat progressed along the shore. The Dynamo GPS system automatically connected points into a line feature with the entered characteristics. At the point where a significant change occurred, a new line segment starting point was entered, an action which automatically terminated and entered the previous line segment in the data base

Shallow water depth along shorelines and numerous piers made it very difficult or impossible to remain close to shore for this survey. Therefore line segments breaks were entered at a point as close to perpendicular from shore as possible at the point of the break

2.3.10 Pier Survey

Every existing pier was surveyed with the waterward end of the pier identified and referenced with the GPS unit. In this survey, the GPS receiver was attached near the side of the boat and the boat was brought as close as possible to the end of each pier, in most cases resulting in a geo-referenced location with 5 feet from the actual end of the pier. Each pier was characterized as:

- *Simple pier* - Only one pier extending from shore and no more than one perpendicular unit, forming a “tee” shape,
- *Multiple pier* - containing several perpendicular units with multiple boat slips, or
- *Complex pier* - containing multiple units perpendicular to shore and many boat slips and perpendicular units

Piers under construction were also identified in the survey, as were old non-functional piers. The latter included sites where only a series of pilings remained, marking the location of an old pier. Each of these was identified in a comments field in the GIS data base. Fields in the piers data dictionary were:

- *Data Point Type* - point
- *Date* - year/month/day
- *Sample Point ID Number* - individual identification number for each point
- *Pier Type* - Simple, Multiple, Complex

3.1 ST. LUCIE ESTUARY HISTORICAL REVIEW

The St. Lucie region remained essentially undeveloped until the late 1800s. Early reports of this natural system seem somewhat contradictory in describing the St. Lucie with regards to the salinity regime, fish populations, and the presence of a nearby inlet. Inlets between Hobe Sound and Ft. Pierce probably opened and closed several times between 1600 and 1900, affecting conditions in the St. Lucie Estuary. In general however, most accounts agree that fresh water flows in the St. Lucie River were always significant, and that the extent of saline intrusion varied due to the presence or lack of an inlet.

Probably the first written description of the St. Lucie Estuary was by Captain Bernard Romans, whose book *A Concise History of East and West Florida* was published in about 1775 [Romans, 1961 (reprint)]. Romans describes an unbroken island running north from Hobe Inlet (Jupiter Inlet) for thirty nine miles to the next inlet, in the vicinity of Mud Creek and Hermans Bay on the Indian River Lagoon (IRL) about 14 miles north of present day St. Lucie Inlet. A formation of peculiar rocks was described in the approximate location of present-day Bathtub Beach, and the mouth of the "*St. Lucia River in 1775*" also was described as directly opposite these rocks. Romans made no mention of an inlet anywhere near the mouth of the river, but stated that from the mouth of the river southward the sound (IRL) was cut into three branches, one of which "disembogues" itself at Hobe Inlet, fourteen miles south. Romans mentions this branch (present-day Hobe Sound) as shallow and full of oyster banks. Hobe Inlet was described as having been closed for many years before 1769, presumably because of a lesser quantity of water coming down the St. Lucie, but that it had been open since at least 1773.

Romans also stated:

> *"That there is some such great water, is further to be gathered from the profusion of fresh water which this river, St. Lucia, pours down. Such is the immense quantity that this whole sound between the above-named island (Hutchinson Island), and the main (land), though an arm of the sea, situate in a very salt region and in general two miles wide, is very often rendered totally fresh thereby: in so much, that it has made the very speculative Mr. De Brahm insist upon having seen mangrove stumps in fresh water."*

Forbes (1821) cites a manuscript of Romans, handwritten on May 21, 1769 describing his arrival at Hobe Rocks (apparently Hobe or Jupiter Inlet), and stating that an inlet was present where no inlet appeared to have been present in August, 1768. This account describes 7 to 10 ft depths at the inlet. Romans concluded that the inlet was caused by fresh water flowing out, not by the sea breaking in. He based this on the presence of heavily colored water flowing out of the inlet, an account of unusually heavy rains in 1768, and the large flow of the St. Lucie River.

Dr. James Henshall (1884) mentions that a point about 3 miles south of Taylor Creek (Ft. Pierce) marked the southern limits of oyster beds in the Indian River Lagoon. Hawks (1887) described the Indian River Narrows area near Vero Beach as the southernmost oyster limit. At Gilberts Bar, which Henshall described as the site of an old inlet which was then closed, Henshall recounted seeing "great quantities of a grass-like plant, resembling wild celery, or eel-grass, upon which were feeding thousands of coots and ducks" in a broad bay at the mouth of the

St. Lucie River. The St. Lucie River, according to Henshall, entered the Indian River Lagoon opposite Gilberts Bar and: "is the largest stream emptying into the Indian River, and its waters, including those of the bay at its mouth, are quite fresh. It is here that the sea-cow, or manatee, flourishes, feeding on the aquatic grass in the river and bay."

Gregg (1902) however mentioned that the salt/fresh interface location in the St. Lucie River varied from 15 to 20 miles from Sewalls Point. Such distances would have put the salt/fresh interface permanently within the North and South Fork channels well upstream of the area generally thought of as being the estuary portion (i.e., Palm City Bay in the South Fork and Kitching Cove in the North Fork). Gregg (1902) reported that tarpon were present in the North Fork in winter and spring, and a few snappers, cravaille, groupers and jewfish could be found near the U.S. 1 bridge. Black bass and bream were mentioned in both forks, with their distribution described as being dependent on season and on rainfall and flow. Gregg also stated that the inlet at Gilberts Bar had re-opened about 10 years previously (1892), thus reestablishing salt water intrusion into the system.

The preceding accounts all indicate that the natural St. Lucie was a complicated system, even before humans had begun to significantly alter the region. The earliest accounts seem to indicate that the St. Lucie River was predominantly a fresh water system throughout the period to the 1880s, even to the Lower Estuary, presumably because of the lack of a nearby inlet to allow tidal interchange. Large fresh water flows were reported for the river, which then entered the Indian River Lagoon and eventually exited to the ocean at Jupiter Inlet or Indian River Inlet.

The fact that two accounts mentioned that the southern distribution of oysters was closer to Vero Beach or Ft. Pierce indicates that conditions in the Indian River Lagoon south of Ft. Pierce or Indian River Inlet may have been unsuited, possibly because of fresh water influences of the St. Lucie River. Other accounts mentioned oyster bars being present in Hobe Sound, but not any closer to the St. Lucie. Dr. Henshall's account of grasses at the mouth of the St. Lucie is not specific and could indicate the presence of turtle grass or wild celery, possibly even shoal grass. None of the located published accounts makes any mention of oysters or submerged aquatic vegetation within the St. Lucie River itself, and the sketchy information would seem to be more descriptive of a fresh water system at least to the time that the inlet was opened in 1892.

A 1683 map by Alonzo Solana apparently showed no inlet near the mouth of the St. Lucie River (Hutchinson, 1975), although Jonathon Dickinson reportedly waded an inlet of the "*St. Lucea River in 1694*" (Stuart News, 1964). It has been stated that many charts in the early 1800s show an inlet in the St. Lucie Inlet area, but that other evidence suggests that no inlet existed until the construction of one in 1892.

The first reported efforts to control the system occurred in 1840 or 1844, when members of the Indian River Occupation Group of East Florida dug by hand an inlet across the island at the location of the present St. Lucie Inlet (Ziemba, 1968). This inlet did not remain open for long and by 1858 was again reclosed and a thick growth of manatee grass beds returned to the Indian River Lagoon and the St. Lucie River, as based on a description by Andrea P. Canova (J. Hutchinson, 1975). In 1892, another attempt was made by local residents to open the inlet. Within 24 hours, outrushing water from the Indian River Lagoon and St. Lucie River had expanded the channel to over 100 ft wide (Ziemba, 1968). It was this opening of the channel that

Gregg had referred to in 1902. By 1898, the channel had widened to between 1,500 and 1,700 ft wide and 6 to 7 ft deep at low tide (Gunter and Hall, 1963), and had reached 2,600 ft in 1922 (U.S. Army Engineer District, Jacksonville, 1959). This is the currently existing St. Lucie Inlet today.

Major alterations to drainages and freshwater flows to the river started about 1913 and continued through the late 1940s when the St. Lucie Canal was widened and deepened to its present capacity, expanding the maximum capacity of the canal from 5,000 to about 10,000 cfs. In the period from 1898 to 1930, numerous civic projects in the region d in a vastly expanded the economic base and caused massive changes to the natural system. By 1913, the City of Stuart was growing rapidly, with several development projects selling land along the St. Lucie River and Manatee Pocket (Ziemba, 1969). Filling of marshes along the Stuart riverfront was hailed in the Stuart Times as a major civic improvement (Ziemba, 1970a). The first Palm City Bridge was being planned and a Dixie highway (U.S. 1) road bridge was being advocated to parallel the railroad bridge, which had already been constructed. Six miles of canals and laterals were dug in the Palm City area in 1913 (Ziemba, 1970b).

Construction of the St. Lucie Canal (C-44) was the second major event influencing the physio-chemical characteristics of the St. Lucie Estuary. The St. Lucie Canal enters the South Fork 7 miles upstream of the South Fork/North Fork Convergence. The drainage basin, exclusive of Lake Okeechobee, is 185 square miles (U.S. Army Engineer District, Jacksonville, 1959). St. Lucie Canal construction began in 1916 and was essentially completed in 1924 (U.S. Army Engineer District, Jacksonville, 1959). The original capacity of the canal was 5,000 cfs with the lake at a stage height of 15.6 ft (U.S. Army Engineer District, Jacksonville, 1959).

Soon after construction, the St. Lucie Canal experienced serious erosion and sedimentation problems. Shoaling of eroded material occurred as a result of the 1924, 1926, and 1928 storms. The United States government in 1933 initiated construction of fixed spillways at 16 points to reduce shoaling. In 1937, the canal was deepened to 6 ft as a navigation channel and enlarged to its present 8 ft depth and 9,000 cfs capacity in 1949. A new lock and spillway were completed at the lower dam in 1944.

Drainage alterations to the North Fork soon followed. In 1924, the North St. Lucie River Drainage District (now the North St. Lucie Water Control District) completed a series of canals and control structures for flood control in the North Fork basin (Schropp *et al.*, 1994; U.S. Army Engineer District, Jacksonville, 1959). The C-24 Canal (Diversion Canal) was completed in 1919 to alleviate drainage problems in the western part of the basin and connected to the North Fork about 1 mile upstream of the estuary (U.S. Army Engineer District, Jacksonville, 1959). Following flooding in 1947, the C-23 Canal was constructed by the Corps of Engineers as part of the Central and Southern Florida Project, entering the North Fork at Bessey Creek.

3.2 PHYSICAL AND CHEMICAL FEATURES OF THE ST. LUCIE ESTUARY

3.2.1 Bathymetry and Sedimentation

There appears to have been significant deposition of sediments in the deeper central portions of the Middle Estuary and the North and South Forks since the bathymetry was first mapped in 1893. The earliest data sources concerning bathymetry of the St. Lucie Estuary are a U. S. Coast and Geodetic Survey map of the St. Lucie Estuary, dated 1887 and a more detailed U. S. Coast and Geodetic Survey soundings map, dated May 18, 1893 (U.S. Army Engineer District, Jacksonville, 1954) which shows the depth readings from approximately 735 points on 53 transects in the Lower and Middle Estuary and the South Fork. More recent maps include a 1944 edition of the U. S. Coast and Geodetic Survey map of the St. Lucie Estuary which the Corps of Engineers was still using as a bathymetric base map in 1954 (U.S. Army Engineer District, Jacksonville, 1954). The most recent sources are a detailed bathymetric map of the entire estuary developed from 1981 data by the SFWMD (Morris, 1986) and the 1963 NOS map # 11428. The SFWMD is currently concluding a highly detailed bathymetric survey (1998 Bathymetric Survey) of the SLE, which is being integrated with the data base and GIS Interface from this study for future analysis of the estuary.

In the time interval between the earliest and latest maps, maximum depths appear to have decreased from about 10-14 ft to 7-9 ft in most of the system. In the North Fork, Middle Estuary, and Lower Estuary, the changes have been largely confined to the mid-river zones where original depths were 8 ft or greater. In most of these sections, areas that were 9 to 15 ft deep in 1883 are now 7 to 10 ft deep.

Some changes appear to have occurred in the shallower zones along the shore, particularly in the Hookers Cove area of the Lower Estuary, and the south shore of the Middle Estuary along the City of Stuart in the vicinity of Krueger Creek and west of the hospital, where changes from 8 or 9 ft to 5 or 6 ft have occurred. The most pervasive changes have been in the South Fork, where the predominant water depths were once 8 ft or greater throughout much of the South Fork. Such depths are now largely restricted to the area downstream of Poppolton Creek. Maximum water depth throughout most of the South Fork upstream of this point is now less than 5 ft in most places.

Perceived differences in depths could be due to many factors, including the accuracy of the mapping efforts and differences in techniques and intensity of data. However, the above noted changes appear to be of a magnitude that would exceed differences in mapping techniques, and seem to indicate a profound change in the nature of the system.

These changes in depth may be significant in other ways as well. Obviously material has been added to the substrate, building the bottom up. However, the nature of the added material can have a significant effect on the ecology of the system. In some cases, shallower depths may represent an increase in possible habitat for submerged plants and other species that are favored by greater light energy or other conditions caused by the change. However, different types of substrate materials may result in more or less suitable habitat for different types of species.

The nature of the material being deposited is an important facet in evaluating potential ecological effects on the estuary. Some materials may result in conditions which are unsuitable for living organisms. Depths along the margins of the St. Lucie Estuary appear to have changed little in most areas, although substrate type may have changed. In most areas between 1 and 7 ft deep, sediments are either sand or silty or muddy sands. Highly organic or muddy areas are present in the upper reaches of the North and South Forks and near Krueger Creek in the Middle Estuary. Much research has been conducted on the nature of the sediments in the St. Lucie Estuary and in other estuaries, including relevant studies on the transport and sedimentation mechanisms and their significance to this system (Davis and Schrader, 1984; McPherson and Miller, 1987; Shropp, et al., 1994).

Most sedimentation in the South Fork consists of coarse grained sands which have formed sand shoals above the Palm City Bridge, downstream from the bridge nearly to Matchett Point, and at the confluence. This is believed to result from erosion from the St. Lucie Canal (U.S. Army Engineer District, Jacksonville, 1954, 1959). Sediment deposition in the Lower Estuary and near the mouth of the St. Lucie River also appears to be relatively coarse sand materials, but this appears to be largely due to tidal influences from the inlet.

Deposition materials in the North Fork and Middle Estuary appear to be fine clays, silts, and organic matter, often resulting in "muck" or flocculent sediments. Deposition of fine-grained sediments has been estimated as occurring at a rate between 0.2 inches (in.) and 1.0 in. (0.5 and 2.6 cm)/year in much of the estuary (Schrader, 1984; Davis and Schrader, 1984), particularly in the North Fork and in the deep, low energy zones (Haunert, 1988; Schropp *et al.*, 1994). Schropp *et al.* (1994) estimate that such rates would have accounted for 1.3 to 3.3 ft (40 to 50 cm) of sediment accumulation in the North Fork between approximately 1944 and 1994. Such an accumulation rate would be consistent with the changes in mid-river depths in the North Fork and Middle Estuary.

3.2.2 Substrates

Haunert (1988) has produced the most detailed characterization of the bottom substrates of the St. Lucie Estuary, finding coarse materials (generally well sorted sands) along the shallow margins of the estuary, with decreasing size materials in the deeper waters and silt and clay sized particles almost exclusively in the deepest areas of the Middle Estuary and North and South Forks. A tongue of larger size sediments was found to extend up the Lower Estuary where higher tidal velocities occur.

Haunert (1988) divided the sediments of the SLE into six categories depending on particle size distributions as follows:

- *Distribution A* - Well sorted medium generally extending no farther upstream than Coconut Point in the North Fork and Bessey Point on the South Fork.
- *Distribution B* - Medium and fine along shallow shore zones throughout the estuary, including off downtown Stuart in the Middle Estuary.
- *Distribution C* - Well sorted fine sands found only in a few areas along east and west shore of North Fork between Britt Creek and Kitching Cove, and shoal areas in South Fork.
- *Distribution D* - Weakly bimodal muddy sands, transitioning from sand to mud, in scattered mid-depth locations throughout the SLE where currents are variable or drop rapidly.
- *Distribution E* - A collection of very fine sands and clays and very poorly sorted sediments transitional from sands to clays with varied bimodal modes in deeper areas of the upper part of the Lower Estuary, the western half of deeper areas of the North Fork, and scattered areas in the upper South Fork, mainly Palm City Bay.

- *Distribution F* - Unimodal silts and clays, very poorly sorted sediments, and very well sorted clays found primarily in the deep areas in the middle of the Middle Estuary and the eastern half of the deep areas of the North Fork and in the deep areas of the South Fork between Taylor Point and Pendarvis Cove.

Distributions A, B, and C are essentially sandy substrates. Distributions D and E are transitional sandy muds with the Distribution D sand fraction similar to the Distribution B quartz sands and the Distribution E sand fraction similar to the Distribution C sand fraction. Distribution F is a mud that consists essentially of purely silt and clay sized particles (Haunert, 1988).

Haunert also analyzed sediments for organic content and found an extraordinarily high amount of organic matter in the North Fork, with a maximum of 64% in deep water off Britt Creek. Much of the deeper sections of the North Fork had organic contents greater than 20%. Very little organic matter was found in the Lower Estuary (almost all stations <10%), but a large plume was found in the Middle Estuary downstream of the Stuart Treatment Plant. In the South Fork, moderately high (>20%) concentrations occurred throughout Palm City Bay and between Poppolton Creek and Taylor Point. Shropp *et al*. (1994) also reported sediments in deeper portions of the North Fork between Coconut Point and the Club Med resort were black organic rich silts or silty clays with 80% to 93% silt/clays (muds) and 7 to 20% sands. Graves and Strom (1992) reported muck at the mouth of Bessey Creek/C-23 and nearby sites. Philips and Ingle (1960) found muddy sand (comparable to Haunert's Distribution D) to be the predominant bottom type in the SLE in depths to 7 ft. Mud and mud/shell were next in abundance. The occurrence of seagrasses appears to have been most consistent with stations listed as having firm muddy sand as opposed to mud or muddy sand.

The Environmental Studies Center (ESC) of the Martin County Schools has been conducting a student teaching/research project since 1987, in which sediment samples have been characterized as consisting of ooze, silt, mud, or sand. The ESC results indicate that organic-rich fine-grained ooze was most prevalent in the Middle Estuary and North Fork, with the least common occurrence in the Lower Estuary. Coarse-grained sand/ shell type has an opposite distribution. Mud substrates were approximately equally abundant in all segments of the SLE.

Based on evidence that fine grained sediments dominated over sand to all sampled depths (6 ft) in these core samples, Shropp and his colleagues have concluded that accumulation of fine grained sediments with high organic matter content has been a natural feature in the central basin of the North Fork even before the completion of the canals and drainage modifications in the early twentieth century.

3.2.3 Turbidity and Water Clarity

Turbidity and total suspended solids in the estuary are moderate in concentration, with TSS generally within the range from 0.01 to 0.02 g/l. However, high color and organic acid and organic matter content combine with the TSS to severely limit transparency and light penetration. In many areas less than 1 m deep, the Secchi depths are less than 0.5 m and light intensity at the bottom is less than 10 to 15% of the surface irradiance. Dissolved oxygen is generally above 4 mg/l, except in the deeper portions.

Phillips and Ingle (1960) reported Secchi depths of 0.5 to 2.0 m in the Lower Estuary, 0.5 to 2.25 m in the Middle Estuary, and 0.5 to 2.0 m in the North and South Forks from 1957 to 1959. In all cases the lower readings were associated with fresh water discharges from C-44. The water was reported to be a murky chocolate brown color that continued through the inlet during discharge events. Little color difference from this was reported for non-discharge periods in most of the SLE, but clear water was reported at the inlet. Phillips and Ingle also found a sharp line of demarcation between blue sea water and brown estuary water at about Hell Gate Point.

During approximately the same period the U.S. Army Engineer District, Jacksonville (1959) reported Secchi depths in the Outer Estuary (Outer Estuary in the Corps report is equivalent to the Lower Estuary plus the Middle Estuary in this report) of 0.6 to 1.5 m when the St. Lucie Canal was not discharging and 0.2 to 0.75 m during discharge periods. In the South Fork, non-discharge Secchi depths were 0.6 to 0.95 m, and discharge period depths were 0.15 to 0.7 m. Non-discharge Secchi depths of 0.6 to 1.35 m compared to discharge depths of 0.35 to 0.72 m in the North Fork. In general, Secchi depths were 50% to 67% less under discharge conditions.

Chamberlain and Hayward (1996) found an overall median level of TSS in the SLE of 10 mg/l during the three year period from October, 1989 to December 1992, a relatively low value compared to the median values for other Florida estuaries (Friedman and Hand, 1993). TSS was positively correlated with surface salinity and increased with decreasing distance to the inlet.

Haunert and Startzman (1985) recorded turbidity between 5 and 9 JTU in the South Fork during low flow conditions, but found that turbidity climbed to between 10 and 25 JTU during a 2,500 cfs discharge from the St. Lucie Canal. Turbidity in the North Fork remained between 5 and 10 JTU during the discharge.

Graves and Strom (1992) analyzed Storet data for 1973-1992, and found the average TSS concentration for the SLE was 14.7 mg/l and average turbidity was 6.1 NTU with no temporal trends apparent. They found average TSS values of 5.1 mg/l in the C-23 Canal, 5.1 mg/l in C-24, and 7.4 for the St. Lucie Canal. Average NTU values were 4.1 for C-23, 3.0 for C-24, and 5.7 NTU for the St. Lucie Canal.

Color is a highly significant parameter in the SLE. Chamberlain and Hayward (1996) found that the influence of color on transparency and light penetration in the SLE is almost twice that of TSS and an order of magnitude larger than chl-*a*. Less than 25% of all transparency measurements attained the management target value of twenty-five percent of surface irradiance (SI). The portion of incident photosynthetically active radiation (PAR) reaching the 1 m depth ranged from <0.1% to 87 % with a median value of 17.4% SI.

Under almost all flow conditions, median PAR at 1 m reached the target value of twenty-five percent of incident PAR no farther than 2 miles upriver from the inlet, at Hell Gate Point. Median PAR at 1 m never exceeded 15% SI at stations in the South Fork under any flow conditions.

3.2.4 Salinity

Under low flow or non-discharge conditions from the canals, bottom salinity in the Lower and Middle Estuaries average between 24 and 33 ppt, with extremes of 16 and 36 ppt. However, under high flow conditions, salinity may remain between 1.7 and 12 ppt for several days to weeks. These levels equate to a change from a mesohaline (5 to 18 ppt) system to an oligohaline (0.5 to 5 ppt) system.

In the South and North Forks, low discharge salinities range from about 9 to 19 ppt, with extremes to 5 and 20 ppt. High discharge salinities remain very low, from 0.1 to 0.3 ppt at all times. Thus the Forks can be mesohaline, oligohaline, or freshwater (<0.5 ppt) at different periods of a year, resulting in extremely stressful conditions for all but the most adaptable organisms.

Over the 3-year period from 1989 to 1992, Chamberlain and Hayward (1996) found surface salinity in the SLE ranged from 0 to 36.8 ppt with a median of 11.5 ppt. Bottom salinity ranged from 0 to 39.0 ppt with a median of 18.0. In contrast to the mean salinity values for high flow conditions reported by Chamberlain and Hayward, Phillips and Ingle (1960) reported that salinity was always < 1 ppt throughout the SLE during two discharge periods in 1957 and 1958. However, in the absence of discharge from the St. Lucie Canal, they recorded maximum salinities of 30.1 ppt in the Lower Estuary, 25.0 ppt in the Middle Estuary, and 13.0 ppt in both the South and North Forks, similar to results reported by Chamberlain and Hayward under low flow conditions.

Salinity stratification appears variable with the least stratification near the inlet and at the Speedy Point constriction where mixing is greatest (Chamberlain and Hayward, 1996), with median stratification index values from 1.7 to 2.92 ppt/m at most other areas and little stratification in the shallow areas. High salinity stratification (surface salinity <1 ppt; bottom salinity 22.5 ppt at 12 ft) was found by Plillips and Ingle near Hell Gate Point under discharge conditions, but little to no stratification was described for other locations.

The U.S. Army Engineer District, Jacksonville (1959) reported salinity on ten dates between January, 1957 and January, 1959. The following table lists the ranges and the daily means of all stations during periods of 0 cfs discharge from the St. Lucie Canal and periods of discharge from 2,160 cfs to 7,380 cfs. The Outer Estuary in the Corps report is equivalent to the Lower Estuary plus the Middle Estuary in this report.

SLE SALINITY RANGES RECORDED BY CORPS OF ENGINEERS 1957-1959				
	SURFACE SALINITY (ppt)		BOTTOM SALINITY (ppt)	
LOCATION	DAILY MEANS	DAILY EXTREMES	DAILY MEANS	DAILY EXTREMES
Non Discharge Days				
Outer Estuary	12.5- 25.0	6.3-32.8	24.9-32.6	16.2-36.0
South Fork	<1-17.3	<1-19.3	12.6-18.7	7.8-20.5
North Fork	2.5-15.4	2.4-18.5	9.0-17.6	5.4-20.2
High Discharge Days				
Outer Estuary	0.63-2.8	0.17-8.5	1.69-12.3	0.22-29.4
South Fork	0.14-0.25	0.16-0.35	0.14-0.21	0.14-0.27
North Fork	0.17-0.23	0.17-0.31	0.17-0.25	0.17-0.27

This data set indicates that surface salinities throughout the SLE remain under 3 ppt in almost all areas when the St. Lucie Canal discharges more than 2,100 cfs. During non-flow conditions, a substantial range of at least 12 ppt may be present. Those locations with high salinities at non-flow conditions and low salinities at high discharge conditions may represent extremely stressful conditions to many estuarine organisms.

The bottom salinities also appear to present a wide range of conditions, except at the most downstream stations. Under high discharge conditions, the data appear to indicate no salinity stratification in the North and South Forks, but under low flow conditions and under all conditions in parts of the Outer Estuary, stratification may indeed occur.

Haunert and Startzman (1985) found a salinity gradient from 11 ppt at the S-80 in the St. Lucie Canal to 33 ppt at the inlet under low flow conditions. Slight stratification was present in the South Fork. However, 4 days later after 1 day of 2,500 cfs discharge from St. Lucie Canal, water was nearly fresh as far downstream as the Palm City Bridge and there was a fresh water lens above brackish water at the Roosevelt Bridge.

Haunert and Startzman also reported that salinity in the two Forks ranged from 0.5 to 5 ppt (mesohaline) and in the Middle and Lower Estuary from 18 to 30 ppt (polyhaline) respectively before the discharge, but had dropped to 0.5 to 5 ppt (oligohaline) through most of the Middle Estuary and mesohaline as far as Hell Gate Point following 2 weeks of discharge. Highly stratified conditions (coefficient of over 4 ppt/m) occurred between the South Fork and the Outer Estuary. An apparent change in the benthic faunal community has been observed (Haunert and Startzman, 1985) when the salinity was reduced to below 5 ppt. The majority of a 33% reduction in benthic density was due to severe mortality of the bivalve *Mulinia lateralis* and migration of the amphipod *Ampelisca abdita*. An increase in density and extent of the fresh water midge *Chironomus crassicaudatus* was also noted.

3.2.5 Dissolved Oxygen

The median bottom stratum DO value from 1989-1992 was 5.0 mg/l, with a range from 0.1 mg/l to 9.8 mg/l (Chamberlain and Hayward (1996). Over 25% of the bottom DO samples were less than 4 mg/l, and 13% were less than 2 mg/l. DO levels generally decreased during low flow conditions, with 85% of the <2 mg/l samples collected under low flow conditions. Fifty-one percent of the low flow samples occurred during warmer months from June to September, and 51% were associated with high salinity stratification. Haunert and Startzman (1985) reported DO values of 0.9 to 10.4 mg/l in the North Fork and 6.0 to 10.6 in. the outer estuary in June and July, 1978.

3.2.6 Other Factors

Chamberlain and Hayward (1996) found median winter temperatures in SLE to be 21.0^{o} C and median summer temperature to be 29.3^{o} C. Vertical stratification of temperature was rare. Phillips and Ingle (1960) reported SLE water temperatures between 18.0 and 18.7^{o} C in March and between 22.2 and 30.2^{o} C in September. In June and July 1978, average water temperature ranged from 27.1^{o} C at the inlet to 31.5^{o} C in the inner estuary (Haunert and Startzman, 1985). The pH value in the SLE was reported by Phillips and Ingle (1960) to range from 7.0 to 8.2.

Mean and median concentrations of dissolved inorganic nitrogen (DIN) of 0.14 mg N/l and 0.09 mg N/l have been reported (Chamberlain and Hayward, 1996). Generally values were greater near the tributaries than near the inlet, although variability was high. Total nitrogen (TN) had a reported mean value of 1.0 mg N/l (Chamberlain and Hayward, 1996), generally increasing with increasing distance from the inlet and exhibiting a conservative behavior. Graves and Strom (1992) found average TN concentrations of 0.98 mg N/l in the estuary, 1.49 mg N/l in C-23, 1.61 mg N/l in C-24, and 1.48 mg N/l in the St. Lucie Canal, with no temporal trends. Ammonia, nitrate, and nitrite nitrogen have all been found to increase rapidly at the beginning of a discharge from the St. Lucie Canal (Haunert and Startzman, 1985).

Total phosphorus (TP) has ranged from 0.01 to 0.79 mg P/l with a median of 0.15 mg P/l (Chamberlain and Hayward, 1996). TP levels tended to increase with high flow conditions, with a high flow median of 0.26 mg P/l, and were higher near the tributaries and upriver. Graves and Strom (1992) reported average TP concentrations of 0.18 mg P/l in the estuary, 0.18 mg P/l in C-23. 0.25 mg P/l in C-24, and 0.13 mg P/l in the St. Lucie Canal. Total P values of 0.04 to 0.16 have been reported for the smaller tributaries (Graves and Strom, 1992).

Doering (1996) found that mean concentrations of DIN, TN, TP, and other parameters for the period 1990 to 1995 were almost always greater in the freshwater inputs than in the estuary. DIN:DIP and TN:TP ratios were higher in the fresh water inputs than in the estuary. He found the median chl-*a* value for the SLE to be 9.2 mg/m^3 with a mean of 10.3 mg/m^3. Median values generally showed some tendency to decrease with increased flow, and values generally tripled from the inlet to the heads of the tributaries.

3.3 HISTORICAL SAV DISTRIBUTION IN THE ST. LUCIE ESTUARY

These are very few published references to SAV and oyster distributions in the SLE. Phillips and Ingle (1960) have presented the most complete account of SAV occurrence. Other information is largely anecdotal in nature and consists of verbal communications from local sources with intimate knowledge.

SAV appears to have always been relatively sparse in the Lower Estuary, consisting of fairly small beds of primarily shoal grass, star grass, and Johnson’s seagrass with occasional turtle grass and manatee grass. Phillips and Ingle (1960) reported that SAV density decreased sharply between September 1957 and March 1958, presumably because of fresh water discharges, and that re-establishment had only begun at the most downstream station (Hell Gate Point) several months after the cessation of discharge. A re-survey by Teas (1971) found no signs of seagrasses.

In the Middle Estuary, relatively large and moderately dense beds have been reported along the south side of the system and near Rio on the north side at various times. These are reported to have reached 200 feet in width in the 1940s and 1950s, but more recent reports have indicated little to no beds in the Middle Estuary. Beds appear to have been most persistent in this area prior to 1950, and sporadic since then. The last major occurrences were in the early 1960s and during the drought period of the early 1990s. Species composition appears to have varied between shoal grass and widgeon grass, depending on the time and conditions.

Very little SAV has ever been reported in the South Fork, consisting mainly of rare patches of wild celery, common water nymph, widgeon grass, and possibly shoal grass in very shallow locations. Reported locations have been near the mouth of Danforth Creek, upstream of the Palm City bridge, and near Cabana Point.

There have been no recent reports of significant SAV concentrations in the North Fork, but moderately dense beds apparently were present from at least the 1940s to early 1960s on the east side above and below Britt Creek. Widgeon grass was reported as rare to abundant here in the 1940s (phone conversation July 11, 1997 with Hubert Stiller, Sr., commercial fisherman, Port Salerno, Florida) and the late 1950s (Phillips and Ingle, 1960; Gardner, 1984). Sparse SAV cover in this area was also reported from the early 1960s (phone conversation September 30, 1997 with Kevin Henderson, St. Lucie Initiative, Stuart, Florida). There have been unconfirmed reports of dense growths of SAV in the North Fork upstream of the estuary, with some extending downstream to the Tarpon Bay/Kitching Cove area. This appears to have been one of the fresh water species, but identification is not clear.

3.4 HISTORICAL OYSTER DISTRIBUTION IN THE ST. LUCIE ESTUARY

Numerous reports have mentioned the American oyster as present to abundant in the SLE, but there has been very little specific description of abundance, condition, or location. Documented information on historical and current oyster distribution within the SLE appears to be almost non-existent. Numerous studies (Everman and Bean, 1896; Murdock, 1954a, 1954b, 1954c; U. S. Army Engineer District, Jacksonville, 1959; Haunert and Startzman, 1980, 1985; Graves and Strom, 1992) have mentioned mollusk and other benthic macroinvertebrate populations within the estuary, but oysters are very rarely mentioned.

It is unclear whether the studies were concentrating on other constituents of the benthic population and ignored oysters or whether oysters simply were not found. Murdock (1954a) presented anecdotal evidence for the presence of oysters in the South Fork and Outer Estuary, but little specific evidence on condition or abundance. In 1959, oyster populations were described as abundant in the system, and there was no evidence of die-offs of mollusks or barnacles, but no specific data on locations was presented (U. S. Army Engineer District, Jacksonville, 1959). Teas (1971) reported several species of bivalves from the North Fork, but did not mention oysters. Few people currently appear to be aware of the presence of oysters in the estuary, so it is possible that early researchers also discounted their presence and did not look for them.

Apparently, oysters never were abundant in the Lower Estuary, except along mangrove roots and feeder streams (phone conversation November 4, 1997 with John Crawford, commercial fisherman, Jenson Beach, Florida). In the Middle Estuary, significant oyster beds have been reported by several sources as occurring on the north side from Warner Creek to the new Roosevelt Bridge area at least from the 1940s to the present with less dense beds on the south side from the Stuart City Hall to Krueger Creek.

Small beds of usually dead shells have consistently been reported from the South Fork primarily near the Palm City Bridge and Pendarvis Cove (phone conversations July 11, 1997 with Hubert Stiller, Sr., commercial fisherman, Port Salerno, Florida; August 10, 1997 with Daniel Haunert, South Florida Water Management District, West Palm Beach, Florida; August 10, 1997 with Paul Ezzo, South Florida Water Management District, Stuart, Florida). In the 1940s, oysters reportedly were present in low abundance throughout the mangroves lining the shore at that time (phone conversation November 4, 1997 with John Crawford, commercial fisherman, Jenson Beach, Florida). In the North Fork, beds near Seagate Harbor, north of Bessey Creek, along the east shore near North River Shores, and in Tarpon Bay have been consistently reported from the 1940s to present, but none of the reports has indicated significant abundance.

4.1 SAV SPECIES

4.1.1 SAV Species and Distribution

In this study, "Submerged Aquatic Vegetation" (or SAV) includes only submerged vascular plants, including "true" seagrasses (those which are adapted to brackish or saline waters) and fresh water submerged species. In the literature review, several SAV species were identified as having some potential to occur in the SLE system based on range and habitats as reported in taxonomic sources. Seventeen were evaluated in more detail, including six seagrasses (turtle grass, shoal grass, manatee grass, paddle grass, star grass, Johnson's seagrass), three transitional species (widgeon grass, common water nymph, and spiny naiad), and eight fresh water species (redhead grass, wild celery, Eurasian water milfoil, sago pondweed, horned pondweed, hydrilla, hornwort, and waterweed).

The seagrasses *Thalassia testudinum* (turtle grass), *Halodule wrightii* (shoal grass), *Syringodium filiforme* (manatee grass), *Halophila decipiens* (paddle grass), *Halophila englemannii* (star grass or six-leaf halophila), and *Halophila johnsonii* (Johnson's seagrass) have been well documented as occurring in the region (Woodward-Clyde Consultants, 1994; Virnstein, 1987). *Ruppia maritima* (widgeon grass) is generally lumped with the seagrasses, but is not strictly a seagrass because of its tolerance to fresh water and brackish water. Its presence has been well established in the region and it has been reported in the SLE (Phillips and Ingle, 1960).

The South Florida occurrence of fresh water SAV species is less well known. In the genus *Potamogeton*, sago pondweed and redhead-grass may have some potential in the upper SLE or tributaries, but other pondweeds are restricted due to range limits and restriction to strictly fresh water. Of three naiad species in Florida, only *N. guadalupensis* and *N. marina* have ranges that extend to the study area and habitats that include brackish or coastal waters (Long and Lakala, 1971; Godfrey and Wooten, 1979; Wunderlin, 1982).

Several fresh water species in the Hydrocharitaceae family may have limited potential for occurrence in the St. Lucie region. *Elodea canadensis* (waterweed) is a more northerly species that has been reported in fresh and slightly brackish coastal rivers in the Tampa area (Dames and Moore, 1975). Thus it may have very limited potential for occurrence in the St. Lucie region. *Hydrilla verticillata* and coontail (C*eratophyllum demersum)* have been found in Tampa Bay oligohaline tributaries, but always in non-tidal zones where salinity never exceeds 10 ppt. (Dames and Moore, 1975). Although not fully documented as sustainable in brackish water, hydrilla has been reported from Lake Okeechobee (Pesnell and Brown, 1977) and so was included in the literature review. *Myriophyllum heterophyllum* (water milfoil) and *Zannichellia palustris* L. (horned pondweed) have been reported as occurring naturally in brackish water, but the likelihood of occurrence in the estuary is very remote (Long and Lakala, 1971; Godfrey and Wooten, 1979).

4.1.2 SAV Physical Habitat Requirements

Tables 4-1 and 4-2 summarize some of the growth habit and habitat requirements for SAV species. Reproduction and expansion of seagrass beds is primarily by asexual rhizome production, while the fresh and brackish species generally have more varied methods of reproduction. This may make fresh water species better adaptable to variable environments with short to intermediate variability.

Temperature

It appears that all of the SAV species evaluated should be able to tolerate temperatures between at least 20 and 30 ^{o}C.

Water Clarity

A number of factors including color and suspended solids can influence the penetration of light into the water column. Numerous research indicates that turtle grass, shoal grass, and manatee grass require light irradiance levels of at least 10 to 15 % of full sunlight or irradiance at the water surface (SI). Kenworthy *et al.* (1991) and Dunton, (1994) suggest 15% to 18% of SI as an ecological compensation point for shoal grass. Widgeon grass, paddle grass, star grass, and Johnson's seagrass appear to have somewhat lower requirements, perhaps as little as 2 to 3 % of surface irradiance.

The freshwater or low salinity species all appear to have lower requirements, near 1 to 3 %. Light compensation points may be 1% to 2.0% of SI for coontail and Eurasian water milfoil (Stevenson and Confer, 1978; Grace and Wetzel, 1978), and as low as 0.3 and 1.0% SI have been reported for other species (Meyer *et al.,* 1943; Tanner *et al.,* 1993).

Moore (1963) indicated that plumes of turbid water preclude SAV growth. Zimmerman and Livingston (1976) found turtle grass, shoal grass, manatee grass, star grass, and widgeon grass in turbidity ranges of 0 to 55 NTU, but feel that turtle grass is less capable of withstanding longer periods of higher turbidity than manatee grass. Widgeon grass may be limited to turbidity levels below 25 to 35 NTU (Stevenson and Confer, 1978). Wild celery has a reported high tolerance for turbidity and muddy water (Stevenson and Confer, 1978). In general, turbidity and suspended solids levels in the SLE are within acceptable levels for most SAV species.

Nutrients

Substrate nutrient availability also may limit growth (Duarte, 1991; Dennison and Alberte, 1986). Nitrogen has generally been considered to be the more limiting nutrient in marine and estuary systems, while phosphorus has generally been found to be limiting for freshwater SAV (Murray *et al*., 1992). Several recent studies have indicated that P may be more limiting in estuarine systems than previously thought. Fourqurean *et al*., (1992) have found turtle grass in Florida Bay to be P limited and N saturated. Most information concerning marine P limitation has come from areas with carbonate substrates. Short *et al*., (1985) say the difference in nutrient cycling and P limitation between carbonate substrates and terrigenous sediments (muds and silts washed from the adjacent land) is due to the fact that P is more tightly bound to the substrate in the carbonate environment and is less available for plant uptake. Nitrogen appears to be more readily cycled and is usually present as NH_4 in the pore water of the substrates. However, recent studies by Short *et al*., (1993) have shown that N governs peak growing season production, and that N, rather than P, is the limiting nutrient for manatee grass in the central IRL where terrigenous sediments are dominant.

Current and Wave Regime

Turtle grass, manatee grass, wild celery, and sago pondweed all may tolerate moderate current or wave action, while the other species have low or unknown tolerance to moderate currents. Marine seagrasses generally have a high root/rhizome to shoot ratio, generally averaging about 3 to 4, and can survive in higher energy zones (Stevenson, 1988). Most fresh water species have ratios between 0.01 to 0.12, but wild celery has a ratio measured between 0.18 to 0.89, indicating that it may out-compete other fresh water species in high energy zones. Wild celery is also reported to tolerate moderate current or wave action due to a strong root system and basal meristem (Hunt, 1963; Korschgen and Green, 1985), although the leaves are easily damaged by high energy conditions and waves or boat wakes (Stevenson, 1988).

Conover (1968) reported turtle grass biomass peaks at currents of 0.5 to 1.2 knots, while shoal grass peaked at 0.2 to 0.5 knots. Manatee grass can prosper up to 1.6 to 1.8 knots, but declines by 90% at 0.2 and 2.2 knots. Widgeon grass has limited wave and turbulence tolerance due to fragility of its stems, branches, and small roots (Joanen and Glasgow, 1965; Stevenson and Confer, 1978; Verhoeven, 1979). Conover (1968) found peak biomass at 0.2 to 0.6 knots, with a 90% decrease at 0.01 and 0.8 knots. Thus in brackish areas with currents over 0.8 knots, only turtle grass and manatee grass may be found.

4.1.3 SAV Substrate Requirements

Most seagrasses appear to tolerate a wide range of substrate conditions. Virtually all of the seagrasses seem to grow on sandy or silty muds and on sands with some mud content (Reid, 1954; Voss and Voss, 1955; Phillips, 1960a), and almost all SAV species appear to prefer some mud in the substrate. Pure mud or silt substrates appear to be very poor for most SAV species, with sands intermediate in suitability. Small amounts of mud or organics may increase colonization, but substrates with more than 5 to 10% organic matter don’t support most species well. A mix of sand grain sizes is preferable to well sorted sands.

Haramis and Carter (1983) found 88% of vegetation in the Potomac on silty sands or sands and only 10% on silt or clay muds. Montz (1978) reported that loam substrates supported most of the dominant widgeon and wild celery in Lake Pontchartrain, while clay and sand substrates had little. Barko and Smart (1983) found that SAV growth was less when organics were added, with pine and cattail litter and algae the most inhibitory. Extensive work on substrate relationships has been presented by Phillips (1960a) and by Pulich (1985, 1987), particularly for turtle grass, shoal grass, and widgeon grass.

Turtle grass may be a better colonizer of sands and coarse sands than other species, but it appears to require a deep, and possibly calcareous, substrate (Thorne, 1954; Voss and Voss, 1955; Phillips, 1960a). Iverson and Bittaker (1986) postulate that the larger rhizomes and roots in turtle grass may allow it to survive in coarser substrates than shoal grass or manatee grass. Voss and Voss (1955) and Tabb (1958) also note the presence of gray calcareous marl or gray calcium carbonate sediments as characteristic of more vigorous sites. Because of a relatively deep and slowly spreading root system, turtle grass does not appear to colonize readily in areas where hard bottom is present and soft substrate layer has not been deposited (Zieman *et al.*, 1989). Zieman (1972, 1975) states that turtle grass requires a minimum of 50 cm of depositional sediments for lush growth, and Scoffin (1970) suggested a minimum of 7 cm.

Shoal grass can colonize a wide range of substrates from sands to muddy sands, as well as areas with significant shell hash. Firm muddy or silty sands are the best media. Simmons (1957) found shoal grass most often on a general substrate type consisting of sand as the main fraction, with silt usually the next most abundant fraction. Areas with rocks and with more silt than sand did not seem to support any seagrass species. Pulich (1982, 1987) has found that shoal grass often occurs in sites with high H_2S and low dissolved Fe^{2+} levels, with roots covered by blackish deposits of FeS (Pulich, 1987).

Manatee grass may be better suited for muddy sands or muds than turtle grass or shoal grass. Sand does not appear to be suitable, while silty sand and muddy sand is most suitable (Zieman, 1987). Manatee grass has been found on such diverse substrates as hard packed sands (Reid, 1954), silty or clayey sands (Simmons, 1957), and soft black mud (Phillips, 1960a), but Phillips (1960a) reports its occurrence on hard packed sand as uncommon. However, it appears to be most common on mixed mud and sand substrates, varying from extremely soft muddy sand to firm muddy sand dominated by the sand fraction (Phillips, 1960a). The most dense growth has been reported on soft muddy sand.

Little has been published describing the sediment characteristics of any of the *Halophila* species. Star grass, paddle grass and Johnson's seagrass all may occur on sand to mud substrates. However, Johnson's seagrass may be most suited to firm mud and sand, while star grass may be more suited to softer muddy sands. Paddle grass appears to occur mostly on relatively firm sands and silty sands. Phillips (1960a) characterized the paddle grass (probably Johnson's seagrass) habitats in the IRL near St. Lucie Inlet as ranging from sand to pure mud. Sand was the typical substrate in Jupiter Inlet. Hard sand was the only substrate found to support paddle grass at Tarpon Springs. Phillips (1960b) reported star grass on soft to firm muddy sands. Eiseman and McMillan (1980) say that Johnson's seagrass usually occurs on firm substrates, with sands of 0.88-1.25 mm grain size. Phillips (1960a) and Dawes *et al.*, (1989) mention Johnson's seagrass on sands to firm muds.

Widgeon grass is an opportunistic species, partly due to a rapid growth rate and a wide substrate adaptability from firm sands to moderately soft clays and muds and organic sediments (Orth *et al.*, 1992). Silts and silty sands are the most common substrates. Tolerance to substrates with over 10% organic matter seems poor. Widgeon grass has been reported on sands with low organic content and sometimes high shell content in the IRL, Laguna Madre, and Chesapeake Bay (Simmons, 1957; Woodburn and Ingle, 1959; Pulich, 1987; Hurley, 1991). It is also common on soft muddy sands, silts, and clays (Phillips, 1960a; Phillips and Ingle, 1960; Verhoeven, 1979; Hurley, 1991).

Wild celery has a substrate range like widgeon grass, with silty sands most common. Only areas with soft muds or mucks, high organic matter, or high accretion rates are unsuited. It occurs in a wide range of substrates from gravel and hard clay (Hunt, 1963) to firm silty sands (Lind and Cottam, 1969; Bayley, *et al.*, 1978) and coarse silts and sandy loams (Stevenson and Confer, 1978; Hurley, 1991). The most healthy beds have been reported in sandy loam or sandy silt soils with at least 6 to 48 % silt and 1 to 6% organic matter in a sand base (G. Hutchinson, 1975; Hurley, 1991). Rybicki and Carter (1986) suggest that annual sediment deposition of >10 cm could lead to elimination of a wild celery population due to increasing depth of rhizome or tuber burial

Sago pondweed has a similar range of tolerances, but the preferred substrate appears to be somewhat more fine grained. Silty to muddy substrates and silty sands seem to be the most common substrates, as long as the sediment is not hard packed. Sago pondweed has been described as silt loving (Sculthorpe, 1967) and growing in generally silty to muddy sediments in the Chesapeake Bay region (Stevenson and Confer, 1978; Hurley, 1991). Other papers have reported it to occur in a wide range of sediment types from sands to clays to organics, as long as the sediments are not hard packed (Pip, 1987; Kantrud, 1990; Spencer and Ksander, 1995).

Redhead grass appears to be even more common on mud or silt sediments, with less tolerance for sandy substrates. It has been described on firm, muddy substrates in slow moving waters (Stevenson and Confer, 1978; Hurley, 1991), with best growth in muds with moderate organic contents and high N and Ca content. It may be better adapted to slightly finer muddy sediments than sago pondweed (Kantrud, 1990). It is virtually the only species that has been reported in the literature to have favorable growth on mucks, flocculent muds or semi-liquid soils (Mishra, 1938).

Common water nymph appears to do best on moderately firm sands and firm silty sands, but it also will occur on silts and even muck (Lind and Cottam, 1969; Bayley *et al.*, 1978; Stevenson and Confer, 1978). Hydrilla, Eurasian water milfoil, coontail, and waterweed do best on sands and silty sands, but growth appears inhibited by organic matter (Anderson, 1972; Bayley *et al.*, 1978; Barko,1983; Kimbel, 1982). The spiny naiad may be most common on organic soils (Van Vierssen, 1982), although data is very scarce.

Several studies have shown the relationship between growth and reproduction characteristics of species and the ability to tolerate changing conditions and to recolonize after disturbances. Such abilities may be as key as actual substrate preferences to survival in an area of fluctuating environments (such as the SLE). Preen *et al.*, (1995) suggest that physical burying of seed by accreting sediments or abrasion and death of seeds from churning sediments may be responsible for a lack of shallow re-establishment of seagrasses after losses due to floods or turbid conditions. Substrate interactions and growth and morphology of rhizomes and shoots also appear to be critical factors in determining SAV succession and colonization success on bare substrates. Gallegos *et al.*, (1994) have shown that both shoal grass and manatee grass have rhizome growth rates that are two to four times as high as turtle grass, as well as more rapid turnover times and greater flower density, all of which favor more rapid recovery in changing environments. The *Halophila* species also have very rapid turnover times, indicating a relatively high tolerance for changing conditions and recolonization after losses (Kenworthy *et al.*, 1989).

4.1.4 SAV Salinity Tolerance

Table 4-3 summarizes the current knowledge of SAV salinity tolerance. Development of significant densities of true seagrasses appears restricted to salinities from about 22 ppt to 36 ppt in natural environments. The overall tolerance ranges for most seagrasses appears to be much broader, generally from about 15 to 45 ppt, with considerable variability among species. Paddle grass, star grass and Johnson's seagrass may have much narrower tolerance ranges than the other seagrass species. The literature indicates that all of the seagrasses have some short-term (e. g., 1 to 3 days) low salinity tolerance near 10 ppt and a short-term high salinity tolerance between 50 and 70 ppt.

Turtle grass appears to have the highest salinity tolerance and the highest optimum range, reported as thriving in beds where salinities have ranged from 28 ppt to 48 ppt in the Florida Keys, Florida Bay, and Texas (Taylor, 1928; Tabb *et al*., 1959; Adair *et al*., 1994). Phillips (1960a) concluded that the range from 28 to 35 ppt is probably optimum for turtle grass and that 24 ppt is the probable lower limit for normal growth. Zimmerman and Livingston (1976) say that turtle grass is not found in less than 17 ppt in north Florida. Dawes (1987) and Zieman (1975) both considered turtle grass to be characteristic of stable marine environments with salinity consistently between 20 to 36 ppt. The literature also indicates that turtle grass may withstand short durations (perhaps 3 to 7 days) in which salinity drops well below 20 ppt, but longer duration may lead to disappearance (Phillips, 1960a; Sculthorpe, 1967; Zieman, 1982).

Dense beds of manatee grass have been reported in the IRL system and Tampa Bay in areas with 20 to 35 ppt salinity (Woodburn and Ingle, 1959; Phillips, 1960a) and between 28 and 38 ppt in Florida Bay and the Dry Tortugas (Taylor, 1928; Tabb *et al*., 1959). An optimum range for manatee grass is probably between 23 and 30 ppt, although it tolerates a much wider range (McMahan, 1968). Phillips (1960a) found that manatee grass was much more dominant in mixed turtle grass/manatee grass beds when salinities were below 25 ppt, and postulated that it can not compete with turtle grass at the higher salinities.

Shoal grass has a greater salinity range than the other seagrasses, although its naturally occurring distribution does not appear to differ much from other species (thus it is usually found in similar areas). However, it appears to tolerate wide fluctuations in salinity more easily than other species, accounting for its ability to succeed where other seagrasses may not persist. In particular it appears able to tolerate short duration exposures as low as 5 ppt for several days to a few weeks (McMahan, 1968). In Florida and Texas, dense shoal grass beds have been reported in the range between 24 and 38 ppt (Phillips, 1960a; Kenworthy and Fronseca, 1992; Adair *et al*., 1994). Sparse to dense coverage has been reported in the St. Lucie River and Tampa Bay at salinities between 12 and 24 ppt, with 13 to 17 ppt the lower limit for appearance (Woodburn, 1959; Phillips, 1960a). However, sparse populations in the SLE were reported to have died back after "prolonged" periods of several weeks of fresh water (Phillips, 1960a; Phillips and Ingle, 1960).

Little information is available for the *Halophila* species, but the tolerances of all species appear to be fairly similar. Paddle grass (possibly Johnson's seagrass) has been reported at salinities between 24.3 and 38.0 ppt (Phillips, 1960a). Eiseman and McMillan (1980) indicate that Johnson's seagrass occurs in salinities of 24 to 38 ppt, but can tolerate conditions to 43 ppt, and

Dawes *et al.*, (1989) reports both species at greater than 38 ppt. Dawes *et al.*, (1989) also reported that neither paddle grass nor Johnson's seagrass tolerates a 5 ppt salinity, both species dying within a 3-day acclimation period. However, Johnson's seagrass had a broader tolerance to all combinations of salinity (15, 25, 35 ppt) and temperature (10, 20, 30^{o}C) tested.

Star grass has a reported wide range of salinities from 9 to 35 ppt (Phillips, 1960a; Zimmerman and Livingston, 1976; Adair *et al*., 1994), although the lower range appears to include ephemeral low salinity events. Flowering and photosynthesis is inhibited at low (5 to 18 ppt) salinities (Dawes *et al.*, 1982; Moffler and Durako, 1987). Den Hartog (1970) stated that star grass can withstand large decreases in salinity (to 6 ppt) for only short periods of time such as a couple of days. Dawes (1987) and Humm (1956) consider paddle grass and star grass to be limited to stable higher salinities. A lower long-term concentration of about 22 to 24 ppt may be limiting for both species.

Widgeon grass and redhead grass appear to be somewhat unique in that they are not true seagrasses or obligate halophytes, yet are able to tolerate short-term exposures to full sea water (36 ppt). Widgeon grass has an extremely high range of reported occurrence in varied salinity conditions (0 to 45 ppt). However, under natural conditions, dense stands appear to be limited to salinity ranges from 1 to 25 ppt. As salinities approach the optimum ranges for seagrasses, the increased competition from the true seagrasses is presumed to limit the development of widgeon grass. Widgeon grass commonly has been reported in salinities from freshwater (1 ppt) to 32 ppt (Hurley, 1991; Phillips, 1960b; Zimmerman and Livingston, 1976; Dawes, 1987; Adair *et al*., 1994). In most instances, it appears to be restricted to salinities below 25 ppt, and in Europe was reported from only oligohaline and mesohaline (1 to 10 ppt) waters (Verhoeven, 1975), probably due to an inability to effectively compete with other species. Seed set has been reported as occurring only below 29 ppt (Bourn, 1935; McMillan, 1974). A lower limit of 5 ppt has been reported (Anderson, 1972). Richardson (1980) indicates that widgeon grass apparently utilizes an annual growth form with seed germination as the main reproductive method in areas with low salinities where spring rains promote germination, and a perennial growth strategy with over-wintering rhizomes in the more saline sites. Such a dual strategy allows for greater population persistence in areas with high variability in salinity conditions. Richardson (1980) and Seeliger *et al.*, (1984) also indicate highest seed germination in fresh water, with inhibition at between 5 and 18 ppt.

Redhead grass has a salinity range similar to widgeon grass, although the upper limit is somewhat lower. Both species, especially widgeon grass, are reported to acclimate readily to different salinity conditions. Different populations, or plants from the same population raised in different salinities, can show distinctly different salinity tolerances. Redhead grass has been reported in salinities from 1.5 to 20 ppt (Stevenson and Confer, 1978; Hurley, 1991. Other studies indicate a survival range from 5 to 25 ppt (Anderson, 1969; Stevenson and Confer, 1978; U.S. Environmental Protection Agency, 1992). Haramis and Carter (1983) consider it to be dominant (with wild celery) in transitional areas with fluctuating salinity between 0.5 and 10 ppt, but it also occurs in purely mesohaline areas.

Wild celery and sago pondweed are generally considered fresh water species (Anderson, 1972), but the various controlled experiments indicate that the salinity optimum is slightly higher, with natural populations commonly occurring at salinities near 10 ppt (Twilly and Barko, 1990). Both species grow well in fresh water, have shown some short-term tolerance to approximately 16 ppt, and have some ability to acclimate to differing salinities. Sago pondweed has been shown to survive at salinities from 0 to 12 ppt in laboratory experiments (Van Wijk, 1988; Van Wijk *et al*., 1988; Kantrud, 1990; Twilly and Barko, 1990), but growth and seed germination decrease by 50% at between 2 and 8 ppt (Tetter, 1965). For long term population survival, 0 ppt is optimal and 2-3 ppt is probably an upper salinity limit (Tetter, 1965).

Several studies have reported wild celery in parts of coastal rivers where salinities remain near 1 ppt, but absent where salinity varies between about 1 and 13 ppt (Phillips and Springer, 1960; Gunter and Hall, 1962; Davis and Brinson, 1983; Adair *et al.*, 1994). Purcell (1977) indicated a possible short term tolerance to higher salinities, with some regrowth when salinities had fallen to between 3 and 20 ppt. Davis and Brinson (1983) found a break in mean salinity at between 5.3 ppt and 7.6 ppt. Laboratory studies (Bourn, 1932, 1934; Hunt, 1963; Haller *et al*., 1974; Twilly and Barko, 1990) have indicated maximum long term salinity levels of about 2.0 to 7 ppt, with some short term survival to 12 ppt in short term (8 weeks) conditions with gradual acclimation.

Common water nymph, spiny naiad, Eurasian water milfoil, hydrilla, and horned pondweed are essentially fresh water species, but with the ability to persist in waters from 5 to 10 ppt. Tolerances appear to be lower than wild celery and sago pondweed. However, horned pondweed may be able to survive in locales with high annual mean salinities due to its very short annual life cycle and an ability to grow and set fruit during shorter high rainfall periods when salinities are lower than the mean. An upper salinity limit of 7 to 10 ppt appears to be most commonly reported for the common water nymph and the spiny naiad (Haller *et al*., 1974; Stevenson and Confer, 1978; Van Vierssen, 1982; Adair *et al*., 1994). Eurasian water milfoil, horned pondweed, hornwort, and waterweed are essentially fresh water species but Eurasian water milfoil has been reported from similar zones as widgeon grass (Anderson, 1972; Haller *et al.*, 1974; Stevenson and Confer, 1978; Haramis and Carter, 1983).

Evaluation of Salinity Effects

Of species evaluated in the literature review, shoal grass, widgeon grass, wild celery, and redhead grass appear to be the only species showing sufficiently broad tolerance levels that might cover some of the existing salinity ranges in different portions of the North Fork, South Fork, and Middle Estuary regions of the SLE.

Of the true seagrass species, shoal grass appears to have the greatest tolerance for fluctuating salinities in the range from 15 to 25 ppt. Widgeon grass generally has been found to have the greatest salinity tolerance range of all species and one of the highest abilities to adjust to fluctuating salinities. It appears able to tolerate salinities in the range from 5 to 20 or 25 ppt. On this basis, it appears to offer the greatest potential for restoration of submerged vegetation to the Middle Estuary and the North and South Forks. It appears probable that historical SAV beds or occurrences described along the east side of the North Fork, the upper end of the North Fork, near the Palm City bridge in the South Fork, and possibly near Stuart in the Middle Estuary were composed largely of widgeon grass. Redhead grass is an intriguing species due to its wide salinity tolerance and an apparent ability to survive on softer muddier substrates than widgeon grass or shoal grass. It’s occurrence in this region is not adequately documented, but it could be well adapted to the SLE if the range of occurrence extends to the region.

The ability to tolerate fluctuations in salinity may be more critical than mean salinity ranges for a species. Montague and Ley (1993) studied the relationship of seagrass abundance to salinity in northeastern Florida Bay and found that mean salinity had a relatively poor correlation to plant biomass, although there was relatively little seagrass present at salinities below 25 ppt. However, the standard deviation of salinity was the best environmental correlation to both plant biomass and lentic faunal diversity; it accounted for 59% of the variation in biomass. For every 3 ppt increase in the standard deviation, plant biomass decreased by an order of magnitude. They postulated that a 15 ppt standard deviation of fluctuation could be sufficient to prevent the occurrence of any benthic vegetation. This study provides strong evidence that the degree of salinity fluctuation may be more important to seagrass abundance than the actual salinity concentration.

The actual situation in terms of salinity regime and SAV occurrence may be more complicated than just salinity effects. Several studies have implicated interactions of factors in changing SAV distributions. For example, Haramis and Carter (1983) suggest that salinity gradients may affect the distribution of species through interactions between salinity, nutrients and phytoplankton. They noted that historically, SAV was abundant in the Potomac River in mesohaline, transitional, and fresh water zones, whereas currently the only SAV is found in the transitional zone which contains the maximum variation in salinity. They postulate that under historical conditions, both turbidity and nutrient concentrations were lower, resulting in high light penetration and abundant SAV throughout the estuary. Under the current nutrient enriched conditions, increased phytoplankton abundance coupled with increased turbidity has reduced light penetration to levels that preclude SAV growth in the fresh water and mesohaline portions of the river. However, the high degree of salinity fluctuation in the transitional zone limits abundance of either salt or fresh water phytoplankton more severely than the SAV, and the resulting improved light transmittance has allowed SAV to persist in this portion of the system.

It is likely that the apparent low light penetration in much of the SLE interacts with salinity in influencing distribution and establishment of SAV. Since most of the fresh water species appear to have lower light compensation points than the seagrasses, they may also have a better potential for re-establishment in the North Fork and South Fork.

4.2 AMERICAN OYSTER DISTRIBUTION

4.2.1 General Occurrence

The American oyster (*Crassostrea virginica*), also known as the eastern oyster, is an almost exclusively estuarine bivalve mollusk in the Ostreidae family (Livingston, 1990). Because they are sessile throughout most of the life cycle, oysters have adapted to a wide range of environmental conditions and can withstand substantial variations in these factors. The oyster’s natural range extends along the Atlantic coast from the Gulf of St. Lawrence to the Yucatan Peninsula (Galtsoff, 1964). The species also has been widely introduced throughout temperate and tropical seas of the world.

4.2.2 Life History

The life cycle of the American oyster occurs entirely within estuaries. Spawning usually begins as water temperatures near 20°C, and, in Florida, release of gametes (unfertilized male and female reproductive cells) probably occurs through all except the coldest months (Breuer, 1962; Quick and Mackin, 1971; Killam *et al*., 1992). In Florida, there appear to be bimodal peaks in larval production and setting in late spring and early fall. High temperatures and associated low dissolved oxygen or low salinities in mid-summer tend to depress production. It is likely that a mature oyster spawns many times a year in southeast Florida. Depending upon the size of the female, stage of maturation, and water quality conditions, 23 to 86 million eggs can be released by one female per spawning (Davis and Chanley, 1955).

Fertilization occurs externally when the sperm and eggs come in contact in the water column to form embryos. Embryos develop into veliger (first free-floating larval stage) larvae in 24 hours or less, depending upon temperature. The initial larval stage is known as the straight-hinge, or "D-stage" veliger larvae, which has two simple shells (valves) and ring of locomotory cilia. Normal development in this stage is affected by both temperature and salinity regimes. Over the next two to three weeks, the larvae grow through several more veliger stages. These planktonic veligers are the only mobile stages; they can move up and down in the water column and are carried some distance horizontally by currents

When the larvae reaches 260-300 µm in length, it develops a more rounded hinge, a foot, and two simple eyes. This stage is called the pediveliger stage. The pediveliger can still swim, but tends to settle and the foot is used to crawl and investigate the substrate. When a suitable surface is found, a cementlike substance is extruded from a pore in the foot and the left valve becomes attached. There is evidence from several studies that physical and chemical stimuli influence attachment and attraction to suitable substrates. The process of attachment is called “settling” or “setting”, and is one of the important milestones in the oyster life cycle. The resulting, attached, juvenile oyster is referred to as a spat.

At the latitude of the St. Lucie Estuary, spat may develop into mature oysters in 4-12 weeks (Killam *et al*., 1992). Spawning by young of the year and production of two generations in a year is very likely, although the contribution of first-year spawners to year-class strength is probably insignificant (Hayes and Menzel, 1981). Young oysters are predominantly males, and over ensuing breeding cycles tend to transform into females (Galtsoff, 1964), so that large oysters are primarily female, thus ensuring an abundant supply of eggs. Thus, it is probable that egg production and spawning success is strongly correlated to longevity of oysters in a population. Although populations composed of first or second year oysters can reproduce and possibly maintain populations, abundance may remain low unless some oysters are able to survive for several years.

Growth of American oysters is most rapid during the first year (Owen, 1953; Bahr, 1976), with overall shell lengths of 40-50 mm likely by the end of the first year in the SLE region (Berrigan, 1990). Growth becomes much slower (20-25 mm/yr) as maturity is achieved and metabolic reserves are increasingly devoted to maintenance of reproductive activities and soft tissues (Killam *et al*., 1992). Under ideal conditions, American oysters may survive for 10 or more years although 2 to 5 years is most common (Cake, 1983). Gunter (1953) felt that under normal conditions, a mortality rate of about 2 to 4% per month is typical for oyster beds. Episodic events such as temperature or salinity extremes may result in nearly 100% mortality in some cases.

4.2.3 Ecological Role and Requirements

Feeding Activity

The primary ecological importance of the American oyster is as a filter-feeding primary consumer, as prey for numerous higher consumers, and as a habitat-former. All of these are important in the overall ecology of estuaries. American oysters feed primarily on living phytoplankton throughout all stages of life. Veliger larvae ingest particles from 0.2 to 30 µm, with survival at lower temperatures dependent on the supply of chrysophytes. At higher temperatures, chlorophytes and diatoms become more important parts of the larval diet (Davis and Calabrese, 1964). Foods ingested by adults includes diatoms and dinoflagellates, bacteria, and possibly detrital carbon (Killam *et al.*, 1992).

Oyster filter feeding is of extreme ecological significance (Newell, 1988). It is estimated that an oyster filters water at a rate of about 1500 times its body volume per hour (Loosanoff and Nomejko, 1951). Declines of the major particulate carbon filter-feeding assemblage provided by oyster beds is cited by Newell (1988) and others as a major factor in an apparent shift to microbial food webs and increases in zooplankton densities in Chesapeake Bay. It has been estimated that the late nineteenth century oyster population in Chesapeake Bay could pump and filter the entire volume of the bay in 3 to 6 days, whereas the smaller present day population would take 365 days (Kennedy, 1991). These numbers equate to a filtering of about 40 to 75% of the daily carbon production in the bay as opposed to less than 1% under present day conditions (Newell, 1988; Kennedy, 1991).

Predation

The free-swimming larvae are preyed upon by many planktivores (e.g., ctenophores, anemones, some larval fishes), with more than 99% of gametes, embryos, and larvae lost before settlement (Kennedy, 1991). Newly formed spat are eaten by carnivorous worms and various small crabs (e.g., mud crabs and juvenile blue crabs). The larger spat and small adult American oysters are consumed by a variety of predators, including blue crabs, stone crabs, whelks, conchs, oyster drills, boring clams, boring sponges, skates, rays, and fishes such as black drum and redfish (Wells, 1961). Most predation occurs at salinities higher than 20 to 25 ppt, since many of the predator species, especially the oyster drills and boring sponges, do not readily tolerate lower salinities (Butler, 1954a; Wells, 1961; Mackin and Hopkins, 1962; Zachary and Haven, 1973).

Oysters are also subject to several diseases and parasites. In warm climates and lower salinities, the pathogenic protozoan parasite (*Perkinsus marinus*) causes the disease known as perkinsiasis or “Dermo” (Quick and Mackin, 1971; Powell *et* al., 1992; Ragone and Burreson, 1993). Other common warm weather diseases of southern oysters are “MSX”, which is caused by several sporidian protozoans (Haskin and Ford, 1982), and red tide (*Colchlodinium heterolobatum*), reported to cause oyster larval mortality at concentrations of >500 cells/ml (Killam *et al*., 1992).

Substrate and Community Development

Most estuaries are depositional features, dominated by soft sediments with little surface structure or roughness, in which the American oyster can provide the greatest volume of hard substrate due to its shell production. Under natural conditions, oyster reefs can be very large, and provide extensive attachment area for oyster spat and numerous associated species such as mussels, tunicates, bryozoans, and barnacles. Several studies (Pearse and Wharton, 1938; Wells, 1961; Bahr and Lanier, 1981) have found from 40 to over 300 faunal species in beds in oyster beds, including other mollusks, crustaceans, annelids, numerteans, flatworms, sponges, coelenterates, and protozoans

Oyster beds or communities may have different characters depending on the location and environmental regimes. Butler (1954b) has described 4 typical categories for Gulf of Mexico oysters. Category I are beds near the heads of estuaries with salinities from 0 to 15 ppt. They are sparse with high annual mortality, reflecting the marginal nature of the environment, being periodically decimated by fresh water and low salinity in most years. The oysters are mostly small and rounded with smooth whitish shells. Spatfall rates are low, but first year growth is generally good. Growth in later years is slow, but may be good in drought years. These beds are usually free of fouling organisms and have few predators or parasites, and overall faunal diversity is very low.

Category II includes beds, generally in mid-estuary areas, where the salinity fluctuates moderately between approximately 10 and 20 ppt, with an annual average near 15 ppt. This type has the highest population density due to high rate of reproduction, relatively low predation, and abundant cultch production. The salinity range is near-optimal for reproduction, and is sufficiently low to restrict predators. High and uniform growth rate results in distinct year classes distinguishable by size. The valves are usually narrow, smooth and dense, possibly with moderate infestations of boring sponges and clams. Large or small interlocking clusters of shells may develop, with development of permanent hard reefs. Competition for space is intense between and among oysters and mussels.

Category III beds develop near mouths of typical estuaries with average salinity near 25 ppt that ranges from 10-12 ppt in the wet season to 30 ppt in the dry season. The reproductive potential may be highest in this category and growth is good. However, the population density remains lower than in Category II because of higher densities of predators and parasites. Mortality of spat and juvenile oysters is very high, but surviving adults may grow to massive size.

Category IV beds are sparse, occurring at the ocean/ estuary junction, exposed to a consistently high salinity environment ranging from 25 to 36 ppt. This environment is as marginal as Category I due to predator abundance and above optimal salinities. Spat set and survival are low due to predation. Wells (1961) pointed out that oysters in Category IV type environments in the south are often restricted to intertidal zones where increased desiccation and thermal stress may lessen threats from less hardy predators.

General Habitat Requirements

Like most sessile estuarine animals, *Crassostrea virginica* is anatomically and physiologically well-adapted to a wide range of temperature, salinity, and dissolved oxygen. Oysters are particularly capable of surviving environmental extremes, so long as the conditions do not persist for extended periods.

Optimum temperatures for reproduction, embryonic development, and growth of American oysters appear to be 20-30°C (Killam *et al*., 1992); developmental anomalies appear when temperatures move outside this range. Although capable of surviving at salinities from about 5-40 ppt, the optimum range for oyster reef growth and reproduction is in the range of 10-30 ppt (Galtsoff, 1964). The salinity tolerance of larvae is dependent upon the salinity at which the parents spawned (Davis, 1958). An inverse relationship has been observed between the ability of oysters to survive low salinity extremes and temperature (Andrews, 1982; Loosanoff, 1953). Low dissolved oxygen concentrations appear to be much less of a problem for oysters than most other estuarine organisms (Berrigan *et al*., 1991; Kennedy, 1991).

Water movement is important for successful development, as currents replenish food resources, remove waste products, and prevent smothering from sediment accumulation (Galtsoff, 1964; Berrigan *et al*., 1991). Very soft mud and shifting sand appear to be the only substrates that are completely unsuitable for the setting of spat(Galtsoff, 1964). The ideal surface is horizontal and comprised of shell (especially of oysters) (Kennedy, 1991).

Water Depth (Tidal Zonation) Factors

The fundamental considerations related to depth distribution is susceptibility to exposure and potential desiccation or thermal stress (Bahr and Lanier, 1981; Cake, 1983; Osman and Abbe, 1994; Allen and Bushek, 1997). Several studies have shown a relationship of salinity to depth distribution, with oyster populations being mainly limited to the intertidal zone in high salinity areas, but occurring deeper, in the subtidal zone, in low salinity areas (Wells, 1961; Mackin and Hopkins, 1962). Restriction of oysters in high salinity regimes to the intertidal zone appears related to increased predation by other organisms which can not survive in the low salinity regimes (Wells, 1961). Oysters are among the few organisms able to sufficiently tolerate the potential desiccation and thermal stress of this zone. Dissolved oxygen, salinity and related biotic interactions, and currents have been shown to be factors in deeper subtidal beds (Mackin and Hopkins, 1962).

Current (Circulation-Related) Factors

Water movement is crucial to successful dispersal and development of immature stages, as well as survival and growth of sedentary older individuals (Berrigan *et al.*, 1991; Powell *et al.*, 1995a, 1995b) for replenishing food supply, removing waste products, and preventing smothering due to accumulation of sediment. Scouring (erosional) conditions are essential for established beds (Kerswell, 1949; Keck *et al.*, 1973; Marcus *et al.*, 1989; Powell *et al.*, 1995a). Wells (1961) found current velocities up to 66 cm/sec on oyster bars in North Carolina, but MacKenzie (1981) has indicated that current velocities above 150 cm/sec may dislodge and carry away unattached individual oysters.

A number of population modeling studies have indicated that factors related to the magnitude and timing of localized food supply may be of greater importance than salinity and temperature in regulating population structure and stability (Prytherch, 1929; Lund, 1957; Galtsoff, 1964; Soniat and Ray, 1985). A key factor in the small-scale availability of food resources is the flow rate at the reef/water interface (Wilson-Ormond et al., 1997). Although localized movements of individual larvae within the water column may be controlled in part by salinity and temperature, larval dispersal is ultimately dependent upon currents. Moreover, once the spat have set, adequate circulation is necessary for continued survival and growth. American oysters will not live productively in static water.

Dissolved Oxygen Requirements

Juvenile and adult American oysters are capable of surviving in extremely hypoxic conditions (< 1 mg/l DO) for up to five days (Sparks *et al.*, 1957). It appears that larvae and early spat, like juveniles and adults, are capable of anaerobic metabolism, but for somewhat shorter periods depending upon the actual developmental stage (Galtsoff, 1964; Shumway, 1982; Widdows *et al.*, 1989; Mann and Rainer, 1990; Baker and Mann, 1994).

Oysters will not survive hypoxic/anoxic conditions indefinitely (Hoese and Ancelet, 1987). Microxic conditions (< 0.07 mg/l DO) lasting longer than about a day significantly increase mortality rates among post-settlement young (Baker and Mann, 1992, 1994). Hypoxic conditions (< 1.5 mg/l DO) are apparently not lethal, even over several days, but beyond about three days metamorphosis is delayed and growth is suppressed (Baker and Mann, 1994). When hypoxic intrusions coincide with the first two weeks after settlement, the combination of increased mortality, delayed metamorphosis, and reduced growth can significantly decrease recruitment (Osman and Abbe, 1994; Baker and Mann, 1994).

Temperature

There is a greater ability to survive extreme salinity conditions at lower temperatures, and the ability to withstand temperature extremes is greater at near optimum salinities (Davis and Calabrese, 1964). The general acceptable long-term temperature range for adult American oysters appear to extend from about -1 to 32 ^{o}C (Loosanoff, 1958; Kennedy, 1991). Eggs and veliger larvae are more sensitive to temperature extremes, with a tolerance range between about 15 and 35 ^{o}C (Hidu *et al.*, 1974). Temperature ranges for spawning and spat fall of American oysters have been reported between 16 to 28 ^{o}C, with the higher temperatures occurring in more southern areas (Finucane and Campbell, 1968; Quick and Mackin, 1971).

Suspended Solids and Turbidity-Related Factors

Adult oysters have effective morphological adaptations for feeding in much higher levels of suspended solids than are usually encountered under natural conditions (Nelson, 1923; Kennedy, 1991). Oysters from relatively turbid estuaries appear to be able to feed at total suspended solids (TSS) concentrations as high as 0.4 g/l (Nelson, 1923). However, concentrations as low as 0.1 g/l may significantly reduce the pumping rate in adults. Survival of American oyster embryos is reduced by 0.25 g/l TSS, and 100 percent mortality occurs at concentrations $\geq$ 1 g/l (Davis and Hidu, 1969). Larvae are more tolerant of suspended sediment than eggs, but growth is reduced at concentrations as low as 0.75 g/l TSS and completely stopped at 2 g/l (Davis and Hidu, 1969; Carriker, 1986).

4.2.4 Oyster Substrate Relationships

Substrate Requirements

An individual American oyster can live on any substrate capable of bearing the animal's weight, assuming tolerable water-quality conditions, adequate food supply, and adequate circulation prevail. Establishment of a colonial aggregation (i.e., a bed or reef where the oysters themselves become the predominant component of the surficial substrate layer) depends on the areal extent of contiguous underlying suitable substrate. For sustained natural production, the key consideration is appropriate substrate for setting of spat.

American oysters have been reported on shells, sands, firm muds, soft muds, mangrove roots, pilings, seawalls, and other hard surfaces (Butler, 1954b; Dawson, 1955; Wells, 1961; Breuer, 1962; Copeland and Hoese, 1966). Substrate "firmness" is recognized as one of the core variables (V_6) in the Habitat Suitability Index (HSI) model for the American oyster (Cake, 1983; Soniat and Brody, 1988). In Galveston Bay, reefs are limited to areas where firmness is $\geq$ 0.44 kg cm^{-2}; the mean firmness at reef sites is 1.83 kg cm^{-2} (Soniat and Brody, 1988). Sedimentation and turbidity factors also affect the ability of oysters to colonize different substrates, with the greatest ability to clear sediment from shell margins in coarse sand and the poorest ability in fine sand (Dunnington *et al*., 1970).

There has been considerable study of alternatives to natural oyster shell as "cultch" (setting substrate) (Butler, 1955; MacKenzie, 1989; Eckmayer, 1983; Chatry *et al.*, 1986; Haven *et al.*, 1987; Thayer *et al.*, 1997). Crushed oyster shell and gravel additives, or a mix of these, have been the most common substrates used for both clam and oyster beds (Thompson and Cooke, 1991). Oyster shell (uncrushed) is superior as cultch, due to the rugosity of the exterior surface of the right valve (Baker and Mann, 1994; Baker, 1997). By developing an irregular surface with gravel or shell on otherwise flat mud flats, settlement of larvae may be increased, and larvae and young spat may have additional protection from predators (Kraeuter and Castagna, 1977). Myatt and Myatt (1991) have suggested that plantings or maintenance of cultch in groups of relatively small "clusters" is preferable to large, contiguous beds from the point of view of enhancing biotic variety.

Even with natural shell, the "cleanliness" (lack of fouling organisms, silt, oils, etc.) of the cultch is a key factor (MacKenzie, 1989; Adams *et al.*, 1994). Thus shell-planting should not be done too far in advance of anticipated larval settlement (Chatry *et al.*, 1986; Abbe, 1992). However, recently exposed substrates may need sufficient time for bacterial recruitment before optimal setting conditions exist (Bonar *et al*., 1990).

Oyster Bed Development and Characteristics

Although oyster “reefs” appear to provide the most suitable substrates, oyster beds very often do not develop into these “classic” reefs. Mackin and Hopkins (1962) have indicated that subtidal beds in low salinity waters are often very small in size. The large beds in Mississippi Sound and the Louisiana Marsh areas have been described as having only thinly scattered oysters with no solid shell substrate (Mackin and Hopkins, 1962). Butler (1954b) indicates that oyster singles and small clumps are more common on the softer mud substrates because additional weight will cause them to sink into the substrate. Additional oysters may keep settling on small clumps, causing the underlying shells to sink deeper, forming columns or poles of cemented shells extending to 3 ft below substrate surface. Even single shells may sink after they grow to sufficient size and weight. On sticky firm mud bottoms in estuaries, thick reefs may develop, but in other cases, thick reefs may never develop, with the bulk of the underlying dead oysters never exceeding the bulk of the veneer of live oysters on top, even though the bed may remain productive for hundreds of years. This may be due to chemical or physical shell deterioration or to the actions of other organisms (Butler, 1954b).

4.2.5 Oyster Salinity Relationships

Salinity Ranges and Lower Salinity Threshold

As noted by Kennedy (1991), the American oyster is adapted to a very broad salinity regime. Juveniles and adults can apparently survive essentially “fresh” (0 ppt salinity) conditions for at least a few days, and physiologically “recover” (i.e., re-growth and reproduction) provided that salinities $\geq$ about 7.5 ppt are restored and sustained during a given annual cycle. Hoese (1960) and Loosanoff (1953) reported spat survival but no growth at 5 ppt. Table 4-4 summarizes salinity tolerances of American oysters.

Mackin and Hopkins (1962) indicate that a prolonged period at <5 ppt will result in adult mortality, depending on condition, age, temperature, and other factors. Breuer (1962) found some tolerance to salinity as low as 1.4 ppt for several weeks in seed oysters. In several cases where salinity had dropped from normal levels of 15 to 36 ppt to less than 6 ppt, adult oyster mortality ranged from 8% to 36% (Gunter, 1953). In controlled studies, Wells (1961) found that 7 ppt was the point at which most oysters died.

Gunter (1956) thought that adult oysters can survive salinities as low as 2 ppt for about 1 month at low temperatures and 0 ppt for several days by closing their shells and living anaerobically. The survival rate would be dependent on previous condition and food reserves. Normal growth and gametogenesis may be effectively precluded in oysters acclimated to salinities below about 10 ppt (Davis, 1958, Kennedy, 1991). This is why the lower threshold for the V_4 variable, “historic mean salinity,” in the Habitat Suitability Index (HSI) has been set at 10 ppt (Cake, 1983; Soniat and Brody, 1988).

Low salinity is a more critical factor in the early life cycle stages. Optimal salinities for development of eggs into larvae are between 23 and 29 ppt, with a range from between 5 and 15 to over 32 ppt (Clark, 1935). At less than 12 ppt, larvae and spat may develop and grow “too slowly", so prolongation of the critical early life-history phases results in sufficient mortality (mainly predation) to preclude effective recruitment (Kennedy, 1991; Dekshenieks *et al.*, 1993, 1996). Salinity conditions and acclimation of parents at gametogenesis and spawning also may affect the subsequent development of larvae (Davis, 1958; Kennedy, 1991). Spat setting has been reported at 9 to 29 ppt, with average salinity at about 23 ppt and an optimal setting range of 16 to 18 ppt (Loosanoff, 1965; Kennedy, 1991) Daily salinity changes up to 1.6 ppt appear to be tolerated.

Maintenance of salinities ≥ 12 ppt is only critical during the spawning season, which varies according to latitude (and may encompass much of the year in the SLE). However, Finucane and Campbell (1968) reported over 50% of total spat set in Tampa Bay occurred between May 13 and June 17, with a second peak from July 15 to August 20. Presumably high temperatures or high rainfall depressed spawning in mid-summer. Twelve to 15 ppt is generally regarded as the lower limit for acceptable normal development from eggs to spat. However, based on the foregoing discussion and considering that early growth may be substantially faster in the SLE than for the well-studied oyster populations, 10 ppt (perhaps even less) might be an appropriate lower threshold for most of the year based on spawning and setting requirements.

Upper Salinity Threshold

In terms of purely intrinsic physiological considerations there is no upper salinity "threshold" for any life-history phases, except under hypersaline conditions (Copeland and Hoese, 1966). However, it is widely recognized that there is a practical upper threshold for long-term maintenance of meaningful stocks due to the controls imposed by diseases (mainly "Dermo" and "MSX"), predation (by oyster drills, flatworms, ctenophores, anemones, crabs, and fishes), algal blooms, and competition (Gunter, 1955; Mackin, 1956; Goggin *et al.*, 1990). Dermo, implicated as a cause of 50% of adult oyster mortality in Florida, is limited to salinities >9 ppt (Quick and Mackin, 1971; Mackin, 1962).

Cake (1983), Ray (1987), and Ray and Benefield (1997) set the upper salinity threshold for sustainable oyster production at 20 ppt. Chatry *et al.,* (1983) recommended 17.4 ppt, but cautioned that 15 ppt should not be exceeded during the main spawning and setting season. Again, conditions in the SLE may warrant some relaxation of the upper benchmark, since the primary "defense mechanism" of American oyster against most predators and at least perkinsiasis ("Dermo") infections is to outgrow the opponent (Dekshenieks *et al.*, 1993; Hofmann *et al.*, 1995). Therefore, if both young and older oysters grow substantially faster in the SLE (as would be expected due to the annual warm temperatures), rigorous adherence to an upper salinity limit of 15 ppt may not be critical.

Evaluation of Salinity Effects

Keeping salinities in the SLE below 15 ppt is not an issue. Rather, the chief salinity-related limitation on oyster population restoration will be establishing a regime in which a critical lower threshold is maintained long enough to support successful recruitment (a combination of spawning and setting over a sufficient duration, in most years, for survival of an adequate number of juveniles to compensate for attrition among adults).

Based on information in Kennedy (1991), once juveniles achieve a shell length of about a centimeter, at least some should survive and grow (albeit slowly) to maturity if salinities for the remainder of the year stay above 5 ppt *most of the time*. For individuals that achieve maturity, at least some gametogenesis and spawning would be expected if salinities can be sustained above 5 ppt. However, setting is unlikely to be meaningful at salinities much below 10 ppt. There probably would be some setting at salinities as low as 7.5 ppt, but whether it would translate into successful recruitment is very doubtful.

In summary, a practical lower limit of about 7.5-10 ppt may be suitable for planning in the context of SFWMD objectives in the SLE for most parts of the year. It appears, however, that there will need to be a period of at least a month to six weeks, in most if not all years, during which salinities well above 7.5 ppt (ideally > 10 ppt) are virtually constant. This period should coincide with one of the spawning "peaks." At times other than this crucial period, occasional declines in salinity below 7.5 ppt (or even 5 ppt) may be tolerated, especially if relatively-extended low-salinity periods (e.g., on the order of weeks) are confined to the cooler months. Realistically, it appears unlikely that restoration or enhancement of sustainable American oyster beds in the SLE can be achieved if salinities remain below 10 ppt most of the year. It is conceivable that recruitment could be augmented by transplanting from "seed beds" or artificial "nurseries" outside the SLE.

TABLE 4-1
LIFE FORM CHARACTERISTICS FOR SELECTED AQUATIC VEGETATION
(Data Based on Reviewed Literature)

				REPRODUCTIVE SYSTEMS			
SPECIES	FAMILY	SALINITY PREFERENCE TYPE	NATIVE OR EXOTIC	LIFE CYCLE+	SEXUAL VIGOR **	ASEXUAL METHODS PRESENT***	COMMON DEPTHS OF OCCURRENCE (cm)
Turtle Grass	Hydrocharitaceae	Seagrass	N	P	P	Rh	30 - 200
Shoal Grass	Cymodoceaceae	Seagrass	N	P	M	Rh	0 - 150
Manatee Grass	Cymodoceaceae	Seagrass	N	P	M-V	Rh	40 - 150
Paddle Grass	Hydrocharitaceae	Seagrass	N	A	M	N	30 - 250
Star Grass	Hydrocharitaceae	Seagrass	N	P	P-M	Rh	30 - 250
Johnson’s Seagrass	Hydrocharitaceae	Seagrass	N	P, A	N-P	Rh	10 - 200
Widgeon grass	Ruppiaceae	Intermediate	N	P, A	V	Rh	20 - 50
Redhead Grass	Potamogetonaceae	Fresh Water	N	A	M-V	T	50 - 100
Wild Celery	Hydrocharitaceae	Fresh Water	N	P	V	Rh, T	30 - 200
Eurasian Water Milfoil	Haloragaceae	Fresh Water	E	P, A	V	Rh, Tu, F	10 - 400
Sago Pondweed	Potamogetonaceae	Fresh Water	N	A	P-M	T, Tu	50 - 100
Horned Pondweed	Zannichelliaceae	Fresh Water	N	A	V	N	50 - 300
Common Water Nymph	Najadaceae	Intermediate	N	A	M-V	N	50 - 300
Spiny Naiad	Najadaceae	Intermediate	N	A	M?	N?	50 - 300
Hydrilla	Hydrocharitaceae	Fresh Water	E	P, A	V	T, Tu, F	10 - 400
Hornwort	Ceratophyllaceae	Fresh Water	N	A	P	F	50 - 400
Waterweed	Hydrocharitaceae	Fresh Water	E	A	P	F	100 - 500

* = Species presented in approximate order of salinity tolerance
\+ = Life Cycle (A = annual; P = perennial; A, P = annual or perennial)
** = Viability of Sexual Reproduction (N = none; P = poor; M = moderate; V = vigorous)
*** = Types of Asexual Reproduction Present (Rh = rhizome; T = tuber; Tu = turion; F = fragmentation; N = none)

TABLE 4-2
GENERAL HABITAT CHARACTERISTICS OF SELECTED AQUATIC VEGETATION
(Data Based on Reviewed Literature)

SPECIES	PREFERRED TEMPERATURE RANGE (°C)	LIGHT COMPENSATION POINT % of SI**	CURRENT REGIME***	SUBSTRATE PREFERENCE
Turtle Grass	18 - 39	10 - 25	M - H	Deep sands to muddy sands: may require carbonate sources
Shoal Grass	9 - 30	10 - 20	M	Silty sand most common: some on sands and silts
Manatee Grass	12 - 30	10 - 20	M - H	Soft muddy sands to silty sands most common: some on sand
Paddle Grass	20 - 36	2 - 5	L - M	Sand, silty sand or mud; probably needs firmer bottom
Star Grass	9 - 31	2 - 20	L - M	Soft to firm muddy sands
Johnson's Seagrass	21 - 36	2 - 5	L - M	Sand, silty sand or mud; probably needs firmer bottom
Widgeon grass	12 - 39	5 - 20	L - M	Wide range from sand to mud; silt and silty sand most common
Redhead Grass	15 - 30	0.5 - 5	N - L	Best on muds and clays, very soft to firm: tolerates organics
Wild Celery	15 - 36	0.5 - 3	M	Silts or silty to muddy sands; can tolerate soft muds
Eurasian Water Milfoil	1 - 30	1 - 2	L - M	Soft muck to firm silty sand; poor in sand and high deposition environments
Sago Pondweed	5 - 37	0.5 - 5	L - M	Silts or silty to muddy sands; moderate to firm types best
Horned Pondweed	14 - 30	3 - 7	L	Silty sands to muddy sands; less than 30% clays
Common Water Nymph	?	< 3	?	Grows evenly in muds to sands, but needs firm substrate
Spiny Naiad	?	< 3	?	Silts or mud , maybe with peat or other organics

TABLE 4-2, Continued
GENERAL HABITAT CHARACTERISTICS OF SELECTED AQUATIC VEGETATION*
(Data Based on Reviewed Literature)

SPECIES	PREFERRED TEMPERATURE RANGE (°C)	LIGHT COMPENSATION POINT % of SI**	CURRENT REGIME***	SUBSTRATE PREFERENCE
Hydrilla	15 - 36	0.5 - 6	L	Sands or silty sands best; poor in high organic substrates
Hornwort	20 - 30?	1 - 3	L	No apparent preference; can grow suspended w/o soils
Waterweed	15 - 28?	0.3 - 1	L	Wide range from silts to sands

* = Species presented in approximate order of salinity tolerance
** = Surface Irradiance (SI) is the intensity of full sunlight hitting the water surface
*** = Current Regime [N = none; L = low (< 0.2 km/hr); M = moderate (0.2 to 0.6 km/hr); H = high (0.6 to 2.0 km/hr)]

TABLE 4-3
APPROXIMATE SALINITY TOLERANCE RANGES FOR SELECTED AQUATIC VEGETATION
(Data Based on Reviewed Literature)

SPECIES	TOLERANCE RANGES (ppt)			SHORT-TERM LIMITS***		COMMENTS
	OPTIMUM RANGE (ppt)*	COMMON NATURAL RANGE**	NORMAL TOLERANCE RANGE	MAXIMUM	MINIMUM	
Turtle Grass	25-35	22-38	16-50	62	4	Needs stable conditions
Shoal Grass	24-36	22-38	5-55	70	0	Tolerates high variability and wide range
Manatee Grass	23-30	22-36	17-44	52	10	Upper tolerance and range slightly lower than turtle grass
Paddle Grass	27-34	25-35+	22-38	?	5	Scarce data
Star Grass	25-35	22-36	10-40	?	5	Scarce data
Johnson's Seagrass	25-35	24-38	15-43	?	5	Scarce data
Widgeon grass	5-15	1-25	0-45	52	0	Tolerates high variability; Different populations have different ranges and show strong acclimation
Redhead Grass	0-3	0-20	0-25	36	0	Good acclimation ability
Wild Celery	1-4	0-10	0-13	16	0	Good acclimation ability
Eurasian Water Milfoil	1-5	0-8	0-14?	20?	0	Generally low tolarance
Sago Pondweed	2-3	0-6	0-12	16	0	Some acclimation ability
Horned Pondweed	1-4	0-5	0-10	20	0	Little data; short life cycle allows presence during low salinity periods
Common Water Nymph	1-5?	0-9	0-10	?	?	Scarce
Spiny Naiad	0-5?	0-10?	0-10?	?	?	Almost no data
Hydrilla	0-4	0-7	0-12	13	0	Low tolerance under natural conditions?
Hornwort	0-1	0-1	0-6	8	0	Scarce data
Waterweed	0-?	0-2?	0-10?	10?	0	Almost no data

Species presented in approximate order of salinity tolerance
*Optimal growth conditions
**Long-term survival in field conditions
***For periods up to about 7 days

TABLE 4-4
APPROXIMATE SALINITY TOLERANCE RANGES FOR THE AMERICAN OYSTER
(Tolerances Expressed in Relation to Expected Temperatures in the SLE System)
(Data Based on Reviewed Literature)

LIFE CYCLE STAGE	TOLERANCE RANGES (ppt)			SHORT-TERM LIMITS***		COMMENTS
	OPTIMUM RANGE*	COMMON NATURAL RANGE*	TOLERANCE RANGE FOR 1 TO 5 DAYS**	MAXIMUM	MINIMUM	
Adults	10 - 20	10 - 32	0 - 32+	36+	0	Generally withstand all conditions unless change is too rapid or combined with other stress such as high temperature; upper limit usually due to predation/disease.
Juveniles	10 - 20	10 - 32	0 - 32+	36+	0	Probably slightly less tolerant than adults; more susceptible to starvation due to feeding cessation near 10 - 12 ppt.
Spat	20 - 23	15 - 29	10/12 - 32+	32+	5	Feeding and growth restricted under 12 ppt, leading to increased losses due to predation, etc. Higher salinities better for larvae and spat, but are offset by higher predation, leaving effective maximum of about 20 ppt.
Larvae	23 - 27	15 - 29	12 - 32+	32+	10	Feeding and growth restricted under 12 ppt, leading to increased losses due to predation, etc. Higher salinities better for larvae and spat, but are offset by higher predation, leaving effective maximum of about 20 ppt.
Eggs/embryos	23 - 27	15 - 29	12 - 32+	32+	5 - 10	12 ppt again seems to be appropriate lower limit, but rapidity of change and other factors such as temperature and prior conditioning of parent oysters can affect resistance.
Sustainable population	15 - 20	12 - 20	10 - 29	32	12	Generally can survive seasons with 7.5 ppt, with some periods as low as 5 ppt, but maintenance of a minimum of 12 ppt is necessary during crucial spawn and set periods for several weeks (probably spring and fall). Upper limit of 20 to 25 except for short intervals is necessary to restrict predators and disease.

* = Long term normal conditions
** = Levels normally tolerated for period shown
*** = For periods of about 0 to 12 hours

5.1 SUBSTRATE SURVEY

Substrate was sampled at 519 points in the SLE study area and the substrate at each point was categorized as one of the nine substrate types defined in Section 2.3.6. In general, grain size decreases with increasing distance from the shoreline. Medium to coarse sands are found adjacent to the shoreline in exposed reaches with larger fetch (open water distance across which winds and waves can increase) and in areas with high velocity water movement such as the constriction at Speedy Point and the Lower Estuary. Finer sands and firm muds with organic detritus are often found near shore in the sheltered reaches and coves such as Kitching Cove. With increasing distance from shore and increasing depth, sand grain size tends to decrease and muck content increases. Much of the substrate in depths from 3 to 7 feet is composed of mucky or muddy fine sands, sometimes with a substantial amount of shell hash mixed in. At depths greater than 7 feet, the substrate is most often primarily muck. In the deepest areas (approximately 11+ feet) and in much of the central portion of the North Fork, substrates consist of a less coherent mucky material which can be described as ooze. The mucks and ooze are composed of a mix of fine colloidal materials, including clay, silt, and small organic particles.

A number of methods were used to generate a substrate map of the SLE from this point data (see Section 6.1). Figure 5-1 was generated using the triangulated irregular network (TIN) method, and appears to best describe the substrate conditions of the SLE, consistent with our observations from the field. This figure illustrates the concentration of ooze-type sediments in the deeper portions of the North Fork, except in the downstream end where higher velocity currents may restrict the development of ooze conditions. Figure 5-1 also appears to fairly accurately illustrate pockets of ooze-type sediments in the middle of the Middle Estuary, with more consolidated muck substrate throughout most of the Middle Estuary, except for areas less than 7 feet deep.

In contrast, the only well defined area of muck or ooze substrate in the Lower Estuary appears to be in Hooker Cove on the north side of Hell Gate Point. It is likely that the point causes a current reduction or eddy effect in this area, allowing deposition of the finer particles in deeper parts of the cove. Throughout the rest of the Lower Estuary, sands and firm muds appear to dominate the substrate conditions.

In the South Fork, muck and mucky sands appear to dominate the deeper areas between the Palm City Bridge and the confluence with the North Fork. Ooze deposits are not nearly as extensive as in the North Fork, but may be present in pockets in the deepest areas. Much of the South Fork appears to consist of sand bottom, ranging from coarse sands to mucky fine sands. Most of the bottom in the vicinity of the Palm City Bridge and downstream to about Matchett Point contains relatively coarse sands with low contents of fine particles or organic matter. This sandy area appears to coincide with the deposition of bank erosion materials from the St. Lucie Canal as described by the US Army Engineer District, Jacksonville (1959). Relatively coarse sands are also found around Arbeau Point and at the downstream side of Speedy Point in the Middle Estuary. At the upper (south) end of the South Fork, substrate grades from sands to mucky or muddy fine sands to a mud and mangrove detritus type, going from the Palm City Bridge to Palm City Bay.

Both Kitching Cove in the North Fork and Palm City Bay in the South Fork occur at the upper end of the estuary with minimal inflows from tributaries, and both contain generally firm mud to detritus substrates in many areas. In most other areas of the SLE, the firm mud and detritus types (Categories 6 and 7) shown in Figure 5-1 may be to some extent artifacts of the ArcInfo interpolation process. Mucks and mucky or muddy fine sands may better describe these areas. Other small coves such as Bessey Cove also may have more mud and detritus than shown in Figure 5-1.

5.2 SAV SURVEY

5.2.1 General Presence and Distribution

Figure 5-2 shows the distribution of SAV resources located during the 1997 field surveys. The only significant SAV beds occurred in the Lower Estuary. These beds were most extensive downstream of the study area, south of Hell Gate Point. The beds extended upstream to a point north of the Sewells Point Bridge along the east shore, but ended well downstream of the bridge on the west shore. The Lower Estuary beds generally were less than 10 feet in width, often less than 5 feet, and reached a maximum width of about 50 feet in only minimal areas. Shoal grass was the dominant species throughout most of this area, with Johnson’s seagrass as the secondary species. Star grass and widgeon grass were found only at a couple of points.

The only other documented occurrences of SAV consisted of a few plants in the South Fork just upstream of the Palm City Bridge and at the mouth of Danforth Creek. Widgeon grass was found in both locations, while wild celery and common water nymph were found only at the creek mouth. There had been unconfirmed reports of some kind of vegetation seen earlier in the spring near the mouth of Bessey Creek in the North Fork and off the hospital on the south side of the Middle Estuary, but no evidence was found in the field surveys.

5.2.2 Shoal Grass

As described in Section 5.2.1, shoal grass was found only in the Lower Estuary. Its most upstream occurrence was 750 feet upstream of the Sewells Point Bridge along the east shore of the Lower Estuary. Downstream occurrence continued below Hell Gate Point beyond the project area. In the beds within 350 feet upstream of the bridge, shoal grass had an average cover of about 10 %, and the canopy height (length of shoots and leaves) was consistently between 15 and 20 cm. Upstream of this point, canopy cover was less than 10 % at all points.

For about 2,900 feet downstream of the Sewells Point Bridge along the east shore, shoal grass coverage was about 10%. The densest beds occurred from about 3,500 to 6,000 feet downstream of the bridge where cover was between 20 and 40 % throughout. Shoal grass cover then decreased to between 10% and 20% cover to a point about 1,500 feet upstream of Hell Gate Point. From this point downstream, shoal grass cover was always less than 10%. South of Hell Gate Point, cover was usually less than 1% and consisted of individual shoots of approximately 15 cm height in moderate condition.

Shoal grass beds on the east side of the Lower Estuary occurred in a narrow band no more than 10 feet wide in water about 2 to 4 feet deep about 30 to 100 feet from shore. Substrate was generally coarse to medium sands with relatively low amounts of mud or muck. Some scattered shell hash and pebbles were present

In contrast to beds on the east shore, shoal grass was found no farther upstream than about 6,200 feet downstream of the Sewells Point Bridge (2,600 feet upstream of Hell Gate Point on the west side). It was present at only two of eight sampling points in this area with cover of approximately 1%. Bed width is between 5 and 10 feet wide in 1.5 to 4 feet of water and substrates of medium sand with some mud or muck. Shoal grass condition in this area was rated as moderately stressed with discoloration and a canopy height of 15 cm.

Downstream of Hell Gate Point on the west side, shoal grass condition was rated as normal to good, with cover ranging between 10% and 50% in irregularly spaced beds in 3 to 5 feet of water.

5.2.3 Johnson's Seagrass

Johnson's seagrass was found in small clusters as far as 350 feet upstream of the Sewells Point Bridge on the east side of the estuary. Condition upstream of the bridge was considered moderate with cover of less than 10%. Johnson's seagrass occurred about as far downstream as shoal grass, but cover was usually under 10%.

On the west side of the Lower Estuary, Johnson's seagrass was present at only one of eight sampling points. At all points where both shoal grass and Johnson's seagrass were present, shoal grass was the dominant species. Johnson's seagrass generally occupied the same depths and substrates as shoal grass, although it occurred in shallower depths in some sandy areas.

5.2.4 Star Grass

Star grass was found only along the east shore of the SLE from Hell Gate Point to about 1,500 feet upstream. Cover was always much less than 1%, being present as scattered individual shoots. It was present only where both shoal grass and Johnson's seagrass were present and was always the third species in abundance. As such, it is present in the data base only under the comments field. The only location where it was found at the recorded data points of the 1997 SAV theme in the GIS data base was at Point Sv1997ptid # 88 (numbering is from the SLE GIS data base).

5.2.5 Widgeon Grass

Widgeon grass was found at only three locations. The first was at Point Sv1997ptid number 86 along the sand bar near the center of the channel south of Hell Gate Point (actually downstream of the study area) on coarse sand in less than 1 foot of water. It was present as single shoots with a cover of less than 1%, and showed low vitality and stressed condition. Shoot length was about 15 cm. Surrounding sampling points had small patches of shoal grass and Johnson's seagrass, generally in deeper water (3 to 5 feet).

The second location was on a medium to coarse sand bar at the downstream end of the island south of the Palm City Bridge (Point Sv1997ptid #1). Scattered individual plants were present in an area approximately 40 feet in diameter. Total cover was much less than 1%. Shoot length of the largest shoots was about 25 cm, with most being half that size. No obvious signs of damage were noted, but plant vitality was rated as low.

At the third location (Sv1997ptid #3), widgeon grass was present as the third most abundant of three species (after wild celery and common water nymph) and is identified only in the comments field of the GIS data theme. Only a few individual shoots with negligible cover were found in an area about 120 feet in diameter and 1 foot deep along the coarse to medium sand bar in front of Danforth Creek. This location is along the west shore of the South Fork just downstream (north) of the Palm City Bridge. Plants had low vitality and ranged from 5 to 15 cm in length. Buds appeared to be present in a few plants and periphyton cover was moderate.

5.2.6 Wild Celery

Wild celery was found only at Sv1997ptid # 3 at the mouth of Danforth Creek. The population consisted of scattered individual shoots in the SLE at the mouth of the Creek and some larger scattered clumps within the lower end of the creek. Total cover was less than 1%, and the plants were restricted to a smaller area than widgeon grass at the same location, generally within 40 feet of the creek mouth, along the edges of the sand bar in 1 to 2 feet of water. Depth of occurrence in the creek ranged to about 3 feet. Shoot length in the estuary averaged about 15 cm, but larger plants (to 30 cm) occurred in the creek. Plants in the estuary appeared to be moderately stressed with pale color and low vitality. Periphyton cover was moderate.

5.2.7 Common Water Nymph

Common water nymph also was found only at Sv1997ptid # 3 at the mouth of Danforth Creek in the same location and extent as wild celery, but apparently not extending into the creek. Only a few (<5) plants were found, all between 5 and 15 cm in length. Vitality was moderate to low, with moderately heavy periphyton cover. Substrate was medium to coarse sand, and plants were in 1 to 1.5 feet of water.

5.3 OYSTER SURVEY

5.3.1 Oyster Distribution in the SLE

Evidence of oyster occurrence was found throughout the study area from the north side of Hell Gate Point in the Lower Estuary to the upper end of Palm City Bay in the South Fork and the upper end of Kitching Cove in the North Fork. However, the distribution of significant beds or shell concentrations and of live oysters was substantially less.

In the North Fork, one occurrence of scattered live and dead oysters was found at the upper end of Kitching Cove (sample point Oy1997ptid # 98). However, the density of both live and dead oysters was less than 5% of bottom area within a 50 foot radius, and the size of all shells was less than 5 cm, indicating that few oysters appear to have reached maturity in this area. The condition of the live oysters was rated as poor due to shell discoloration. The next occurrence of live oysters in the North Fork did not occur until the Bessey Creek Point area along the East Shore and North River Shores along the west shore, about 3.5 miles downstream. From these points to the confluence with the South Fork, there are scattered oyster beds with live and dead oysters (Figure 5-3).

Live oysters were found in scattered locations in the South Fork from approximately the mouth of Palm City Bay to the confluence area. Several beds are present in the South Fork, but they are relatively small in size and generally occur as very narrow bands along the shoreline in 2 to 5 feet of water. Most live oysters in the South Fork were found in one of the beds discussed in the next section.

In both density of beds and areal extent of beds, the Middle Estuary contains the majority of the oyster resources in the SLE. The larger beds are concentrated in the upstream portion from Speedy Point to Rio along the north shore and as far downstream as Krueger Creek along the south shore. Downstream of Krueger Creek, beds become much smaller in size, with only about 5% of the Middle Estuary bed acreage downstream of this point.

Live oysters were located at only 6 scattered locations in the Lower Estuary. All were close to the east shore except for one location (Oy1997ptid # 647) on the north side of Hell Gate Point. This location had a small bed of <20 feet diameter, with an overall shell density of over 50% (live and dead) and a live oyster density between 6 and 20%. Dead oysters were of all sizes, while live oysters were mostly < 10 cm, but in good condition. In all of the locations on the east shore, live oysters were generally < 5 cm in size and condition was rated as poor or moderate in 4 of 6 sites. Algal growth and shell discoloration were more abundant in this area.

Other oyster resources along the north side of the Middle Estuary and east side of the Lower Estuary were found during the pier and shoreline surveys. These consisted of oyster populations on several piers and seawalls. The area of occurrence was from approximately Rio to about 1,200 feet upstream of the Sewells Point Bridge. Virtually all of the oysters on the piers and seawalls are intertidal, as opposed to the subtidal beds. These intertidal oysters represent the majority of the oyster resources in the Lower Estuary and lower end of the Middle Estuary.

5.3.2 Oyster Beds

Tables 5-1 and 5-2 list the characteristics of all of the oyster concentrations which were judged to be of sufficient size or density to be defined as a bed. The location of oyster beds in the SLE is shown in Figure 5-4, which also shows the substrate distribution.

A total of 207 acres of oyster beds have been identified in the SLE. The distribution among reaches is shown below:

SLE Reach	Number of Beds (%)	Total Area Acres (%)	Mean Bed Size Acres
Lower Estuary	0 (0.0)	0.00 (0)	0
Middle Estuary	11 (41)	149.7 (72)	13.6
North Fork	7 (26)	34.4 (17)	4.9
South Fork	9 (33)	23.4 (11)	2.6
Total	**27 (100.0)**	**207.5 (100)**	**7.7**

These numbers illustrate that the Middle Estuary contains almost half of the oyster beds of the SLE and almost three quarters of the total acreage. The South Fork and North Fork are similar to each other, although resources are concentrated in a few larger beds in the North Fork. Figure 5-4 shows that the beds in the North Fork are concentrated in a relatively narrow area between North River Shores and Dyer Point, while the smaller beds in the South Fork are more evenly distributed along its entire length. The acreage in the Middle Estuary is centered in the western half, upstream of Rio.

The density of live oysters in the beds of the SLE appears to be low, with an average of 1 to 5% cover (equates to about 1 to 20 oysters per square meter) in 24 of the 27 beds. The actual density is closer to one oyster per square meter in most cases. Beds 17 and 22 in the middle reaches of the South Fork had densities of 6 to 20%, and bed 13 near Warner Creek in the Middle Estuary had a density of 21 to 40%. These three beds were of below average size, so their total population contribution is probably similar to that of one of the largest beds.

On the basis of this limited data, no other obvious patterns of oyster bed characteristics in relation to location in the SLE or distance from the mouth of the estuary are apparent. However, notes were recorded on the presence of other bivalve and mollusk species found in the substrate and oyster surveys and some occurrence patterns may exist for them.

The primary species found were brackish water clam (*Rangia cuneata*), coot clam (*Mulinia lateralis)*, ribbed mussel (*Modiolus demissus*), and barnacles (*Balanus* spp.). Mussels and barnacles were noted at only 2 of the 11 beds in the Middle Estuary, and a few brackish water clams and dead coot clams were noted at one of these. Both of these beds were near the west end of the Middle Estuary.

Large numbers of mussels were noted at 3 of 7 beds in the North Fork and 2 of nine beds in the South Fork, both near Pendarvis Cove. Barnacles were also abundant in 2 beds in the North Fork and 1 in the South Fork. All of these occurrences were within 1.5 miles of the convergence near the middle of the estuary system. The brackish water clam was found in 5 of the 9 beds in the South Fork and 1 bed in the Middle Estuary. Moderate to high abundance of these clams was found only in the portion of the South Fork upstream of the Palm City Bridge. Only a few brackish water clams, usually dead, were found in the lower South Fork and upper Middle Estuary. The brackish water clam appeared to occur in highest densities in areas upstream of the main oyster occurrences in the North and South Forks, and appear to indicate areas and salinity conditions in which oysters may not be able to survive.

The coot clam was found in several locations in the South Fork, generally downstream of the Palm City Bridge, and in the North Fork, generally downstream of North River Shores, as well as the upper end of the Middle Estuary. The great majority of coot clams were dead, and much of the shell hash found appeared to consist of broken coot clam shells. Coot clams were most often found in the muck and mucky/muddy fine sands in the deeper portions of the estuary, conditions in which oysters did not occur. There were only two instances in which coot clams were noted within the oyster beds. In this case. coot clam concentrations appeared to be centered in areas with lower estimated salinity regimes than indicated as preferable in the literature. Very few clams were noted in the Middle and Lower Estuary sections where salinities appear to be most suitable. Although shells were found in abundance in parts of the North and South Forks, a very low percentage of live clams was noted in these areas.

None of the above mollusk species were noted in the lower part of the Middle Estuary or in the Lower Estuary. One dead southern oyster drill (*Thais haemastoma*) was found in the Middle Estuary and a few instances of oyster drill damage were found in dead shells in the lower Middle Estuary.

5.3.3 Oyster Substrate and Depth Relations

The vast majority of the locations where oysters were found contained coarse to medium sands or mucky/muddy fine sands. All beds were centered on one of these types (Table 5-1). The centers of oyster beds appeared to be in the mucky/muddy fine sands or along the interface of this type and the well sorted fine sands. The outer edges of the oyster beds tended to reach into areas where muck substrate was present. However, in these portions, oyster density was usually low (<10% bottom cover) and shell hash was often present.

As seen in Table 5-1, most of the oyster beds extend over depths from 2 to 6 feet. The mean depth for the shallow edge of the bed is 2.5 feet and for the deep edge is 5.9 feet. In general, beds in the South Fork were at the most shallow depths, but this may be a reflection of limited depth in much of this area.

5.4 SHORELINE SURVEY

5.4.1 Shoreline Characteristics

Tables 5-3 and 5-4 show the type and extent of shoreline features in the different reaches of the SLE. Eighty-four percent of the shoreline is composed of four types. The remaining 11 types represent only 16% of the shoreline features.

Vertical seawalls are the most extensive type of shoreline feature, covering 27% of the total shore. The survey did not differentiate between types of seawalls, but concrete and wood seawalls appeared to be approximately equal in extent and comprised most of this type. Some metal seawalls are also present. In almost all cases, the seawalls appeared to be in good to excellent condition, with little collapse noted. The actual extent of seawalls is actually greater than the above number. In many cases, rip rap is present on the waterward side of the seawall, and often a sandy slope or fringe of mangroves has developed between the wall and the water. In these cases, the outermost feature was included as the main shoreline feature. Seawalls represent one of the two largest shoreline types in the Middfle Estuary (48%), North Fork (21%), and South Fork (28%), and are the third largest feature in the Lower Estuary (13%). Oysters are present along the intertidal portions of some seawalls on the north and east sides of the Middle and Lower Estuary between Rio and the Sewells Point bridge, but are essentially absent along other areas of the SLE.

Unvegetated sandy slopes and beaches is the second largest shore type, covering 22%. In most cases, these areas consist of narrow (<10 feet) sandy slopes below grassed lawns and in front of seawalls. These areas appeared to be relatively stable throughout the estuary, but in front of lawns, they generally have developed as a result of some wave or boat wake erosion of the lawn.

True beaches or wide sand areas are generally rare. The main such area is in front of the Club Med resort on the North Fork. Sandy slopes are common in all reaches except the South Fork. Sandy slopes are the largest shoreline feature in the Lower Estuary, representing 51% of the shoreline. They are the third largest type in the Middle Estuary (19%) and North Fork (21%).

Mangrove fringe covers 21% of the shoreline. This coverage is almost entirely along the North and South Forks, where coverage is 26% and 36% respectively. Most of these areas in the South Fork front large stands of mangrove forest. In the North Fork, about one third of the coverage abuts mangrove forests (mainly in the north end), and the rest abuts flatwoods and single and multi-family residential areas. There is virtually no mangrove fringe in the Middle Estuary, and that in the Lower Estuary fronts other land uses such as residential and exotic species stands.

Rip rap represents the fourth major shoreline type in the SLE, comprising 14% of the total shoreline. The main use of rip rap is in the Lower Estuary (19%) and the Middle Estuary (26%), with only 10% of the North and South Forks armored by rip rap. In many cases in the Lower and Middle Estuary reaches, rip rap is present on the waterward side of seawalls as extra protection for the walls. In these cases, the rip rap also reduces the amount of wave reflection from the shoreline. During the field survey, it appeared that SAV beds and emergent vegetation were more abundant along areas with rip rap than exposed vertical seawalls, but no differences were apparent for oysters. If anything, oysters were more abundant along seawalls than rip rap shores.

None of the other shoreline feature types in Tables 5-3 or 5-4 comprise more than 5% of the total shoreline or shoreline in any reach, with two exceptions. Upland hammock or forest comprises 11% of the North Fork shoreline. This is primarily a pine flatwoods fringe along the west shore on slightly higher bluffs between the water and an apartment/ condominium project. Grassed unarmored slopes, essentially lawns in areas with very little elevational change, represent 10% of the South Fork shoreline. These are primarily in the upstream reaches near the mouth of Palm City Bay where wave and boat wake development appear to be low.

The shoreline appears to be well stabilized throughout most of the SLE, possibly with minor amounts of sandy material being eroded from sandy slopes. Based on this survey, it would appear that erosion of shoreline materials along the SLE itself, is not sufficient to account for the changes in bathymetry and sedimentation noted in the estuary.

5.4.2 Adjacent Land Uses

Tables 5-5 and 5-6 show the different land uses adjacent to the SLE and the percentage of shoreline occupied by each land use. Low density residential is the largest land use category in all reaches of the SLE, occupying over 50% of the total adjacent land use. Low density residential use ranges from 88% in the Lower Estuary to 43% along the South Fork. Undeveloped or vacant land in transition represents the next largest land use type with 11%, and medium and high residential use is 9% of the area.

Natural vegetation cover accounts for only 15% of the adjacent land cover of the SLE shoreline. The main vegetation cover consists of upland hardwood hammocks comprising 9% of the Lower Estuary shoreline and mangrove swamps adjacent to 23% of the South Fork. Mangrove swamps are abundant along the South Fork and present in the North Fork, but almost non-existent elsewhere. The hammocks along the Lower Estuary are remnants of tropical hammocks; most are parts of residential lots. Upland vegetation along the South Fork and North Fork is primarily pine flatwoods and disturbed flatwoods.

These data indicate that the SLE is essentially an urban estuary, at least in terms of adjacent land use and associated stormwater loadings. Over three quarters of the shoreline consists of urban land use with an additional 12% consisting of land generally in transition to urban uses.

5.5 PIER SURVEY

A total of 673 pier structures was found in the study area. Of these 590 were classified as single piers, 64 as multiple piers, and 19 as complex piers. The distribution of pier types in the SLE is shown in the following table.

Estuary Segment	Number of Piers		
Pier Type	East or North Shore	West or South Shore	Total Segment
Lower Estuary			
Single	84	74	158
Multiple	4	5	9
Complex	1	0	1
Total in Segment	89	79	168
Middle Estuary			
Single	88	50	138
Multiple	7	5	12
Complex	4	1	5
Total in Segment	99	56	155
North Fork			
Single	84	44	128
Multiple	18	2	20
Complex	5	3	8
Total in Segment	107	49	156
South Fork			
Single	76	90	166
Multiple	8	15	23
Complex	4	1	5
Total in Segment	88	106	194
Total SLE			
Single			590
Multiple			64
Complex			19
Total Piers			673

The proportion of piers is relatively evenly distributed among the four segments of the SLE, with a somewhat higher proportion in the South Fork. The south shore of the Middle Estuary and the west shore of the North Fork are generally under-represented. By far, the greatest proportion (88%) of piers are single. These are generally associated with single family residences or larger apartment complexes with little emphasis on water activities.

The multiple and complex piers are generally associated with commercial water dependent facilities. The only complex pier in the Lower Estuary is at the Bay Tree Lodge, while those in the Middle Estuary are near Northside Marina, High Seas Fabrication, and downtown Stuart. In the North Fork, the larger piers are associated with Harpers Landing, Stuart Brokerage, and Harbor Inn on the east shore and Cutter Sound and Harbor Ridge on the west shore. Other multiple piers are present at Club Med Resort, Tarpon Bay Yacht Club and other sites. The major complex piers in the South Fork are associated with Martin County Marina on the west shore and Woods Cove Marina, Monterey Motel and the De La Bahia complex on the east shore.

Piers in the SLE system are generally in excellent repair. Only four out of 168 piers in the Lower Estuary are in sufficient disrepair to render them largely unusable. Five of 155 piers in the Middle Estuary are in disrepair, with an additional four (between the railroad bridge and city hall in Stuart) reduced to isolated pilings. All piers in the North and South Forks are in good repair. Two new piers were under construction, on the west shore of the Lower Estuary and south shore of the Middle Estuary.

Most piers are open piers specifically for mooring boats. Two piers on the east side of the Lower Estuary and one on the east side of the North Fork have enclosed boathouses or structures at the ends. In addition, one of the structures recorded in the Middle Estuary was the boardwalk in downtown Stuart, and six structures represented concrete breakwaters.

TABLE 5-1
DISTRIBUTION OF OYSTER BEDS IN THE ST. LUCIE ESTUARY

BED #	DISTANCE (ft) TO MOUTH	SLE REACH	SIZE (acres)	LENGTH (FT)	WIDTH (ft)	MIN DEPTH (ft)	MAX DEPTH (ft)	SUBSTRATE*	LOCATION
11	19,755	M	65.40	3630	690	2	7	M/mfs to C/mfs	N side at Rio, shore to 350 ft out
1	23,600	M	28.10	2925	380	2	8	M/mfs to C/mfs	N. Side w. of Rio, shore to 100 ft out
4	19,985	M	23.53	1680	606	2	7	M/mfs	S side mid Stuart, 150 to 450 ft out
3	24,050	M	20.07	2350	425	2	7	M/mfs	S side US1 bridge to hospital, 100 to 500 ft out
8	37,270	N	11.71	1970	280	3	7	C/mfs	W side, 1100 ft n of Bessey, 200 to 500 ft out
14	40,000	S	8.47	2750	150	2	5	M/mfs	W side 700 to 3,000 ft s of Palm City Bridge, 0 to 120 ft out
18	34,870	N	8.10	1050	160	4	8	M/mfs with hash	S side, 150 to 450 ft off Seagate harbor
10	38,555	N	7.33	680	420	4	6	M/mfs to C/mfs	E side at North River Shores, 100 to 150 ft out
17	33,710	S	6.01	1450	190	1	7	C/mfs to M/mfs	W side 700 ft S of Pendarvis Cove, 15 to 215 ft out
2	14,960	M	5.56	1000	230	3	7	M/mfs	S side e Stuart and Krueger Ck, 400 to 500 ft out
21	33,490	N	4.01	1090	180	2	8	C/mfs to M/mfs	E side N end of Speedy Point, 100 to 150 ft out
23	36,570	S	3.80	1625	155	1.5	5	M/mfs	W. side, Danforth Ck and Matchett Point, 30 to 300 ft out
5	18,840	M	2.85	1440	100	2	6	M/mfs to hash	S side w of Krueger, 50 to 400 ft out
22	30,440	S	2.65	1135	100	2	6	M/mfs	E side, Bessey Point to Frazier Creek, 50 to 150 ft out
16	32,965	S	1.72	485	200	2	4	C/mfs to m/mfs	N of mouth of Pendarvis Cove, 20 to 120 ft out
20	35,620	N	1.57	680	130	1	6	M/mfs with hash	E side, 400 ft e of Coconut Point, shore to 70 ft out
13	15,885	M	1.57	400	190	4	6	C/mfs	N side e of Warner Creek, 150 to 300 ft out
9	40,125	N	1.36	480	120	4	6	C/mfs to M/mfs	E side at North River Shores, 100 to 150 ft out
12	16,100	M	0.81	470	90	2	6	C/mfs	N side e of Warner Creek, from shore out
6	18,295	M	0.74	370	100	2	5	C/mfs	S. side e of Krueger, 20 to 100 ft out
25	18,980	M	0.57	880	40	3	6	M/mfs to C/mfs	N side at Rio, 300 to 350 ft out
24	25,990	M	0.51	120	190	4	8	C/mfs	Mid channel, 1,000 ft NW of railroad bridge
27	40,320	S	0.43	230	70	1	2	M/mfs	N side of small island 1,500 f SW of Palm City Bridge
19	34,045	N	0.35	290	70	5	7	M/mfs with hash	S side, 200 ft off Lighthouse Point
15	34,185	S	0.16	225	40	3	3.5	M/mfs	NW side Pendarvis Cove, 30 to 120 ft out
26	40,730	S	0.08	30	102	1.7	3	C/mfs to M/mfs	S side of small island 1,500 ft Sw of Palm City Bridge
7	36,500	S	0.04	136	25	2	2	M/mfs to C/mfs	E. side, 250 ft n of small island by De La Bahia
Total			**207.51**						
Mean			**7.69**	**1095**	**201**	**2.5**	**5.9**		

* M/mfs = Mucky/muddy fine sand
C/mfs = Coarse/medium firm sand

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TABLE 5-2
CHARACTERISTICS OF OYSTER BEDS IN THE ST. LUCIE ESTUARY

BED #	SLE REACH	% LIVE COVER	% DEAD COVER	% TOTAL DENSITY	LIVE SIZE (cm)	DEAD SIZE (cm)	RECENT DEAD	SIZE RECENT DEAD (cm)	CONDITION	OTHER SPECIES
16	S	1 to 5	41 to 70	42 to 75	Mostly 5 to 10	Mostly 5 to10	No	NA	Good, no stress	Extensive mussels
5	M	1 to 5	41 to 70	42 to 75	Mostly 5 to 10	Mostly 5 to 10	No	NA	Good, no stress	None noted
2	M	1 to 5	21 to 40	22 to 45	Mostly 5 to 10	Mostly 5 to 10	No	NA	Good, no stress	one noted
20	N	1 to 5	6 to 20	7 to 25	Mostly 5 to 10	Mostly 5 to 10	No	NA	Good, no stress	Some dead *Mulinia*
15	S	1 to 5	1 to 5	2 to 10	Mostly 5 to 10	Mostly 5 to 10	No	NA	Good, some stress	A few dead *Rangia*
23	S	1 to 5	5 to 20	7 to 25	Mostly 5 to 10	Mostly < 5	No	NA	Good, no stress	None noted
27	S	1 to 5	1to 5	2 to 10	Mostly 5 to 10	Mostly < 5	No	NA	Moderate to poor	Moderate *Rangia* mixed in
4	M	1 to 5	41 to 70	42 to 75	Mostly 5 to 10	Mostly 5 to 10	Yes	Mostly < 5	Good, no stress	None noted
1	M	1 to 5	21 to 40	22 to 45	Mostly <5	Mostly <5	No	NA	Good, no stress	Some live mussels, dead *Mulinia, Rangia*
21	N	1 to 5	71 to 100	72 to 100	Mostly < 5	Mostly 5 to 10	No	NA	Good, no stress	None noted
17	S	6 to 20	6 to 20	12 to 40	Mostly < 5	Mostly 5 to 10	No	NA	Good, no stress	Extensive mussels/barnacles
8	N	1 to 5	41 to 70	42 to 75	Mostly < 5	Mostly < 5	No	NA	Good, no stress	Extensive mussels
10	N	1 to 5	21 to 40	22 to 45	Mostly < 5	Mostly < 5	No	NA	Good, no stress	Extensive mussels/barnacles
22	S	5 to 20	41 to 70	46 to 90	Mostly < 5	Mixed, all sizes	No	NA	Good, no stress	None noted
11	M	1 to 5	6 to 20	7 to 25	Mostly < 5	Mixed, all sizes	No	NA	Good, no stress	None noted
13	M	21 to 40	21 to 40	42 to 80	Mostly < 5	Mostly 5 to 10	Yes 10%	Mostly < 5	Moderate, discolored	
18	N	1 to 5	71 to 100	72 to 100	Mostly < 5	Mostly 5 to 10	No	NA	Moderate, discolored	Extensive musels/barnacles
3	M	1 to 5	71 to 100	72 to 100	Mixed all sizes	Mixed all sizes	Yes <10%	Mostly 5 to 10	Good, no stress	Mussels and barnacles
14	S	1 to 5	71 to 100	72 to 100	All < 5	Mostly 5 to 10	No	NA	Good, no stress	*Rangia* present
19	N	1 to 5	41 to 70	42 to 75	All < 5	Mostly 5 to 10	No	NA	Good, no stress	None noted
12	M	1 to 5	6 to 20	7 to 25	All < 5	Mostly 5 to 10	No	NA	Good, no stress	None noted
6	M	1 to 5	41 to 70	42 to 75	All < 5	Mostly < 5	No	NA	Good no stress	None noted
25	M	1 to 5	6 to 20	7 to 25	All < 5	Mixed, all sizes	No	NA	Good, no stress	None noted
9	N	1 to 5	6 to 20	7 to 25	All < 5	Mostly < 5	Yes	Mostly< 5	Good, no stress	None noted
7	S	1 to 5	41 to 70	42 to 75	All < 5	Mostly 5 to 10	Yes 20%	All < 5	Good to poor	Live and dead *Rangia*
24	M	1 to 5	21 to 40	22 to 45	All < 5	Mixed, all sizes	Yes 10 %	All < 5	Good, no stress	None noted
26	S	1 to 5	71 to 100	72 to 100	All < 5	All < 5	Yes	All < 5	Poor, discolored	Moderate *Rangia* mixed in

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TABLE 5-3
EXTENT OF SHORELINE TYPES IN THE ST. LUCIE ESTUARY

SHORELINE TYPE	REACH OF SLE (Distance in feet)				
	LOWER ESTUARY	MIDDLE ESTUARY	NORTH FORK	SOUTH FORK	TOTAL
Brackish/Saline Emergent Marsh	0	0	190	136	326
Freshwater Emergent Marsh	0	0	641	1,332	1,973
Mangroves	1,907	305	19,361	20,341	41,914
Exotic Species	1,829	161	1,212	209	3,411
Native Hammock/Upland Forest	289	0	8,385	0	8,674
Mixed Uses <50 feet long	1,360	423	675	0	2,458
Tributary Channel	0	372	2,901	2,141	5,414
Culvert/Outfall	0	0	0	19	19
Grassed Unarmored Slope	0	1,602	3,246	5,412	10,260
Sandy Slope/Beach	16,664	7,180	15,783	4,807	44,434
Rip Rap	6,263	10,014	7,161	5,460	28,898
Vertical Seawall	4,190	18410	15,842	15,600	54,042
Bridges/Other Structures	192	53	0	191	436
Docks/Boardwalks/Marinas	0	0	0	866	866
None	0	0	202	0	202
Toal	**32694**	**38,520**	**75,599**	**56,514**	**203,327**

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TABLE 5-4
DISTRIBUTION OF SHORELINE TYPES IN THE ST. LUCIE ESTUARY

SHORELINE TYPE	REACH OF SLE (% of Shoreline)				
	LOWER ESTUARY	MIDDLE ESTUARY	NORTH FORK	SOUTH FORK	TOTAL
Brackish/Saline Emergent Marsh	0.0	0.0	0.3	0.2	0.2
Freshwater Emergent Marsh	0.0	0.0	0.8	2.4	1.0
Mangroves	5.8	0.8	25.6	36.0	20.6
Exotic Species	5.6	0.4	1.6	0.4	1.7
Native Hammock/Upland Forest	0.9	0.0	11.1	0.0	4.3
Mixed Uses <50 feet long	4.2	1.1	0.9	0.0	1.2
Tributary Channel	0.0	1.0	3.8	3.8	2.7
Culvert/Outfall	0.0	0.0	0.0	0.0	0.0
Grassed Unarmored Slope	0.0	4.2	4.3	9.6	5.0
Sandy Slope/Beach	51.0	18.6	20.9	8.5	21.9
Rip Rap	19.2	26.0	9.5	9.7	14.2
Vertical Seawall	12.8	47.8	21.0	27.6	26.6
Bridges/Other Structures	0.6	0.1	0.0	0.3	0.2
Docks/Boardwalks/Marinas	0.0	0.0	0.0	1.5	0.4
None	0.0	0.0	0.3	0.0	0.1
Total	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

TABLE 5-5
EXTENT OF LAND USES ADJACENT TO THE ST. LUCIE ESTUARY

SHORELINE LAND USE	FLUCCS CODE(s)	REACH OF SLE (Distance in feet)				
		LOWER ESTUARY	MIDDLE ESTUARY	NORTH FORK	SOUTH FORK	TOTAL
Commercial/Industrial/ Institutional	140,150,170	192	4,768	2,718	1,827	9,505
Medium to High Density Residential	120,130	0	3,402	9,757	5,800	18,959
Low Density Residential	110	27,969	21,896	35,927	24,476	110,268
Marina/Docks	180	0	2,954	2,865	1,711	7,530
Vacant/Undeveloped	190	100	3,922	14,354	5,073	23,449
Other Uses	N/A	319	341	0	50	0,710
Exotic Species Vegetation	N/A	369	246	1,242	531	2,388
Marsh	640	0	0	0	351	0,351
Mangrove Forest	610	0	0	6,604	12,827	19,431
Upland Hammock Forest	400	2,821	990	1,163	624	5,598
Other Upland Forest	400	0	0	969	3,248	4,217
Total	**N/A**	**31770**	**38,519**	**75,599**	**56,518**	**202,406**

TABLE 5-6
DISTRIBUTION OF LAND USES ADJACENT TO THE ST. LUCIE ESTUARY

SHORELINE LAND USE	FLUCCS CODES	REACH OF SLE (% of Shoreline)				
		LOWER ESTUARY	MIDDLE ESTUARY	NORTH FORK	SOUTH FORK	TOTAL
Commercial/Industrial/ Institutional	140,150,170	0.6	12.4	3.6	3.2	4.7
Medium to High Density Residential	120,130	0.0	8.8	12.9	10.3	9.4
Low Density Residential	110	88.0	56.8	47.5	43.3	54.5
Marina/Docks	180	0.0	7.7	3.8	3.0	3.7
Vacant/Undeveloped	190	0.3	10.2	19.0	9.0	11.6
Other Uses	N/A	1.0	0.9	0.0	0.1	0.4
Exotic Species Vegetation	N/A	1.2	0.6	1.6	0.9	1.2
Marsh	640	0.0	0.0	0.0	0.6	0.2
Mangrove Forest	610	0.0	0.0	8.7	22.7	9.6
Upland Hammock Forest	400	8.9	2.6	1.5	1.1	2.8
Other Upland Forest	400	0.0	0.0	1.3	5.7	2.1
Total	**N/A**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

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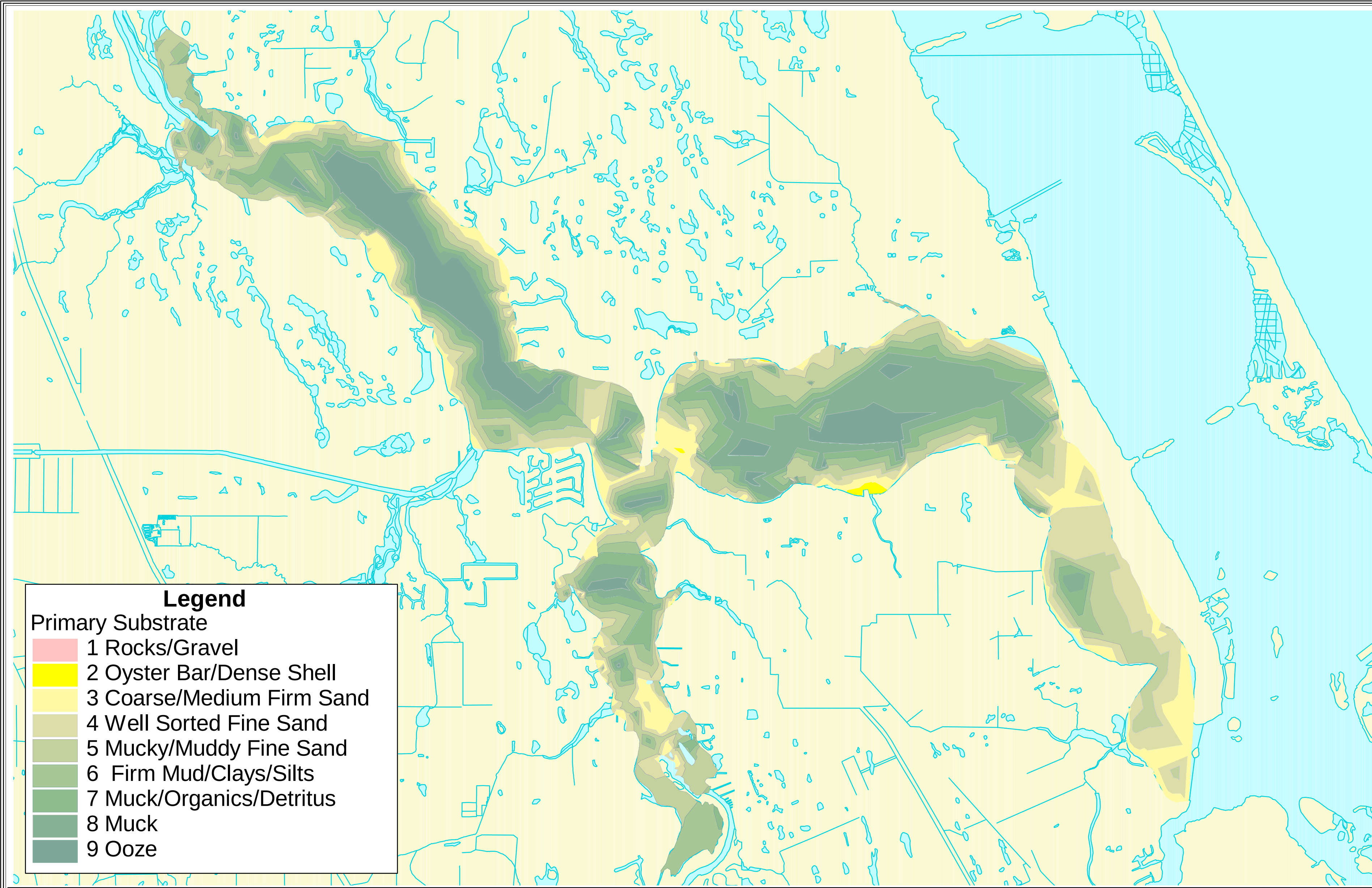


URS Greiner Woodward Clyde

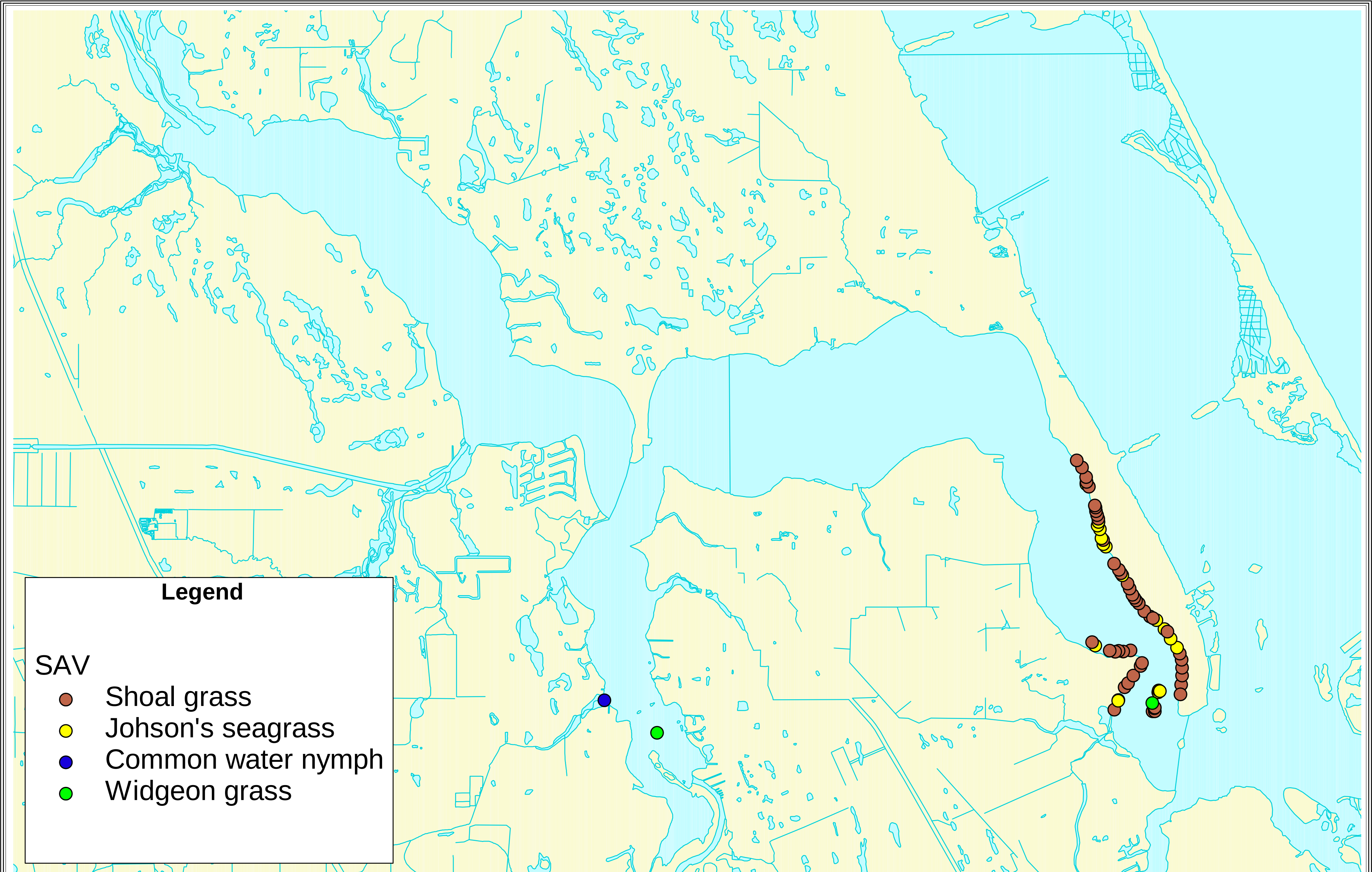
1 0 1 2 Miles

N

Projection: State Plane, East Zone

Substrate
St. Lucie Estuary, Florida

Figure 5-1



URS Greiner Woodward Clyde

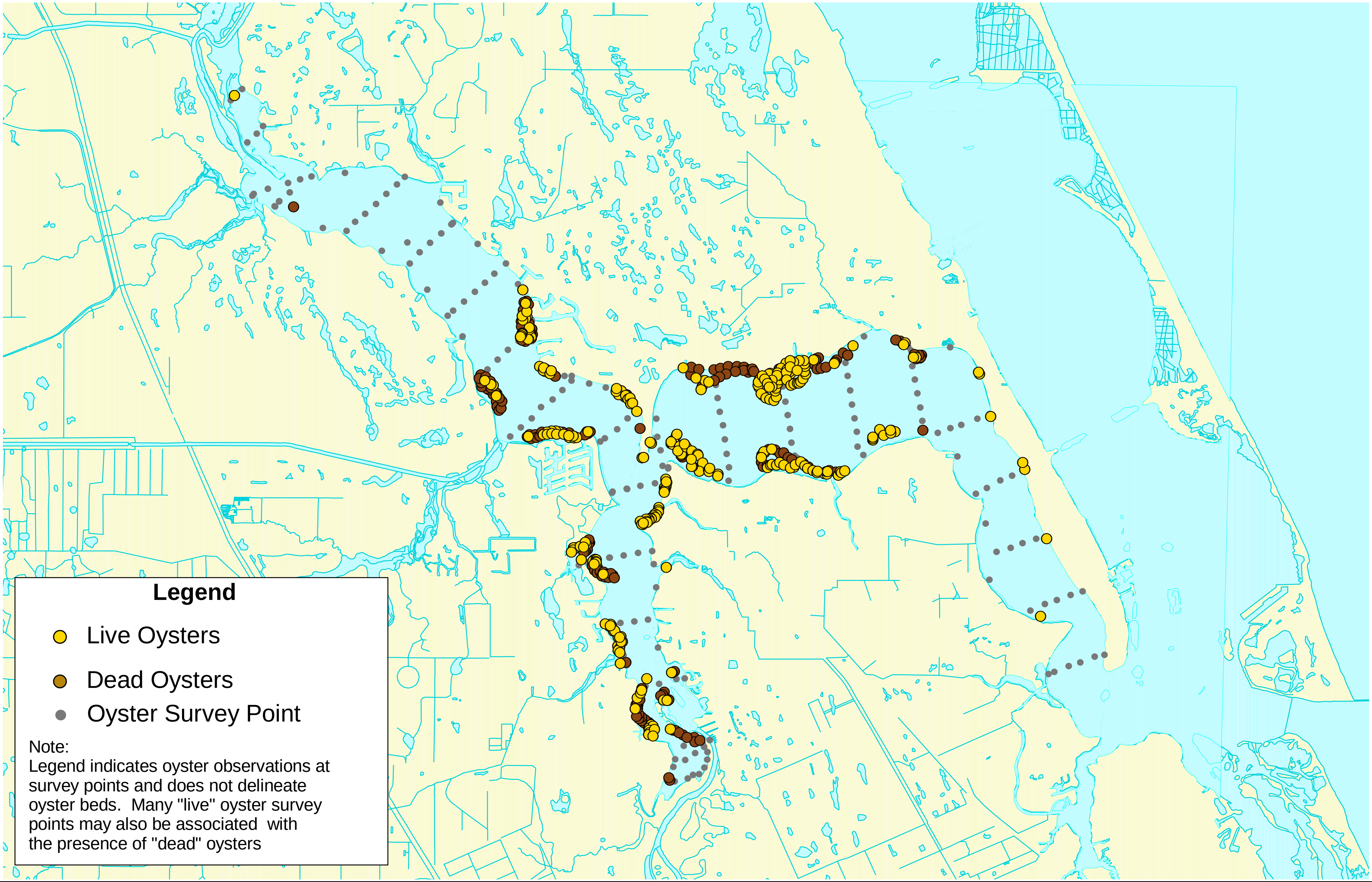
N

1 0 1 2 Miles

Projection: State Plane, East Zone

Submerged Aquatic Vegetation (SAV)
St. Lucie Estuary, Florida

Figure 5-2



URS Greiner Woodward Clyde

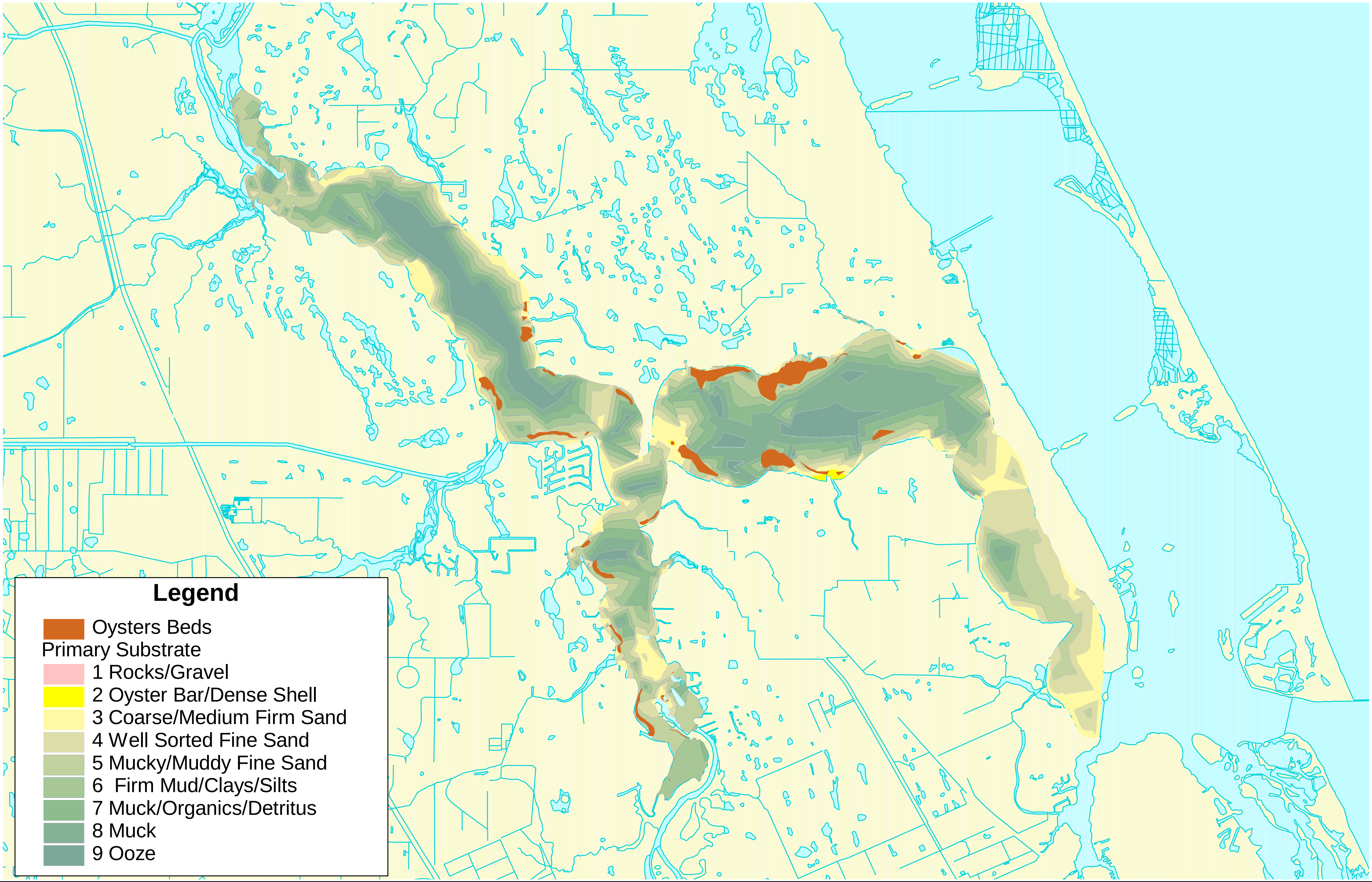
N

1 0 1 2 Miles

Projection: State Plane, East Zone

Live and Dead Oysters
St. Lucie Estuary, Florida

Figure 5-3



URS Greiner Woodward Clyde

1 0 N 1 2 Miles

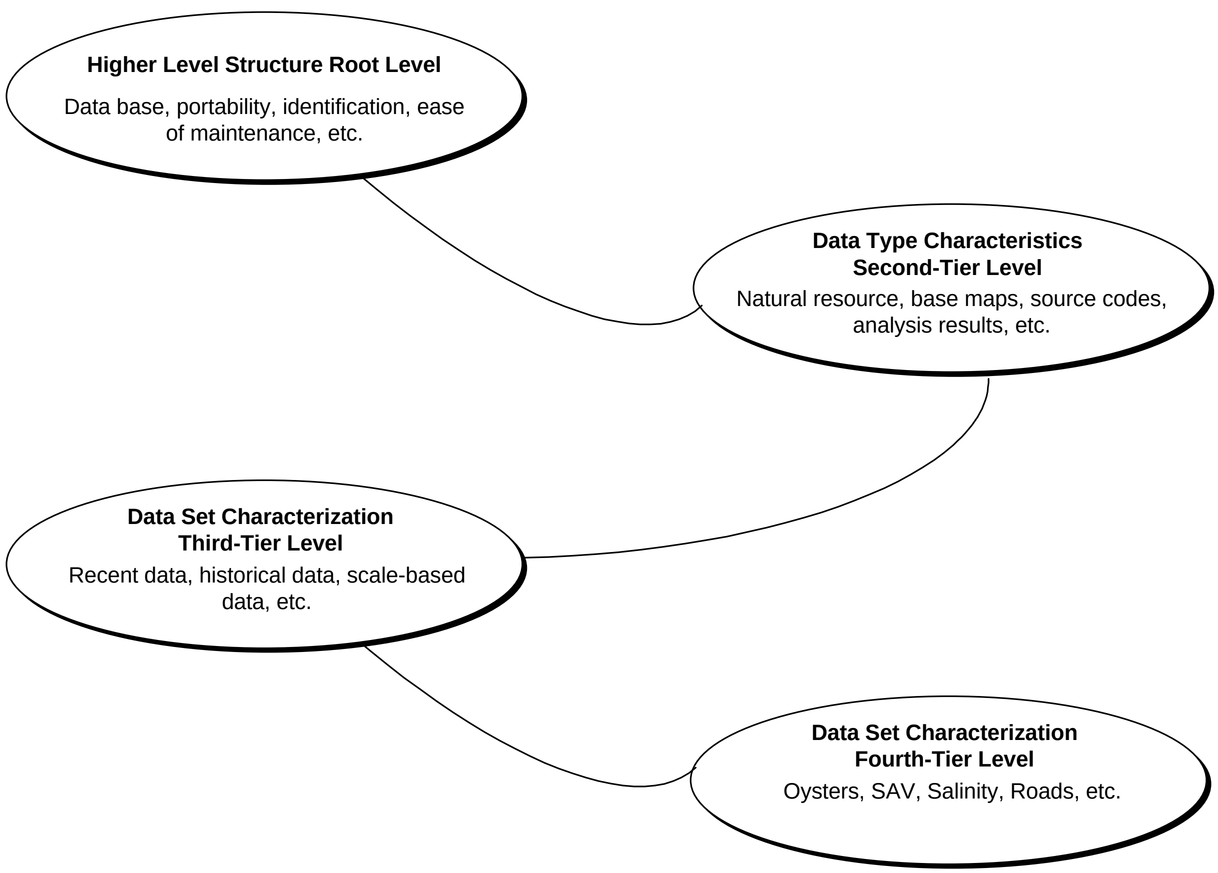
Projection: State Plane, East Zone

Oyster Beds and Substrate
St. Lucie Estuary, Florida

Figure 5-4

6.1 GIS DATA BASE DESIGN

It was anticipated that data collection efforts and environmental analysis for the St. Lucie Estuary will continue to evolve beyond the scope and duration of this project. In the conceptual data base design, questions relating to how information is stored, maintained and retrieved leads to common data characteristics which can form the basis for data directory structure. From this perspective, the conceptual model for the Oyster and SAV GIS data base was based on fundamental characteristics shared by groups of data as graphically shown in flow diagram below (data base conceptual model).



Database Conceptual Model

Primary issues considered for the higher-level data base structure were:

- Data base portability ("How will the data base and applications be transferred from platform to platform?")
- User identification of data base ("What is in the data base?")
- Data base maintenance ("How is the data base updated, edited and maintained?")

Data base portability, identification and maintenance can be simplified by a hierarchical structure where all data partitions (folders) are stored under a single "root" directory.

The information collected and generated in the study was further characterized by:

- *Data type* ("Resource type data, Basemap type data, Results of an analysis, etc.")
- *Data set* ("Recent data set, Historical data set, Scale-based data set; 1:100,000, 1:40,000, *1:24,000 scale data sets, etc.")*
- *Data layer* ("Oysters, SAV, Salinity, Roads, etc.")

A *data type* attempts to separate information according to their anticipated needs, analysis or intended use. In the data base conceptual model, five types (categories) were identified. These categories are as follows:

- Natural Resource
- Base Map
- Analysis
- GUI Application
- GUI Source/Executables

Natural resource data are information which uniquely characterize the specific natural environment of the study area. Information such as surveyed oyster maps, maps of modeled salinity, and substrate are data which represent the unique resources of the St. Lucie Estuary .

Base maps are information which provide a geographic reference to the natural resource data. Base maps include roads, coastline, land-marks, and so on.

The *analysis* category includes the results of analyzing the natural resource data within the context of specific objectives and scope. For instance, the potential oyster and SAV location maps (GIS data layers) can be characterized as results of an analysis.

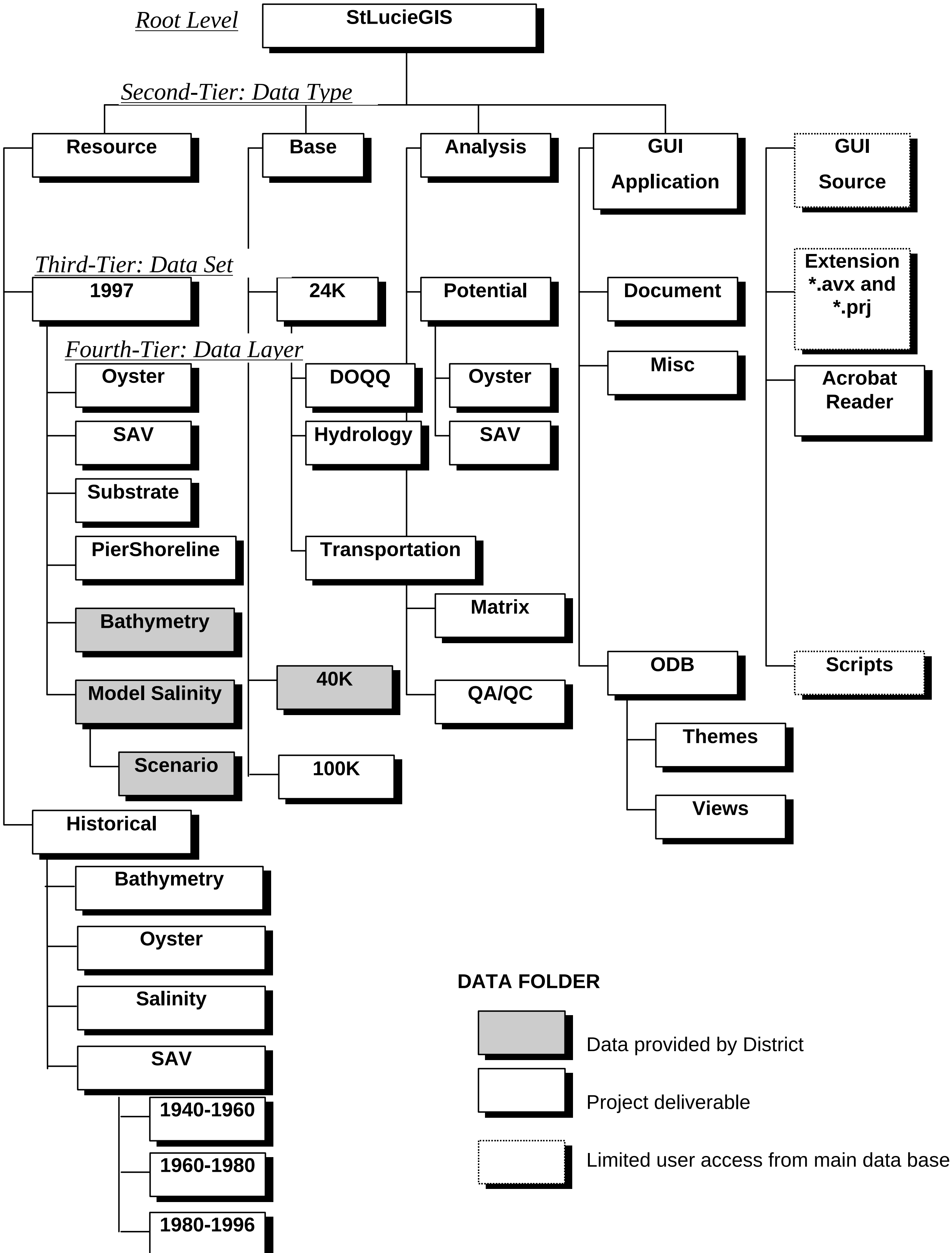
Furthermore, the data type concept distinguishes the GUI programs and source codes as a unique *type* separate from "data". The data base hierarchical design includes a second-tier of folders underneath the root level, which separates out the different types of information (as shown in the data base conceptual model flow diagram and the data base structural model diagram).

Within a given data type, information can be further subdivided into *data sets*. A data set identifies the next level of unique characteristics between data of the same type. Since the St. Lucie Estuary study is centered on temporal-based spatial trends of biologic indicators, the data set for the natural resource type was partitioned by time. As shown in the structural data base model flow diagram, the third-tier of folders which represent data sets are partitioned into a “1997” folder and a “Historical” folder. Additional sets (third-tier folders) can be added to the data type as yearly data is collected in the future.

Similarly, the basemap data type was sub-divided into data sets based on unique map scales (Scale-based data set). The primary reason is to facilitate and promote the mapping of base maps at common scales, accuracy and precision limits. For instance, map accuracy degrades significantly, if one is to mix and match 1:100,000 scale roads with 1:24,000 scale coastline GIS layers and creates a 1:500 scale hard-copy map. The intent of having a distinct scale-based folder for basemap layers is to ensure that data of common scales are grouped and stored together.

A *data layer* is a unique GIS theme within a data set. For example, within the “1997” data set of the “Natural Resource” data type, there are unique GIS layers such as oysters, SAV, substrate, shoreline features, bathymetry and modeled salinities. Established as fourth-tier information, data layers are structured as folders within the data sets. Final GIS-based features are stored within each data layer according to ArcView’s theme-based concept. For instance, the oyster GIS feature coverage residing underneath the oyster data layer (folder) may have both polygons and points; oyster beds versus grid samplings at discrete points, respectively. In this case, there will be two oyster GIS feature coverages. The first feature coverage will have polygons and their associated data attributes whereas the latter, being points with point-based data attributes.

The structural model for the overall GIS data base is schematically presented below. The model is based on a tiered data folder structure as conceptualized in data base conceputal model flow diagram. A detailed description to the GIS database is provided in a separate report “GIS Documentation Booklet: Geographic Information System (GIS) Design Documentation”.



Data Base Structural Model

6.2 GIS USER INTERFACE

Customized "point-and-click" menu-based interfaces are a convenient means in which to access and analyze GIS data layers effectively. Such customization involves development of a GIS application where specific programs are written to satisfy unique functions. This section outlines the initial design, utility and limitation(s) of the GIS application as developed for the St. Lucie Oyster/SAV study.

The model for the GIS application is founded on the following practical criteria:

From the User's Perspective

- Ease-of-Use ("How convenient is it to extract a data layer from a remote GIS data base and start using it?")
- Portability ("How can I transfer the data base and application onto my laptop PC in order to make a presentation in the next Water Management District Technical Conference?")

From the System Administrator's Perspective

- Flexibility ("How can I update or modify the GIS application and related data base?")
- Security ("How can I prevent some user from corrupting the original data layers and application?")

From these perspectives, an overall conceptual model for the GIS application has been constructed. The core design for the St. Lucie GIS application incorporates four main components, as listed below:

- *ArcView Extension* ("Delivery means; how the GIS application is delivered to the user")
- ArcV*iew Object Data Bases* (ODB) ("Storage/Retrieval means; how data and properties are indexed, stored and retrieved")
- *ArcView Avenue* ("Programming means; Programming language that the application is written in")
- *ArcView Dialog Designer* ("Point-and-click means; how user interacts with the application")

The GIS application incorporates the use of ArcView's *extension* concept rather than an ArcView *project*, as the final application. The advantage of an extension is that it is independent from a project file. Therefore, a user cannot "accidentally" change the source extension which is quite possible with ArcView projects. Additionally, imbedded extension objects (views, scripts, tables, etc.) do not have to be saved into a separate project file in order to use the application. If the extension is unloaded, all imbedded objects will be uninstalled so that cleanup after the use of the application is efficient. However, the user can save the extension objects into his/her personal project file without altering the source extension. Another advantage of the extension concept is that it resides in a central repository (AVHOME/etc). Therefore, the user does not explicitly need to know the full directory path of the application; a common problem when an application is moved from directory to directory in the computer system.

According to ESRI, ArcView's *object data base* (ODB) is a file-based storage/retrieval system for objects. What this means is that an ODB is simply an ASCII text file which stores a collection of object directory paths, object names, object properties (font, color, size, etc.), and protocols about how the objects will be retrieved in ArcView GIS. The object may be view documents, themes within views, tables, layouts, scripts and so on. In fact, an ArcView project file itself is an ODB which stores all the properties of an ArcView session.

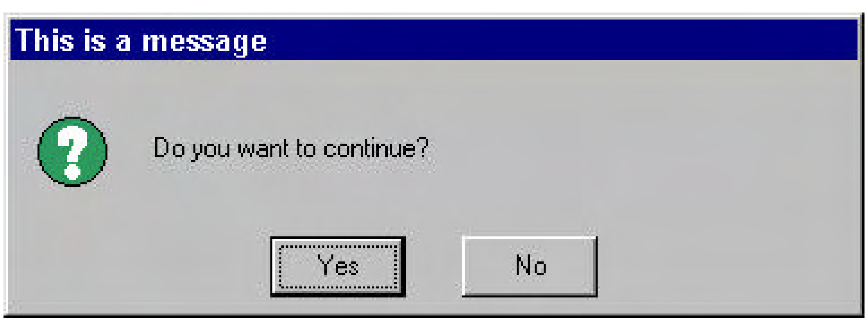
The main advantage in adopting an ODB structure lies in the development of a GIS application with relatively minimal object overhead. This results in a smaller file size for the application which generally translates into faster loading in ArcView GIS. With effective use of ODBs, it is faster to load an extension (and project files as well) since the overhead in imbedded objects can be minimized. Projects which have a large number of objects such as views, tables, layouts, etc can take significant time to load. To resolve this, all the data objects (except for Avenue scripts) are saved as external ODB files which can then be imported on an "as needed" basis by the application.

The St. Lucie GIS application is written entirely in Avenue; ArcView's programming language. Avenue is an object-oriented language which is fundamentally different from procedural language such as, Arc Macro Language (AML); ArcInfo's user programming language. Similar to other object-oriented languages, Avenue is based on objects and requests; where an object is a unique unit of data and function. Requests are made to objects (or classes) to perform an action. All objects in Avenue belong to a class hierarchy which is grouped into functional categories. Avenue *statements* provide the means to structure the object (class)/request events in logical order.

For example, in order to program a popup window which prompts the user to choose either a "yes" or a "no, an Avenue statement involves a *request* ("YesNo") made to the *class* ("MsgBox") where the user's choice will be stored in an *object* ("mychoice"). The Avenue *statement* is written:

mychoice = MsgBox.YesNo("Do you want to continue?","",true)

When executed in ArcView, this Avenue statement will look like this:



An Avenue *script* is then a program for ArcView to perform specific function(s) by making requests to objects/classes within a structured flow of Avenue statements. Further description to the GIS application is provided in a separate report "GIS Documentation Booklet: Geographic Information System (GIS) Design Documentation".

The *Dialog Designer* is ESRI's "free-ware" extension which enhances Avenue customization capability. Dialog Designer is similar to Arc/Info GIS Form edit tool. It supports special popup menus which have built-in objects (similar to AML widgets) such as slider bars, push buttons, label buttons, list boxes, radio buttons, etc. The primary benefit in using the extension is to develop custom menus distinctly different from ArcView's native menus. At times, the native button and tool bars become clustered with "too many special buttons" as customization progresses. The advantage of popup menus developed in Dialog Designer lies in the easy identification of custom functions apart from other button clusters. Applications developed in the Dialog Designer extension can be distributed to other platforms which do not have the extension installed.

7.1 SAV POTENTIAL OCCURRENCE

7.1.1 Substrate Suitability

Figure 7-1 shows the substrates that could be potentially suitable for at least one SAV species that could have some potential for occurrence in the SLE. This indicates that only the ooze substrate is entirely unsuitable for any species. However, on a practical basis, the muck and mud substrates may be suitable only for one or two of the species which actually have not been reported in the SLE and these are essentially freshwater species (i.e., redhead grass), so salinity would further restrict occurrence. Figure 7-1 also superimposes actual SAV locations from the 1997 field survey and the best estimates for historical occurrence. These generally coincide primarily with the mucky/muddy fine sand substrates, with some occurrence also on the pure sand substrates.

7.1.2 Bathymetric Suitability

For virtually all of the potentially occurring SAV species, the potentially suitable maximum depth of occurrence (bathymetry suitability) has been set at 3 feet. This is because the light penetration beyond this depth does not appear to exceed 1 to 5% of surface PAR, which is the level required for positive net carbon assimilation and continued growth of the SAV species found in the region. Light penetration appears to be very poor in the SLE. Field observations of Secchi depth appear to confirm this, with most readings between 0.5 and 2.5 feet. Secchi depth generally corresponds to around 20% of Surface Irradiation. Secchi depth and light penetration appear to be greater in the Lower Estuary than in the rest of the SLE because of the tidal wedges of saline water (lacking the suspended and dissolved organic material and silts, as well as the tannic coloration) that can extend through much of the Lower Estuary. However, as discussed in Section 4, the light requirements of the seagrasses that can tolerate the higher Lower Estuary salinity regime are higher than the light requirements for many freshwater species. Thus, the increased light penetration in the Lower Estuary may be canceled out by the higher requirements of the available species.

Figure 7-2 shows the bathymetry of the SLE, based on recent data supplied by SFWMD. This indicates that the available suitable area of <3 feet is very limited in most of the estuary. Only in the more upstream portions of the South Fork and North Fork is there suitable bathymetry in other than a narrow band along the shore. The larger expanses of suitable depth are generally in the South Fork from the Danforth Creek/Palm City Bridge area upstream (south) and in the North Fork in the Kitching Cove/C-24 area. Much of these portions have mud or ooze substrates that are less suitable for SAV. Only along the sand deposits upstream and downstream of the Palm City Bridge does there appear to be a significant combination of suitable depth and substrate, and the stability of these sand bars may not be a suitability concern. Other areas with relatively wide (>1,000 feet) bands of potentially suitable bathymetry are on the east side of the North Fork south of Club Med, on the North side of the Middle Estuary in the Rio area, and in scattered areas along the lower reaches of the South Fork and the south side of the Middle Estuary along the Stuart shoreline.

7.1.3 Salinity Suitability

Almost all of the SAV found in the 1997 surveys occurred in the Lower Estuary where salinities ranged between 23 and 30 ppt. SAV in this area was composed primarily of the true seagrasses (shoal grass, Johnson's seagrass, star grass). The few remaining instances (widgeon grass, common water nymph, and wild celery) were in salinities between 3 and 7 ppt. Historical records indicate that both shoal grass and widgeon grass have occurred in regions where the salinity range is currently between 13 and 27 ppt, and shoal grass and Johnson's seagrass have occurred in the range to 30 ppt. Almost no records of SAV have been reported from areas where salinity is currently recorded as below 13 ppt. This zone includes almost all of the South Fork and the mouth of the C-44 Canal. These low salinity areas include most of the shallow water areas of the South Fork.

Bathymetry and the low light penetration in the SLE appear to exert the greatest restriction on SAV potential occurrence on an estuary-wide basis. There appear to be several SAV species representing a range of substrate and salinity tolerance levels consistent with substrates and salinities found in portions of the SLE. However, light penetration would appear to represent a major limitation for almost all of these species.

Figure 7-3 shows the estimated areas potentially suitable for at least one species of SAV based on available information, including the single snapshot of salinity conditions. This indicates that almost all of the shallow zones could be potentially suitable for at least one species based on this single salinity regime. However, it must be emphasized that salinity in the SLE is not static and that changes in the salinity regime will greatly affect (and reduce) the ability of SAV to occur. This analysis does not take this factor into account. Since shoal grass and widgeon grass appear to be the two SAV species which would have the best ability to colonize the greatest amount of potentially suitable areas, Figure 7-4 shows the potentially suitable areas for these two species, based on the same assumptions as Figure 7-3. Again, this distribution is based on very simplistic assumptions of light and salinity conditions, and caution should be used in reviewing these distributions.

Thus the second major limitation on SAV distribution probably is the degree or rate of change of salinities in the SLE. SFWMD modeling results for salinity showed only static concentration conditions at the time this project was completed. No data on ranges of conditions or rates of change were available. However, information available from other sources (U.S. Army Engineer District, Jacksonville, 1959) indicates that a wide range of salinity conditions may occur at virtually any part of the estuary, and that the changes in salinity may be very rapid. This rapid change in concentration is the second key limiting factor.

Further analysis of SAV suitability and restoration in the SLE should concentrate on the requirements of individual species, reduction of magnitude and rate of change of salinity, and potentially improving water clarity in the SLE. Currently it appears that shoal grass is the species with the greatest potential for increasing occurrence in the Lower Estuary and Middle Estuary areas, and widgeon grass has the greatest potential for the upper Middle Estuary, North Fork, and South Fork areas.

7.2 EASTERN OYSTER POTENTIAL OCCURRENCE

7.2.1 Substrate Suitability

Figure 7-5 shows the substrates that could be potentially suitable for the eastern oyster in the SLE. This potential substrate suitability range is similar to that for SAV, in that only the ooze substrate is entirely unsuitable. As discussed in Section 5, the major beds appear to be concentrated on the mucky sand substrates, and extend to some degree into the muck, mud, and sand substrates. The extent of potentially suitable substrate appears to be significantly greater than the current distribution of oysters in the SLE. The reported historical range of oysters occupies more of the potentially suitable substrate, but again does not include all possible areas. Thus it seems probable that suitable substrate is generally not the factor limiting population and spatial extent in the SLE.

7.2.2 Bathymetric Suitability

Bathymetric limits for oysters in the SLE appear to be a result of two separate factors. The first is that muck or ooze substrates are present in almost all of the locations in which water depth is greater than 8 feet. The second is that dissolved oxygen levels along the bottom in the deep areas with muck substrates appear to be marginal to unsuitable for oysters. Thus water depth does appear to place a limit on oyster occurrence in the SLE. However, a large part of the estuary is less than this depth and thus oysters should have the potential to occur in much of the SLE, in a range much larger than they currently exist.

7.2.3 Salinity Suitability

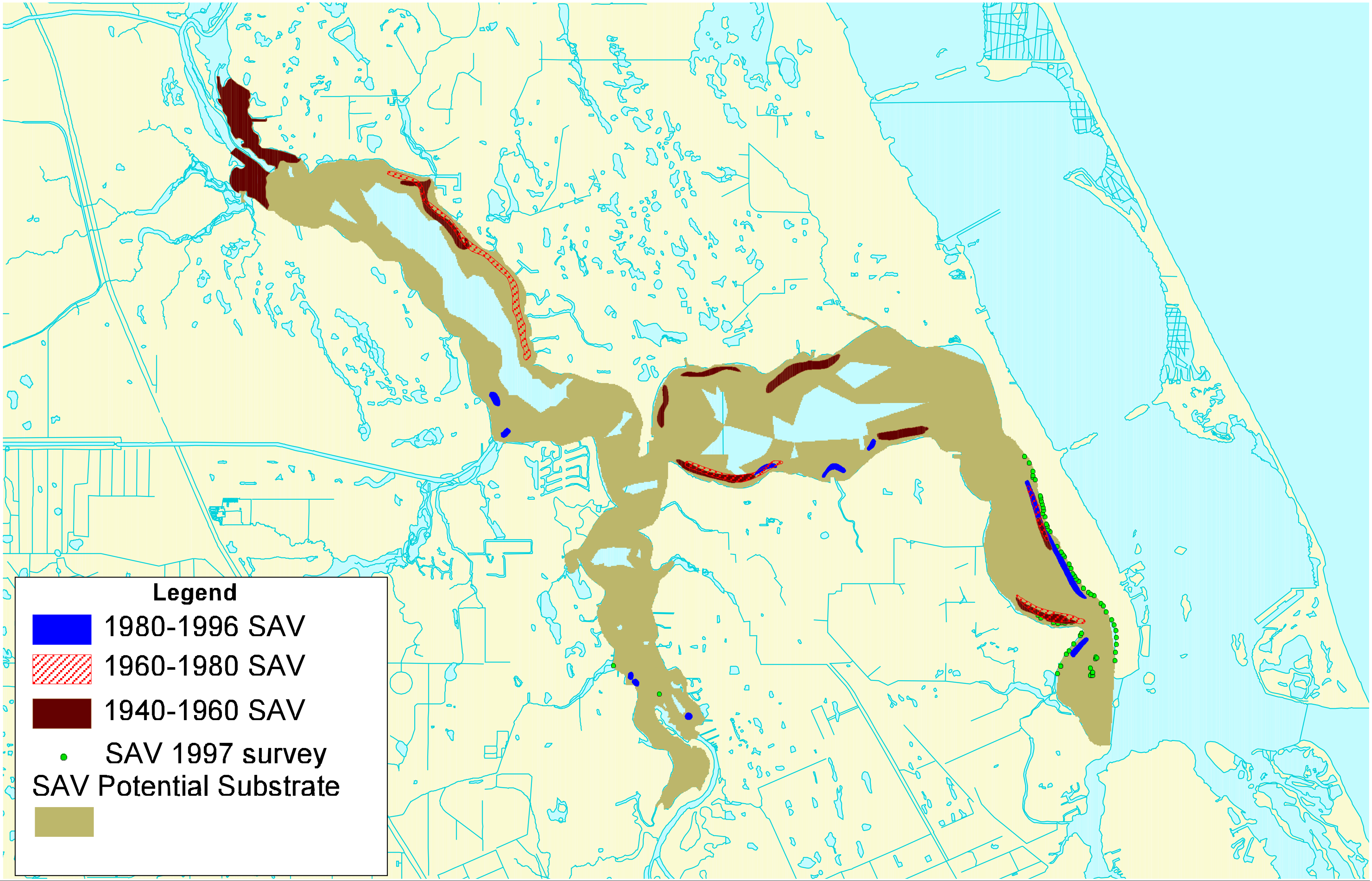
Based on the overall physiological tolerance range of adult oysters, virtually all of the SLE system would appear to have suitable salinity levels. However, as discussed in Section 4, numerous other factors are involved in salinity tolerance in natural environments.

In the first case, population survival appears to be limited by predation and disease at salinities generally above 17 to 20 ppt (Cake, 1983; Chatry, 1987). Based on the 1997 field surveys, there appear to be very limited oyster resources downstream of the middle of the Middle Estuary at Rio. This corresponds to the boundary between the 20-23 and 23-30 ppt zones, based on the salinity model data provided by SFWMD. Oyster resources downstream of this point in the remainder of the 20-23 ppt range appear to consist largely of intertidal populations on pilings and seawalls, indicating that this area corresponds to the zone at which predation becomes limiting. It should be noted however, that very little evidence of predation was seen in the field surveys.

Most of the remaining estuary appears to fall within a salinity range in which at least adult oysters can survive and spawn. The distribution of oysters as found in the field survey, seems to indicate that the main oyster resources are found at salinity ranges from 13 to 23 ppt as indicated by the model conditions.

However, it should be noted that the provided model conditions represent a single static condition at one point in time. Salinity throughout much of the estuary changes rapidly and, in many areas, greatly based on changes in flow and freshwater input. As discussed in Section 4, oysters are much more susceptible to changes in salinity than to actual salinity levels. The rate of change is also extremely important. Oysters can acclimate physiologically to changes in salinity regime, but this acclimation requires time to occur. Salinity changes that occur faster than this acclimation period can be lethal to adult and juvenile oysters. Oyster larvae are more susceptible to salinity changes and generally can not acclimate sufficiently rapidly to survive.

Thus, predicting suitable salinity conditions for oysters based on a static instant in time does not accurately reflect all variables. Restricting the analysis to juvenile and larval suitability may present a more accurate picture, but this also introduces a pronounced seasonal effect, since it would only come into play at specific spawning seasons, which are not accurately known for the SLE. Further analysis of salinity conditions based on larval tolerances at the spawning season, and based on the variation in salinity and rate of change in salinity would produce a more accurate indication.



URS Greiner Woodward Clyde

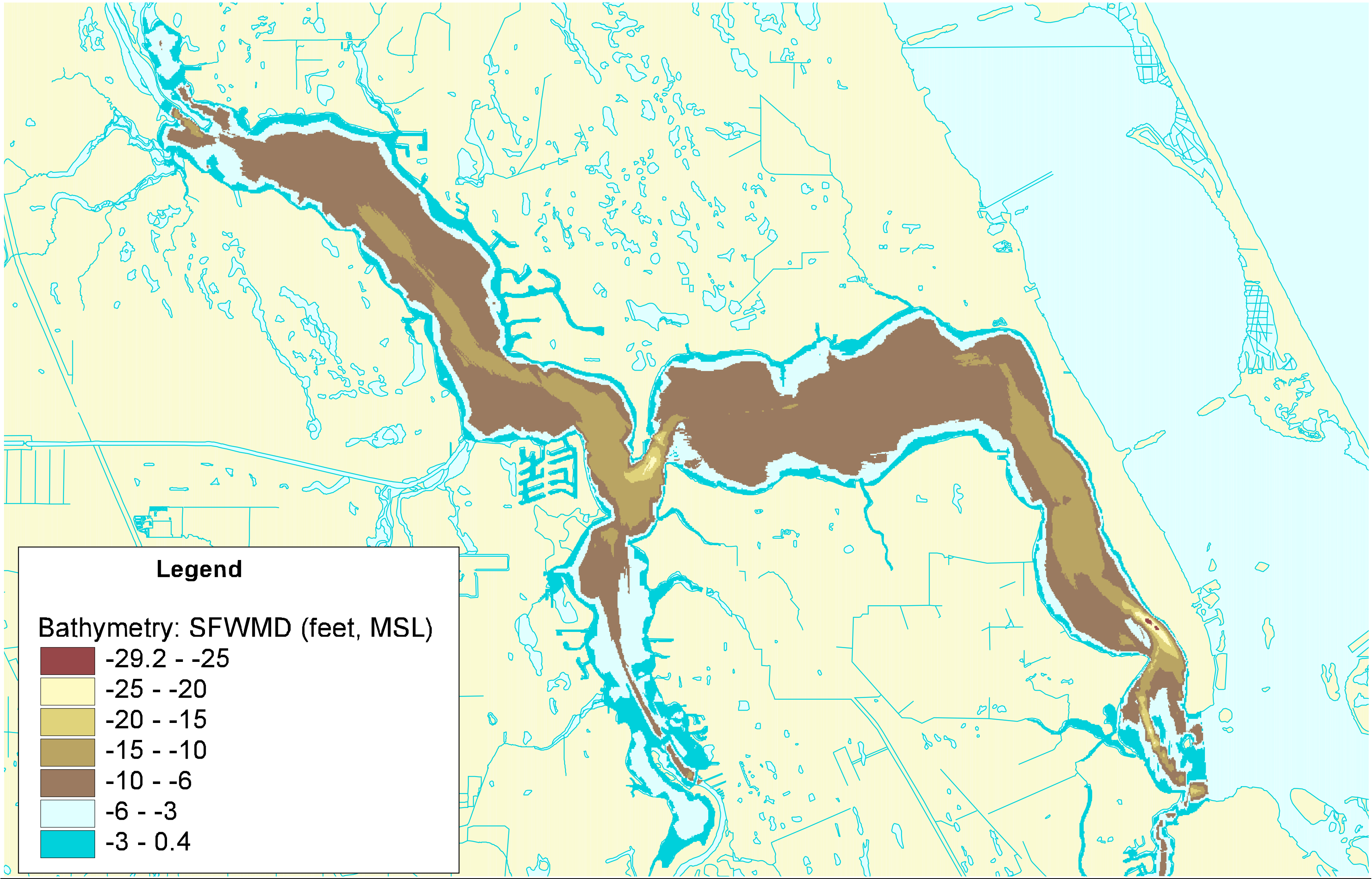
N

1 0 1 2 Miles

Projection: State Plane, East Zone

Submerged Aquatic Vegetation:
Potential Substrate, Historical and Current Occurrence
St. Lucie Estuary, Florida

Figure 7-1



URS Greiner Woodward Clyde

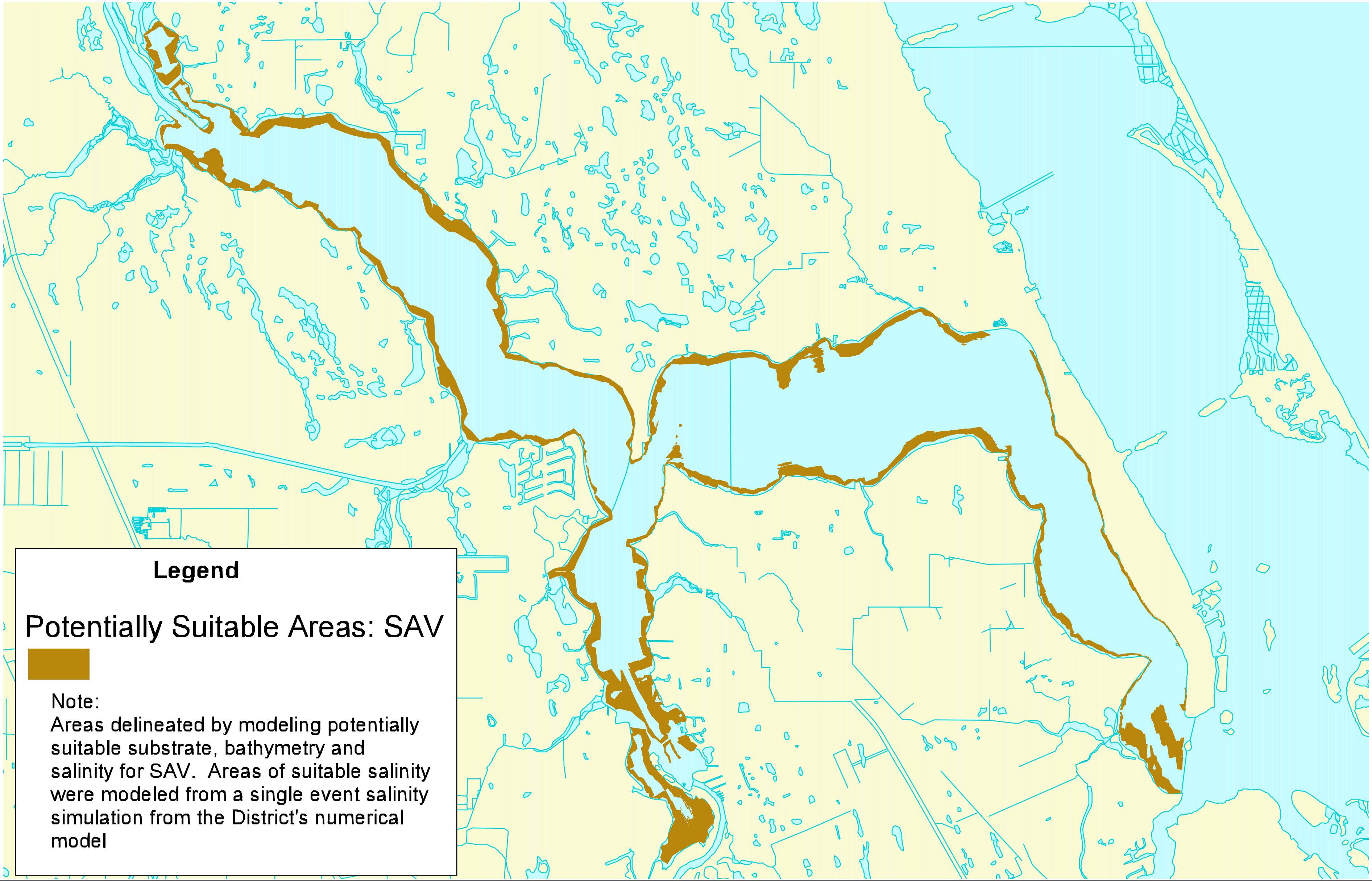
1 0 1 2 Miles

N

Projection: State Plane, East Zone

Bathymetry
St. Lucie Estuary, Florida

Figure
7-2
p. 7-6



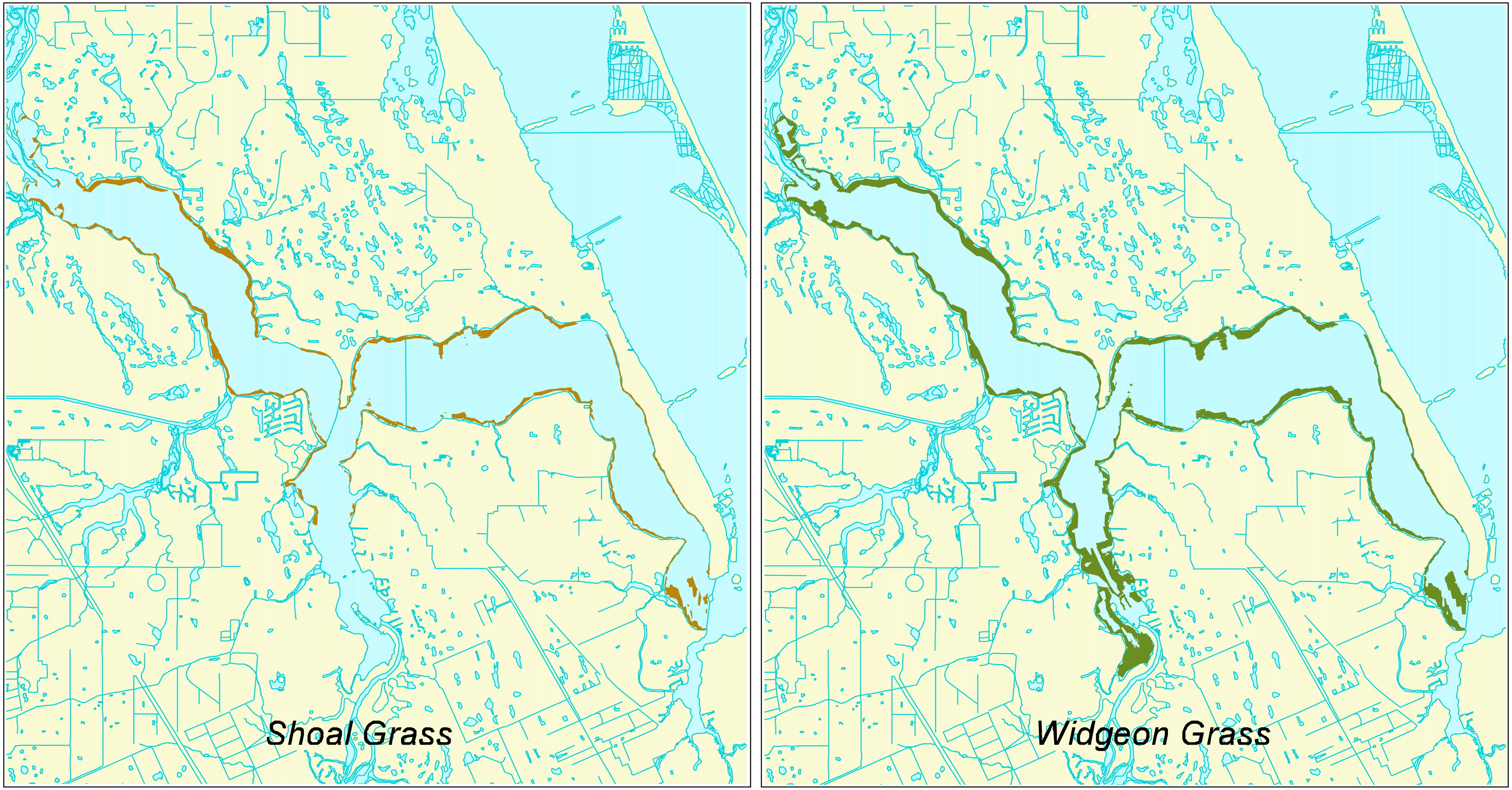
URS Greiner Woodward Clyde

1 0 N 1 2 Miles

Projection: State Plane, East Zone

Potentially Suitable Areas For SAV
St. Lucie Estuary, Florida

Figure 7-3



Legend

- Suitable Areas Shoal Grass
- Suitable Areas Widgeon Grass

URS Greiner Woodward Clyde

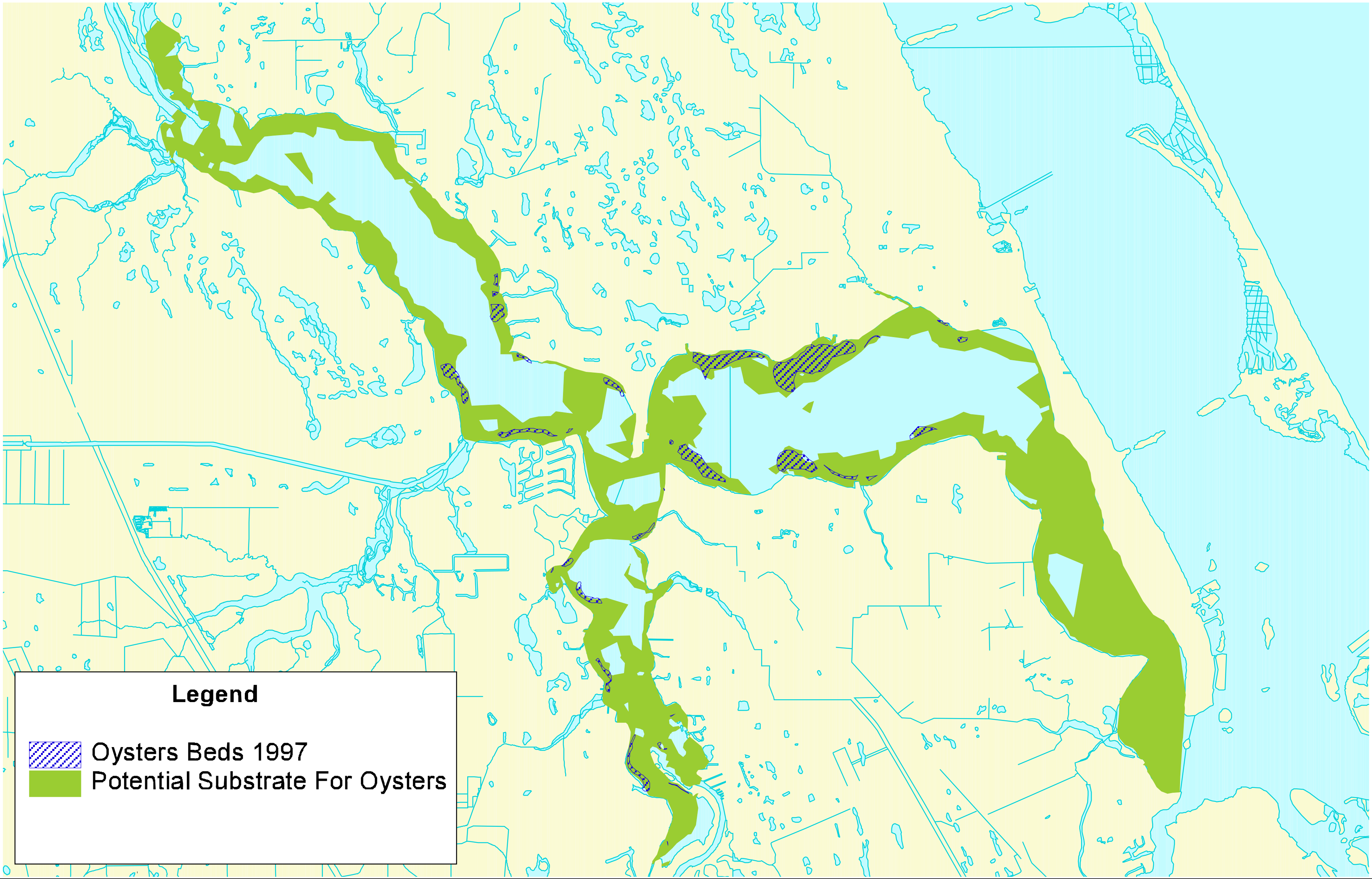
N

1 0 1 2 Miles

Projection: State Plane, East Zone

Potentially Suitable Areas For
Shoal Grass and Widgeon Grass
St. Lucie Estuary, Florida

Figure 7-4



URS Greiner Woodward Clyde

N

1 0 1 2 Miles

Projection: State Plane, East Zone

Areas of Potentially Suitable Substrate
For Oysters And 1997 Surveyed Oyster Beds
St. Lucie Estuary, Florida

Figure
7-5
p. 7-9

8.1 DATA REQUIREMENTS

8.1.1 Bathymetry

The digital bathymetry files supplied by the District arrived too late for a thorough review, but based on a cursory review, it did not appear to show as much shallow zone in the North Fork as we noticed in field surveys. It is recommended that the bathymetry be reviewed and checked against other existing sources for consistency.

8.1.2 Substrate

The substrate shaded contour map used for the suitability analyses was generated from the field survey point data using the TIN method. For this generation, each substrate class was given a numerical ranking based on approximate grain size (i.e. muddy fine sand - 5, muds - 6, muck - 7). In the generation of the map, ArcView's 3-D Analyst was used to interpolate between existing data points and assigns an intermediate class number between the points. In some cases, there are fairly sharp breaks between substrate types and both sides of the break were not always sampled, particularly where one side was considered to be an unsuitable substrate like muck. In the map generation, the area between two sampling points with sands (5) and muck (7) may have been given a value of 6 (muds), even though substrate went directly from sand to muck. Absolute accuracy of the map is always a function of the density of sampling points, and any additional data increases accuracy. The field sampling data is relatively dense in the shallow areas most suitable for oysters and SAV, but filling in some of the gaps in the less suitable areas would reduce inaccuracies caused by interpolation in map construction. Additional field surveys in specific areas could increase accuracy. Several existing data sources have data which is compatible and could be used to fill in these gaps without further field work. These include:

- ♦ Substrate data from the Martin County Environmental Studies Center from 1987 to 1998.
- ♦ Substrate data in Haunert (1988), Philips and Ingle (1960), Shropp, *et al.*, (1994).

Most of this data is not geo-referenced to the level of the field data, but in many of the large expanses of similar substrate type, this level of accuracy is not needed. It is recommended that the substrate data from the above mentioned studies be digitized and added as a data layer to the SLE GIS data base, converting the substrate descriptions to the closest substrate category used for this project. The various coverages could then be merged or intersected to produce more detailed coverages of substrate.

8.1.3 Light Penetration

Very limited Secchi depth measurements were taken during this project, but the limited results indicate that light penetration may be a very major limiting factor in the establishment of SAV in the SLE. Substrate and salinity, particularly in the North Fork and South Fork areas, appears to be potentially suitable for at least some SAV species. Because of the wide ranges of salinity tolerance of various species, at least one species should be able to exist under the salinity conditions in most of the SLE, assuming relatively stable salinities. It seems likely that another factor may also be limiting SAV occurrence, and that light penetration may be the most likely factor. Light penetration monitoring should be considered in some form to better define the photosynthetically active zone and potentially suitable areas of the SLE.

8.1.4 Shoreline Features and Piers

The shoreline features survey appears to include most of the information needed to assess adjacent conditions. Recommendations for future shoreline surveys include the following:

- Adding a length of segment field to the date base prior to field surveys (this was added to the data in post-processing for this project),
- Using a very shallow draft boat and poling or paddling the shoreline to allow for more efficient close approach to the shore to increase location accuracy. The SLE has many extensive shallow shelf areas that made approach under motor very difficult and time-consuming, as well as causing bottom disturbance.

The existing pier survey locations appear to be very accurate, based on comparison to the U.S. Geological Survey's 1995 Digital Ortho Quad (DOQ) photographs. The pier GIS data base can be compared to these photos to determine the change in pier number and location between 1995 and 1997. It is recommended that any future DOQs that are obtained be added to the data base to provide a means to update pier information without field surveys.

8.1.5 SAV

SAV resources in the SLE are extremely low, based on results of the 1997 field survey. However, this survey was conducted in the late summer season, after the prime water clarity period. There had been unconfirmed reports of possible occurrences of minimal amounts of SAV in other locations early in the season. Additional surveys conducted earlier in the season may identify other potential locations of SAV appearance.

8.1.6 American Oysters

This project has identified the major oyster concentrations and distribution range in the SLE. Now that the locations have been found, future studies are recommended to characterize the population and identify factors relevant to management and restoration of oysters in the SLE. The following studies are recommended to develop this information:

- *Characterization of individual oyster beds*. This study produced a qualitative characterization of oyster resources sufficient to estimate total population and areas of greatest concentration, but a more quantitative characterization should be developed. This should be based on quadrat studies sufficient to develop a statistical profile of the resources in each bed. This would allow a size class or age class distribution determination for both live and dead oysters which would help to identify mortality patterns and the frequency at which periods of mortality occur at different locations in the estuary. It will prove a baseline against which future population size can be monitored.

- *Monitoring of oyster mortality and recently dead oysters.* Periodic surveys to identify recently dead oysters are recommended to aid in determining relative mortality among locations and periods in which mortality or above average mortality occur. Such data may be used to correlate mortality patterns to environmental conditions and events in the SLE.
- *Determination of peak spawning periods and critical seasons for juvenile survival.* As mentioned previously, oyster larvae and juvenile life stages are more susceptible to salinity extremes and fluctuations than adult oysters. Therefore the periods in which eggs, larvae, and juvenile stages are most abundant are periods in which extremes and fluctuations should be avoided. Currently, there is no data on the reproductive cycle of oysters in the SLE. Based on data from similar areas, it is likely that the spawning season lasts from spring to fall, with the main peak around late spring and a possible secondary peak in early fall. A more definitive identification of these critical events is necessary to define periods for which salinity management efforts should concentrate. We feel that control of salinity in the SLE for prolonged periods will be very difficult to achieve. However, to maintain or establish a sustainable oyster resource, it is crucial to stabilize salinity during these critical life history periods. Information on spawning periods and distribution of spawning activity within the SLE is regarded as one of the most important data needs, in order for salinity to be managed in the most effective manner.

8.2 SUITABILITY ANALYSIS

8.2.1 Substrate

Use of a more detailed data base (Section 8.1.2) in the suitability analyses may lead to a more refined determination of potentially suitable areas for oysters and SAV.

8.2.2 Salinity

A major point discussed in this report and the earlier literature survey is that, particularly for oysters, the critical factor in survival tends to be the degree of fluctuation and the rapidity or rate of change in salinity rather than the absolute salinity concentration. Because of the wide possible physiological tolerance range of oysters, use of an absolute or static salinity value appears to be of little use in predicting the suitable areas of the SLE. It is very highly recommended that the salinity modeling efforts include a mechanism to define possible salinity ranges at each location, as well as an ability to estimate the rate of change at any location. This would require estimates of salinity under numerous flow conditions. It would also require sufficient temporal resolution to define the rate of change, as well as to define salinity conditions at time periods found to be most crucial for population survival (see Section 8.1.6).

8.2.3 SAV Suitability Analysis

Most of the SAV suitability analysis reported in this report is based on evaluation of suitability of all reviewed SAV species. However, no one species can exist throughout the "potentially suitable" areas, and the estuary cannot be managed based on this wide range. The literature review report indicated that salinity conditions for the true seagrasses are likely to occur only in a relatively small portion of the Lower Estuary under virtually any potential flow conditions, while most shallow zones suitable for SAV occurrence are upstream of this area. Consequently, SAV species that are more adapted to lower salinity regimes may offer the greatest potential for establishment of submerged vegetation in the SLE. It is recommended that additional effort be given to evaluating these species, especially widgeon grass, for suitability in the SLE. Shoal grass has the highest potential for the Lower Estuary areas.

The GIS interface system developed for this project makes it possible to perform suitability analysis for any of the individual species or combinations of species. Suitability criteria have been developed in this study for each of the individual species. Various combinations of these criteria can be utilized, and the criteria can be modified or refined based on additional data or user needs. The suitability analysis results shown in this report should not be construed as an absolute condition. The tools that have been provided are intended to be used as a dynamic system to refine criteria and management strategies over time. It is recommended that the suitability analysis be performed for individual species or groups of related species and refined over time, using various scenarios of substrate bathymetry, and salinity. Utilizing dynamic simulations of salinity ranges and change rates to refine the SAV analysis is also recommended.

Light regime also appears to be a major restriction to SAV in the SLE. The bathymetry analysis tends to include the effects of light intensity, but additional specific data on light conditions and requirements of individual species could add to the detail of the analysis.

8.3 GIS AND DATA BASE SYSTEMS

The purpose of using GIS technology is to promote and to facilitate effective analysis and presentation of data collected in the study. However, as with any data collection activities, the end result of using GIS is no better than the “quality” of the data itself. If the goal is to identify long-term trends and impacts to estuarine resources, it is just as important to maintain the data base with precision. In this effort, the GIS data base and user application developed for the study took into consideration practical factors relevant to systems administration and user needs.

From the administrative perspective, the GIS data base was developed within a structured design such that data base expansion and data changes can be made with minimal effort. Similarly, the GIS user application was developed as generically as possible such that additional functions and/or updates can be made without having to “rewrite” the entire Avenue-based application. The benefit to the user is that data can be retrieved and analyzed with minimal systems-related distractions.

In order to ensure long-term usability, it is recommended that the data base be updated using compatible specifications provided in the GIS Design Documentation. Similarly, it is recommended that the user application be upgraded with future versions of the ArcView GIS.

8.4 MANAGEMENT RECOMMENDATIONS

8.4.1 SAV Management

To effectively assess and manage for SAV resources in the SLE, it must be recognized that different species will be suited for different areas. We recommend that management efforts recognize these differences and evaluate the system on a species by species basis.

Light penetration is also considered to be a significant limiting factor for SAV in the SLE. It is also recommended that salinity and light penetration factors be considered simultaneously in managing for SAV enhancement. Since much of the waters in the shallow zones of the North and South Forks naturally may be highly stained by tannins, a reduced target depth of restoration may be necessary for these areas. If SAV is restricted to exceptionally shallow depths, then wave and boat wake effects and wave reflection from hardened shores may be important considerations in establishment and should be reviewed in developing management strategies. Piers and channels may also have a relatively larger effect if suitable zones are limited.

Salinity management for SAV should concentrate both on stabilizing average concentrations and reducing the rate of change. It is recommended that management efforts concentrate on shoal grass and widgeon grass, since these species appear to offer the greatest potential for colonization of large areas. Consideration may be given to further research on the suitability of redhead grass for this region since it may be better able to tolerate mucky substrates than the species found in the system.

8.4.2 AMERICAN OYSTER MANAGEMENT

Although the field study identified no significant predation or other factors in the higher salinity areas, the scarcity of oysters in the Lower Estuary appears to support the literature based conclusions that there is an operational high salinity tolerance limit and that oysters may never occur in abundance in the lower Middle Estuary or the Lower Estuary. The results indicate that management and restoration efforts should focus first on the upper Middle Estuary, the lower half of the North Fork, and parts of the South Fork removed from the St. Lucie Canal and main navigation channel.

Areas of greatest potential reproductive activity should be defined. These are likely to be areas where there is a combination of maximum oyster maturation (to maximize gamete production) and suitable conditions for survival of immature life stages. Management of the magnitude and rate of salinity change is critical for a sustainable oyster population in the SLE. In the event that large scale or continuous amelioration of changes is not possible, then micro-management in these critical areas and during critical life cycle periods may be adequate to maintain a population. Although oysters may reach a sexually mature stage within one growing season, significant reproduction capability requires two to three years to develop. Thus, prime areas would need to be protected from high mortality events for at least this interval to maintain a sustainable population.

This study, supported under contract C-7779 from the SFWMD and Indian River Lagoon Surface Water Improvement and Management Plan (SWIM), combined a literature and existing data search to describe the present and historic conditions of the SLE and the tolerances of several SAV species and the eastern oyster to salinity, substrates, and other factors with a field survey of substrates, SAV and oyster distribution in the SLE to characterize these resources and provide recommendations for management and enhancement of SAV and oysters in the SLE.

The field survey was conducted in the summer and autumn of 1997. The data from the field surveys was geo-referenced in the field with a 5m or better resolution differential GPS system and directly entered on a laptop computer in ARCINFO compatible format. The data was then entered into an ARCINFO-based GIS system.

An ARCVIEW-based interface was developed specifically for the SLE system. This GUI-based interface contains shortcuts and specific tools for performing “what if” analysis and simulations to evaluate potentially suitable areas for SAV and eastern oysters in the SLE. Additional data summarizing historical SAV and oyster distribution has been entered into the GIS coverages. Detailed bathymetric data was obtained from SFWMD, and a contour coverage of substrate types was developed from the field survey data. Data from a SFWMD salinity model can be input directly into the GIS data base to allow assessment of various combinations of substrate, water depth, and salinity conditions in relation to tolerances of various species.

The results indicate that SAV resources in the SLE are currently restricted essentially to narrow bands along the Lower Estuary downstream of the Sewells Point Bridge that are composed of shoal grass with Johnson’s seagrass and a few star grass plants. A few plants of widgeon grass, common water nymph, and wild celery were found in the South Fork in the vicinity of Danforth Creek and the Palm City Bridge, but no beds were found. Numerous areas of oyster beds were located, totaling over 200 acres. These are concentrated in the upper Middle Estuary off Stuart and Rio and in the lower half of the North Fork and throughout the South Fork in smaller amounts. The beds consist of scattered shells and small clumps rather than tightly cemented oyster “reefs”. The proportion of live oysters was low, with an average density probably near 1 oyster per square meter. In most areas, most shells were less than 5 cm in length, indicating that most oysters die before reaching full sexual maturity and reproductive capacity. The most productive areas appear to be in the upper Middle Estuary area.

Preliminary modeling of potentially suitable areas of the SLE for SAV and oysters indicate that at least some species of SAV should be suitable for the shallow zones with sandy or mucky sand substrates throughout most of the estuary. The model salinity data was based on only a single static concentration gradient and did not account for changes in salinity over time. It appears that the magnitude and rate of change are important in controlling establishment of SAV, but sufficient salinity results are not yet available to further assess potentially suitable areas. The literature review indicates that shoal grass and widgeon grass should be the most suitable SAV species in much of the SLE system. Light penetration also appears to be a significant controlling factor.

Model results with the single salinity condition indicate that the areas where the greatest oyster resources were found in the field survey are probably the most suitable oyster locations in the estuary. The scarcity of fully mature oysters is probably due to the salinity fluctuations, which causes mortality before a large reproductive base can be attained. The field data supports literature based conclusions that areas deeper than 7 to 8 feet contain muck or ooze sediments that are unsuitable for both oysters and SAV. In addition, these areas have low available light and low dissolved oxygen conditions, further restricting oysters and SAV from these deeper zones.

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