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Integrating in situ *quantitative geographic information tools and size-specific, laboratory-based growth zones in a dynamic river-mouth estuary*

MARK S. PETERSON[a,*], MARISA R. WEBER[b,†], MELISSA L. PARTYKA[a,‡]
and STEPHEN T. ROSS[b,§]
[a] *Department of Coastal Sciences, The University of Southern Mississippi, Ocean Springs, Mississippi, USA*
[b] *Department of Biological Sciences, The University of Southern Mississippi, Hattiesburg, Mississippi, USA*

ABSTRACT

1. The ultimate determination of coastal habitat suitability requires the integration of both dynamic (i.e. water mass characteristics) and stationary (structural) habitats. An approach using real-time streamed data collection, remote sensing, and GIS modelling to compare and contrast seasonal and spatial patterns in these habitat components of the eastern and western distributaries of the lower Pascagoula River estuary is described.

2. Structural and dynamic habitat characteristics are described using GIS and integrated with published growth data on juvenile mullet (*Mugil* spp.) and spot (*Leiostomus xanthurus*) to reveal zones of accelerated growth. Both mullet and spot had their greatest growth when water temperature and salinity (dynamic habitat) were physiologically optimal. The lack of spatial difference in the dynamic habitat between distributaries resulted in no growth zone differences for both species.

3. The integration of the growth zones with the structural habitat component showed that the west distributary, with its greater availability and reduced fragmentation of main channel marsh edge, should provide a greater area of essential fish habitat than the east distributary for juvenile spot, a marsh-edge associate. Because juvenile mullet are less associated with structural wetland habitat, growth zones and the stationary (structural) habitat were not integrated.

4. The approach of integrating real-time geo-referenced water quality data with regional fish growth-rate data is an important step towards a quantitative understanding of the hierarchical nature and inherent variability of dynamic coastal environments. The use of this holistic approach

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*Correspondence to: Mark S. Peterson, Department of Coastal Sciences, The University of Southern Mississippi, 703 East Beach Drive, Ocean Springs, Mississippi 39564-7000, USA. E-mail: mark.peterson@usm.edu

[†] Current address: Post, Buckley, Schuh & Jernigan, Ecology Division, 1250 Wood Branch Park Drive, Suite 300, Houston, Texas 77079, USA.

[‡] Current address: Center for Marine Science, 5600 Marvin Moss Lane, University of North Carolina — Wilmington, Wilmington, North Carolina 28409, USA.

[§] Current address: Museum of Southwestern Biology, Department of Biology, MSC 03-2020, University of New Mexico, Albuquerque, New Mexico 87131, USA.

should lead to more effective management of estuarine systems, especially in regard to potential impacts within the estuary's watershed and to its coupling with offshore environments.

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INTRODUCTION

Most estuarine-dependent fishes and invertebrates (nekton) have complex life histories exemplified by spawning offshore (or nearshore), by larvae recruiting into estuaries and settling into nursery habitat where they grow to late juveniles or adults, followed by migration of adults back offshore to spawn (Beck *et al.*, 2001). The integrity of these coupled coastal landscape features is vital for sustained fishery production. In the last decade, there has been a paradigm shift from defining nursery habitat based solely on structural features (e.g. marsh edge, open water, oysters, seagrass, etc.) associated with increased feeding opportunities and protection from predators, to one based more on spatially and temporally dynamic environments within the estuarine landscape (Peterson, 2003; Stoner, 2003; Browman and Stergiou, 2004). Success within this holistic view is directly linked to habitat diversity, and habitat quality and quantity, all nested within a framework of abiotic variability (Simenstad *et al.*, 2000; Stoner *et al.*, 2001; Manderson *et al.*, 2002, 2003; Peterson, 2003; DeLong and Collie, 2004).

Coastal ecosystems worldwide are under increasing pressures from human activities (Vitousek *et al.*, 1997; Jackson *et al.*, 2001; Sala *et al.*, 2004), and numerous estuarine habitats have been (or are) degraded to some extent. Without a better understanding of habitat and potential prey distributions relative to water quality variables, including temporal and spatial variability, it is difficult to assess habitat function and thus the status and trends in habitat quality and productivity. Effective management requires an understanding about how natural and anthropogenic sources of variability in abiotic variables affect fish (and other nekton) population dynamics (Rose, 2000). In fact, the direction, extent and scale of environmental variability within estuaries may be a defining characteristic in itself (Boyer *et al.*, 1997).

Part of the difficulty of examining large coastal features is how the mosaic of habitat types in an estuarine landscape is viewed. One approach to assessing this estuarine mosaic is to view it holistically as an environment possessing both dynamic (short-term physical-chemical and biotic variability, salinity, prey fields) and stationary (long-term structural variability, sediment type, wetland context) components (Peterson, 2003), each having its own influence on nekton. The timing, positioning and the amount of overlap between the dynamic and the stationary components may determine the survival and growth rates of juvenile nekton as they pulse into the estuary.

Recently published research has taken a number of different approaches to examining habitat holistically. For example, Stoner (2003) argued that functional habitat for queen conch juveniles in the Caribbean region was determined by spatio-temporal interaction of environmental features such as depth, bottom type, salinity, and temperature and ecological processes such as oceanographic features, prey fields, biochemical prey cues which can be localized, patch size, local topography, size-related shift in habitat use, and types and abundance of predators which form a 'complex array of variables that affect larval delivery, settlement, growth and mortality'. Clark *et al.* (2004) used historical data and geographic information system (GIS) tools to incorporate hydrologic variables and habitat type into a model that indicated both were important in predicting density of postlarval brown shrimp in Texas.

Because organisms, especially those in estuaries, generally live in a spatially and temporally dynamic landscape, GIS modelling is becoming more widely used in the management of resources owing to its versatility and capability of integrating multi-scaled ecological processes. Most current models rely on a single type of static data such as point source data (Keleher and Rahel, 1996; Gallaway *et al.*, 1999; Rubec *et al.*, 1999; Sabol *et al.*, 2002; Clark *et al.*, 2004) or interpretation of aerial imagery (Lathrop *et al.*, 2001). Real-time geo-referenced data collection shows promising results in data acquisition in different aquatic environments and at different scales, such as obtaining water quality data along the three-dimensions of the system, integrating fisheries data sets with water quality mapping, delineating essential fish habitat (EFH) or locating sites for Marine Protected Areas. However, similar oceanographic equipment is typically expensive (Greenstreet *et al.*, 1997; Sieburth and Kester, 1997). Recently, however, Ross and Ott (2001) and Hains and Kennedy (2002) have developed cost-effective methodologies for *in situ* rapid data collection using towed instrument arrays. We wanted to build on these techniques by combining the conceptual model of dynamic and stationary environmental linkages (Peterson, 2003) with remote sensing and GIS technology. In this paper habitat is treated hierarchically, with juvenile habitat being the broadest available type where fish recruit as young, EFH being restricted to places where spawning, breeding, feeding, and growth to maturity occur, and nursery habitat being the narrowest and defined as a place where juvenile stages contribute more per unit area to the production of individuals that subsequently recruit to adult populations, on average, than production from other habitats in which juveniles may occur (Beck *et al.*, 2001; Minello *et al.*, 2003). The goal was threefold: (1) to describe the dynamic and stationary (structural) habitat in the study area; (2) to integrate the stationary and dynamic habitat data; and (3) to integrate the dynamic and stationary habitat data with published growth data on early juvenile mullet (*Mugil* spp.) and spot (*Leiostomus xanthurus*) collected locally to reveal zones of accelerated growth in the lower Pascagoula River estuary, Mississippi, USA. Overall, in this paper we attempt to develop an approach for integration of stationary and dynamic habitat data, not to determine ideal EFH for juvenile fish. Thus, the latter objective is used to illustrate the utility of the approach and not to do a complete analysis.

MATERIALS AND METHODS

Study area

The lower Pascagoula River is a micro-tidal river estuary located in south-eastern Mississippi, USA (Figure 1). As a whole, this is a relatively undisturbed watershed of world recognition, having been distinguished as the only large (i.e. $>350\,\mathrm{m^3\,s^{-1}}$ virgin mean annual discharge) river system in the contiguous 48 states with no dams or impediments to movement on the main channel (Dynesius and Nilsson, 1994). The Pascagoula River Basin drains about 24 844 km^2 and splits into two distributaries about 23 river km north of the Gulf of Mexico (GOM). The two distributaries differ at their connection with the GOM in that the east branch is bordered by a large shipyard and is dredged to allow ship traffic, whereas the west branch has a relatively non-impacted shallow marsh with *Juncus roemerianus* and *Spartina alterniflora* bordering the shoreline. The lower river experiences wide fluctuations in flow as well as salinity, water temperature and other abiotic factors, and thus is an excellent watershed to use as a model for studying the relationship between dynamic and stationary habitat types and how these fluctuations influence fish growth and EFH for estuarine-dependent nekton.

Stationary habitat mosaic and classification

Stationary (structural) habitat was identified using false-colour infrared Quickbird® satellite imagery with 2.8 m spatial resolution. Imagery was supplied in geo-referenced format and projected in Universal Transverse Mercator (UTM) coordinates for zone 16N using the World Geodetic System (WGS) 1984 datum. The study area consisted of nine individual images mosaicked without feathering using ENVI® 3.2 software. The mosaic was built using a nearest-neighbour resampling method.

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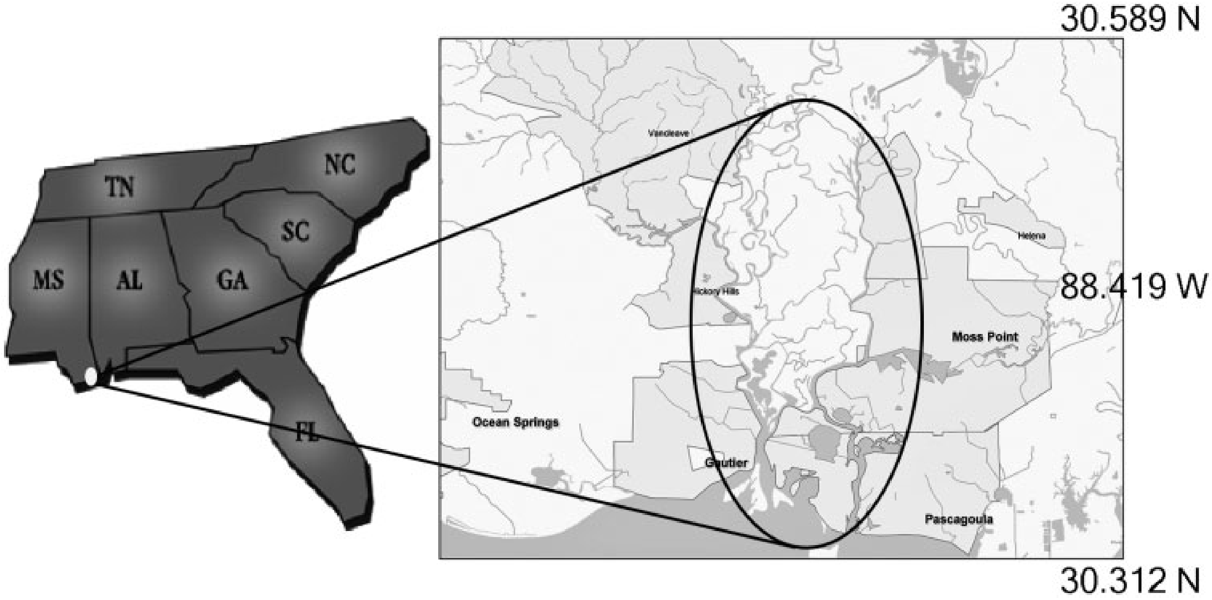

Figure 1. Map of the lower Pascagoula River estuary, Mississippi, USA.

An unsupervised classification method with 30 original classes, a maximum of 15 iterations and a convergence threshold of 95% was conducted on the mosaicked base map in ERDAS Imagine® 8.6. Types of land use and land cover (LULC) were allocated for each cluster using the raster attributes editor, while the classifier signature editor was used to collapse clusters into five classes based on visual interpretations of the preliminary classification and personal knowledge of the study area. Upland, palustrine forest, wetland forest, and some large scrub-shrub habitats were included in the forest classification, while upland habitats that overlapped with residential areas and industrial areas including sandbars and roads were designated as anthropogenic features. All water was classified into a single habitat type. Marsh habitat was divided into low and high marsh classifications based on differences in spectral reflectance in the near-infrared band. The high marsh category had an intermediate reflectance between low marsh and forest. It was characterized by higher reflectance plants such as *Phragmites australis*, *Typha* sp., *Spartina cynosuroides* and taller *Juncus* sp. and *Spartina* sp. present on the berm adjacent to the marsh edge. Low marsh habitat had a lower near-infrared reflectance and was characterized by emergent marsh habitats and inner marsh habitats. Details of these characterizations can be found in Weber (2004).

The final five merged categories were high marsh, low marsh, forest, water, and anthropogenic structures. A final supervised classification was then conducted on the five classes based on the spectral signature of each category using a maximum likelihood algorithm. An accuracy assessment of the final classified map was conducted by using a set of 150 stratified random points generated over the study area using ERDAS accuracy assessment. Percentage accuracy and KAPPA statistics were computed for each habitat category and all categories combined. KAPPA is a discrete multivariate measure that uses an error matrix to measure the accuracy of map interpretation (Jensen, 2005). Designated pixels and the nine surrounding pixels were analysed for accuracy by comparing the original image to a number of other data resources including the National Wetlands Inventory's (NWI) vector files, black and white aerial photos and personal verification on the ground of the study area (Stehman and Czaplewski, 1998). K values greater than 0.80

(i.e. 80%) represent strong agreement or accuracy between the classification map and the ground reference information. *K* values between 0.40 and 0.80 represent moderate agreement whereas values less than 0.40 represent poor agreement (Jensen, 2005).

Field methods and equipment

Water temperature (°C), salinity (psu), dissolved oxygen (mg L^{-1}), pH, total chlorophyll (mg L^{-1}), turbidity (NTU), depth (m), current speed (m s^{-1}), and latitude/longitude were collected horizontally from March 2003 to February 2004 (March, May, July, October, December, February) and vertically from May 2003 to February 2004 (May, July, October, December, February). An integrated sampling system was used incorporating a YSI-6600 data sonde with attached flow-cell, an ISCO^{TM} peristaltic pump and a Raymarine$^{®}$ L-760 Fishfinder with depth-sounder and DGPS. The system was powered with a deep cycle 12-V AGM battery. All data were instantaneously downloaded to an onboard notebook computer through Nexsens$^{®}$ iChart$^{®}$ v4.006. Duplicate sets of equipment were installed on two separate vessels to allow for concurrent sampling along both distributaries of the lower Pascagoula River. Data for vertical and horizontal profiles were obtained over a consecutive two-day period.

For horizontal samples, water was continuously drawn into the flow-cell through a 9.52 mm internal diameter (ID) polypropylene tube and evacuated down-current through another tube. The intake was set 1 m below the surface at amidships to maintain the intake tube below the surface while the boat was under way and to reduce interface effects such as wind-driven cooling. Each vessel followed a cruise track that provided equal weighting of the east shore, west shore and mid-channel. Specifically, the vessels moved about 500 m upstream along the east side of the channel, about 500 m upstream along the west side, then about 500 m upstream in mid-channel, repeating this pattern over the entire study area (Table 1). Data were collected by the sonde and fishfinder at 1s intervals and the 10 s mean value was recorded within the database. The speed of the peristaltic pump was set such that it took 45 s for a parcel of water to be drawn into the YSI and subsequently evacuated. This 45 s delay was incorporated into the iChart$^{®}$ program to counter the fact that the vessel was in constant motion, alleviating the spatial discrepancy between the locations where a water sample was drawn in and the point of sample detection by the YSI.

Vertical-profile data were collected at designated locations at 1km increments along both distributaries, from the mouths through the extent of the salt-wedge, a minimum of 13 km upstream. Samples were taken at the bottom, mid-water and surface, with exceptions made at locations where shallow depths made sampling at all depths impracticable. A length of 9.52 mm ID tubing was attached to a 9.98 kg concrete weight along with a polypropylene guideline. The weight was quickly lowered from the anchored vessel to the bottom, or a maximum of 9.7 m owing to pumping constraints. Data collection began once the system was cleared of air and continued for 2 min. The ensemble was then raised to the mid-water level for another two minutes and the procedure repeated again at the surface, 15 cm below the waterline. Information on bottom depth (m), sampling depths (m), beginning and ending sampling times and any confounding environmental conditions were recorded in the database.

Table 1. Segment (km) and total track (km) lengths for the western and eastern distributaries of the lower Pascagoula River, Mississippi, USA, plus a grand mean of both segments

River distributary	Mean segment length (km)	Total track length (km)
West river	0.506	34.97
East river	0.536	33.49
Grand mean	0.521	34.23

GIS methods — horizontal profiles

Data streams collected in the field through iChart® software were exported into Microsoft® Excel 2000 for evaluation of missing and extreme values. In the instance of a few missing data points (1–5 missing records; only 1.06% of all records), empty cells were filled with interpolated data based on pre- and post-missing data cell values. If large blocks of data were missing (more than 5 missing records; only 1.07% of all records), the missing records were not used in the analysis. Extreme values (only 0.68% of all records) are defined as those falling two standard deviations outside the range of eight neighbouring data points (four pre and four post) and those data points were replaced using the mean of the eight data points. Each file was exported to Microsoft® Access 2000 (.mdb) and then saved in a dbase format (.dbf), the format used by ESRI® ArcCatalog™ 8.2 to convert the data into an XY feature class for visual interpolation. The resulting coordinate points were spatially referenced in a UTM projection for zone 16N using the WGS 1984 datum.

Interpolations of horizontal data were bound within polygons of each distributary originally generated within ERDAS IMAGINE® 8.6 and exported as arc-interchange files (.e00). Once data were projected on the base map with these river polygons, points south of the polygons were omitted and points falling outside the polygons were moved over the water surface using the edit tools.

An inverse-distance-weighted (IDW) interpolation algorithm was used to convert each point file into grid format. Each horizontal profile was interpolated using the respective polygon of the river as a boundary, with the maximum number of inputs for a cell size of 2.29. Power was set at 2, radius type was variable and search was set at 12 with no maximum distance. Z-values corresponded to the water quality variables being interpolated. The output was a horizontal profile of each collected YSI variable reclassified to match published categories for each variable (Anonymous, 1959; Bricker *et al.*, 1999; Ross *et al.*, 2001; EPA, 2003) for each sampling event ($n = 6$).

GIS methods — vertical profiles

iChart® reports containing data from a single sampling day were exported as comma delineated files (.csv), which were readable by Microsoft® Excel 2000, where they underwent manipulation and consolidation. Data from vertical collections were first partitioned according to location and secondly by depth using recorded sampling times. The data were then trimmed such that all records beyond 2 min, in addition to the first 40 s of sampling were removed, to account for changeover between vertical depths and initial acclimation periods. The mean latitude/longitude and bottom depth for the time spent at each location were calculated and used to geo-reference the three sampling depths; however, the remaining variables were averaged individually within each vertical sampling depth. These mean values were saved as a separate file (.xls) and exported to Microsoft® Access 2000 format (.mdb). The data were converted directly from this format, via ESRI® ArcCatalog™ 8.2, into XY feature class files for visualization.

The point shape files were added to ESRI® ArcScene™ 8.2, a 3-D mapping extension, with the base map of the area as the background. Each point of the shape files contained data from three vertical sampling depths, which had to be separated for visualization. Three copies of the file were added to the scene and data queried such that only one vertical depth's information was displayed. Setting the symbology, base-height and extrusion for each file completed visualization. The symbology refers to the water-quality variable chosen for display as well as the scale and colour scheme used. The base-height and extrusion are characteristics unique to this program and referred to the distance and extent that the symbology would be projected below the base map, mimicking the reality of the water-column. Each vertical depth's data were displayed in relation to the others by manipulating these two characteristics such that the values used were inverse quotients of the sampling depths (e.g. base-height = −(samp_dpth/1000)). Each variety of setting, i.e. vertical depth and symbology, was saved as an individual layer file (.lyr) for ease of recall.

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The final maps produced for presentation of vertical data were made by displaying one water-quality variable for each sampling event set over a grey-scaled image of the original base map. The whole scene was then rotated and angled to give the clearest view of each location's data. This 3-D scene was exported as a 2-D image (.jpg) and added to a blank presentation in ESRI® ArcMap™ 8.2.

Growth model

The water temperature and salinity were selected to be mapped from the array of water-quality variables because water temperature (controlling factor) and salinity (masking factor) (*sensu* Miller *et al.*, 2000) strongly influence growth in fishes. Moreover, size-specific published laboratory growth rate data of young (<25 mm total length (TL)) juvenile mullet, *Mugil* spp. (64.1% *M. cephalus* and 35.9% *M. curema*) and young (15–20 mm TL) juvenile spot, *Leiostomus xanthurus* (Peterson *et al.*, 2000a, 2004) were projected onto the horizontal maps of water temperature and salinity patterns because they are numerically abundant, and their response to water temperature and salinity are published from this region. Growth rate results of these controlled experiments were entered into Arcview to delineate potential growth zones (GZs) for young juvenile mullet and spot in the lower Pascagoula River estuary, Mississippi. These growth zones were extrapolated spatially (east and west distributaries (south of Interstate 10)) and temporally with Arcview for the months that this size juvenile mullet (March, May and July; Render *et al.*, 1995; Ditty and Shaw, 1996) and juvenile spot (December, February, March; Pattillo *et al.*, 1997; Peterson *et al.*, 2000b) are generally abundant in the estuary. This was conducted by computing a spatial query with water temperature and salinity layers for each month sampled and reclassifying each layer into a new coverage to create three maps that represent variation in growth zones for juvenile mullet and spot. Growth zones in the GIS model were determined by considering the laboratory water temperature and salinity conditions (important controlling and masking factors; Miller *et al.*, 2000) as midpoints of a range based on field values in the appropriate time period. The resultant growth zones were categorized as primary (GZ1) to quintary (GZ5) growth zones with GZ1 representing the highest potential growth rates and GZ5 the lowest potential growth rates (Table 2). These maps were used to explore temporal and spatial differences in growth zones for each species.

Finally, the stationary (satellite image classification) and dynamic habitat (estimated growth zones) components for juvenile spot were linked by calculating the area of overlap between the growth zone

Table 2. Growth zones generated from laboratory growth expressed as mean (± sem) percentage increase in wet weight by species (Peterson *et al.*, 2000a, 2004) corresponding with salinity and water-temperature data collected from the lower Pascagoula River, Mississippi, in 2003–2004

Growth Zone	Temperature (°C)	Salinity (psu)	Mean Relative Growth Rate (%; ± sem)
Juvenile mullet, *Mugil* spp. (<25 mm TL)			
1	27–32	10–18	79.01 (5.24)
2	27–32	18–30 & <10	76.34 (5.18)
3	22–27	>10	68.66 (5.72)
4	22–27	<10	55.72 (6.56)
5	14–22	any salinity	46.75 (6.29)
Juvenile spot, *Leiostomus xanthurus* (15–20 mm TL)			
1	19–27	>10	339.06 (11.72)
2	19–27	<10	246.86 (29.48)
3	14–19	10–18	223.71 (4.24)
4	14–19	0–3 & >18	182.41 (4.24)
5	8–14	any salinity	65.39 (3.78)

polygons with low marsh (emergent marsh) and anthropogenic structures (as an indicator of habitat fragmentation). To achieve this, the classified raster image was converted into vector format using the Spatial Analyst extension. Low marsh and anthropogenic structure habitat types were selected only from the bank-to-bank width of each distributary and converted to individual shapefiles. Lastly, the growth zone files were intersected with shoreline habitat and the area of overlap (m^2) was calculated using XTools extension.

RESULTS

Stationary (structural) habitat mosaic and classification

Out of the five stationary (structural) habitat types identified in the study area for the entire lower Pascagoula River estuary, forest was the most abundant habitat (49.24 km^2), followed by water (45.04 km^2), emergent low marsh (25.54 km^2), high marsh (20.58 km^2) and anthropogenic features (15.24 km^2) (Figure 2). An accuracy assessment of the total study area showed that 86.67% of the habitat features were classified correctly and there was a strong agreement between the classification and the ground reference used (KAPPA = 0.8263). Most discrepancies occurred when low and high marsh classes were confused with one another (Table 3).

Dynamic habitat maps and GZs patterns

Dynamic habitat maps were generated for all variables measured by the integrated system (see Table 4 with all summary statistics) but for the purposes of this paper the focus is on water temperature and salinity only as there were quality laboratory-based growth data available from the region. These generated dynamic habitat maps illustrate variability either on a spatial, temporal or both scales, as shown by spatial variation in salinity characteristics between the east and west distributaries in the same month (Figure 3(A)). Likewise, vertical stratification also existed along the length of each distributary of the system, with the channellized east branch allowing penetration of the salt wedge further up-estuary than the west (Figure 3(B)).

The construction of the final growth zone maps required an integration of the water temperature and salinity patterns (e.g. Figure 4) with the projected size-specific growth rate data from the literature. Maps based on growth zones illustrated the spatial and temporal dynamic nature of the environment potentially encountered by early juvenile mullet and spot (Figure 5). For example, early juvenile mullet grew faster when exposed to high water temperature and salinity in the laboratory; therefore, the GIS model predicted the highest growth zones during May and July. Primary growth zones (GZ1 and GZ2) were located on the east distributary at the mouth of the river and in the middle portion of the river in May (Figure 5), illustrating the mosaic of dynamic habitat characteristics within and between distributaries. Fishes are poikilotherms and have reduced metabolic capabilities in cold temperatures (Jobling, 1993) and thus early juvenile mullet are not expected to grow at high rates during March owing to the low temperature experienced during this month prior to peak recruitment into the estuary. Finally, early juvenile mullet are less associated with stationary (wetland structure) habitat at this stage (<25 mm TL) as they are more pelagic and feed predominantly in the plankton (Eggold and Motta, 1992). In contrast, the GIS model showed that March was the best month for early juvenile spot to achieve higher growth zones. During March, the east and west distributaries were similar in that the full area of each branch had GZ2 abiotic characteristics (Figure 5). December and February had low water temperature and thus growth rates were reduced. Early juvenile spot, however, require stationary habitat (wetland structure) during this stage of development (Hales and Van Den Avyle, 1989; Patillo *et al*., 1997) and thus the stationary habitat is important to incorporate into a more complete understanding of EFH (see below).

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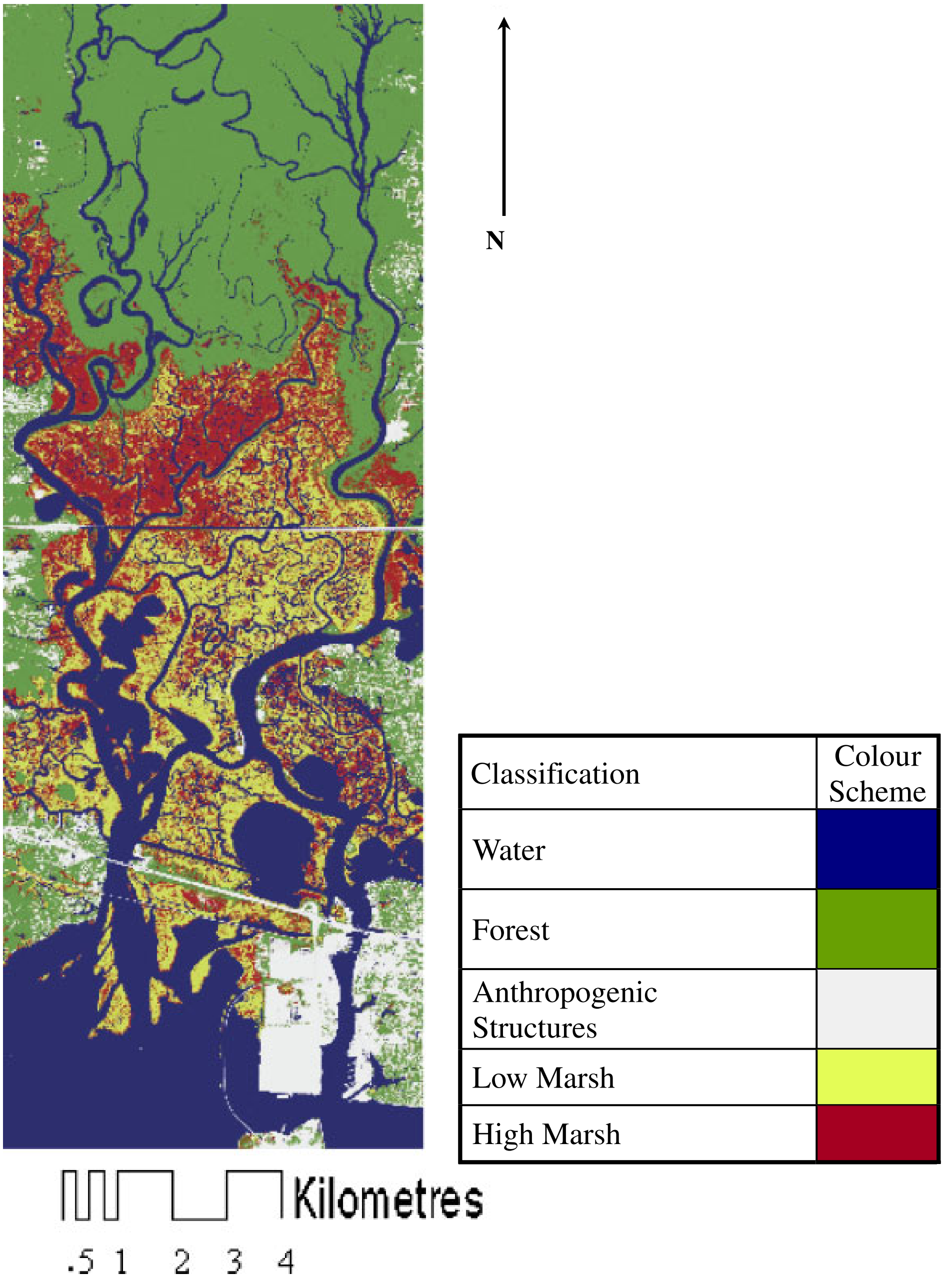

Figure 2. Final supervised classification base map of the lower Pascagoula River estuary, Mississippi, USA.

Linkage of stationary and dynamic habitat components for early juvenile spot showed that from December through March (peak recruitment period), water temperature and salinity did not vary much between east and west distributaries and thus the dynamic component (growth zones) did not vary (Figure 5). Although water temperature and salinity were homogeneous throughout the system at those times,

Table 3. Percentage accuracy for habitat classification by habitat category with KAPPA values

Habitat category	Accuracy (%)	KAPPA
Forest	93.6	0.9070
Water	100	0.9049
Low marsh	72.4	0.8017
High marsh	68.8	0.4963
Anthropogenic features	82.4	0.9248

Table 4. Summary of all horizontal water-quality variables by collection date and distributary location (east and west). Values are presented as the mean ± 1 standard deviation for the entire east (E) or west (W) distributary (Dist.). DO = dissolved oxygen

Variables	Dist.	March 03	May 03	July 03	October 03	December 03	February 04
DO (mg L^{-1})	E	8.59 ± 0.28	7.50 ± 0.44	5.31 ± 0.94	6.64 ± 0.46	10.20 ± 0.45	10.16 ± 0.43
	W	8.52 ± 0.21	7.07 ± 0.24	5.57 ± 0.41	8.02 ± 0.00	9.00 ± 0.88	10.43 ± 0.55
Total chlorophyll (mg L^{-1})	E	6.85 ± 3.52	10.11 ± 2.99	7.26 ± 1.54	3.59 ± 0.48	3.90 ± 4.77	15.36 ± 18.95
	W	7.51 ± 7.33	8.15 ± 0.95	18.13 ± 43.71	3.01 ± 0.03	4.59 ± 2.99	4.91 ± 3.77
pH	E	6.13 ± 0.15	7.34 ± 0.52	6.55 ± 0.31	7.27 ± 0.38	7.75 ± 0.42	7.61 ± 0.41
	W	6.21 ± 0.03	7.30 ± 0.38	6.27 ± 0.07	6.69 ± 0.01	6.87 ± 0.22	6.65 ± 0.34
Salinity (psu)	E	0.22 ± 0.65	4.95 ± 4.84	0.52 ± 1.45	10.11 ± 5.81	9.03 ± 7.39	6.75 ± 6.16
	W	0.03 ± 0.01	1.51 ± 2.34	0.03 ± 0.06	5.69 ± 3.97	1.95 ± 1.62	0.74 ± 0.74
Temperature (°C)	E	16.98 ± 0.46	27.06 ± 0.38	27.79 ± 1.36	23.68 ± 0.30	11.23 ± 0.75	11.95 ± 0.43
	W	16.82 ± 0.27	26.96 ± 0.32	27.04 ± 0.42	23.37 ± 0.25	10.25 ± 0.26	11.84 ± 0.57
Turbidity (NTU)	E	100.49 ± 194.07	128.54 ± 363.23	19.38 ± 70.84	6.28 ± 2.56	60.06 ± 204.80	36.99 ± 27.82
	W	43.90 ± 55.27	14.07 ± 5.53	235.18 ± 448.58	5.27 ± 3.06	31.07 ± 21.92	31.12 ± 24.14

examination of the stationary component indicated that the area of main channel low marsh (marsh edge) and anthropogenic structure habitats (another component of the environment; Peterson, 2003) did differ between the east and west distributaries (Table 5). The main channel of the east distributary had an overall greater area of both habitat types than the west distributary but the percentage of the two habitat types was about equal in the east distributary with low marsh (48.89%) being slightly greater than anthropogenic structure (37.04%), whereas the west distributary had a majority of its habitat classified as low marsh (70.62%; Table 5). These percentages are considered conservative estimates as conduits between the main channel and small ponds and tidal creeks that could affect predicted growth zones were not taken into account. This potential underestimation of the stationary component (see Figure 2) in both distributaries was due to our need to complete the sampling run in one day and thus only main channels could be mapped. These differences in stationary habitat types illustrate that recruiting spot would have a greater availability of low marsh (preferred habitat at that stage) and less habitat fragmentation in the west distributary even if water temperature and salinity were identical and predicted growth zones all similar.

DISCUSSION

Estuaries encompass an array of environments along coastal landscapes with relatively stationary habitat nested within a dynamic abiotic and selective biotic background (Peterson, 2003; Stoner, 2003) which

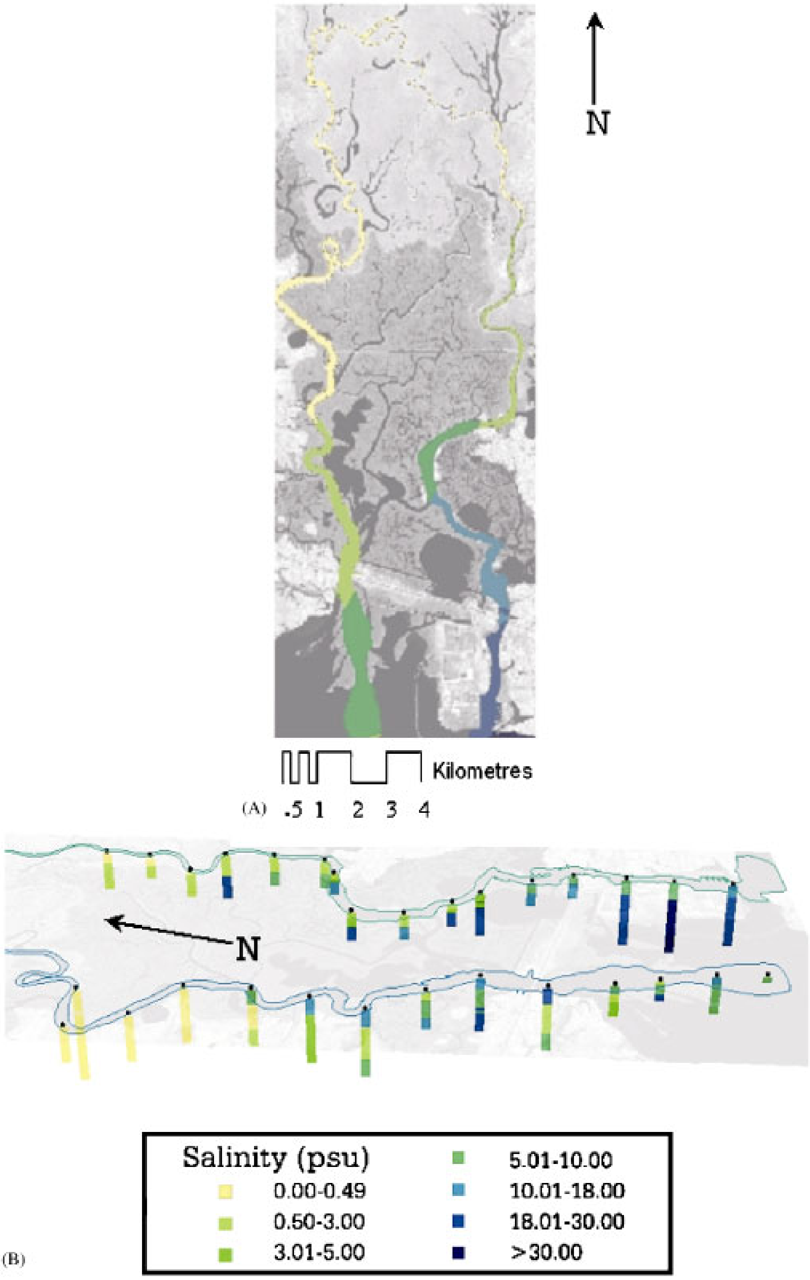

Figure 3. (A) Horizontal salinity (psu) profile collected in December 2003 from the lower Pascagoula River estuary. (B) Vertical salinity (psu) profile collected in December 2003 from the lower Pascagoula River estuary.

jointly contribute to the delineation of EFH and ultimately the identification of nursery areas. Our approach allowed us to quantify and visualize both stationary and dynamic habitat components in the lower Pascagoula River estuary and to make comparisons between the two distributaries. Our approach

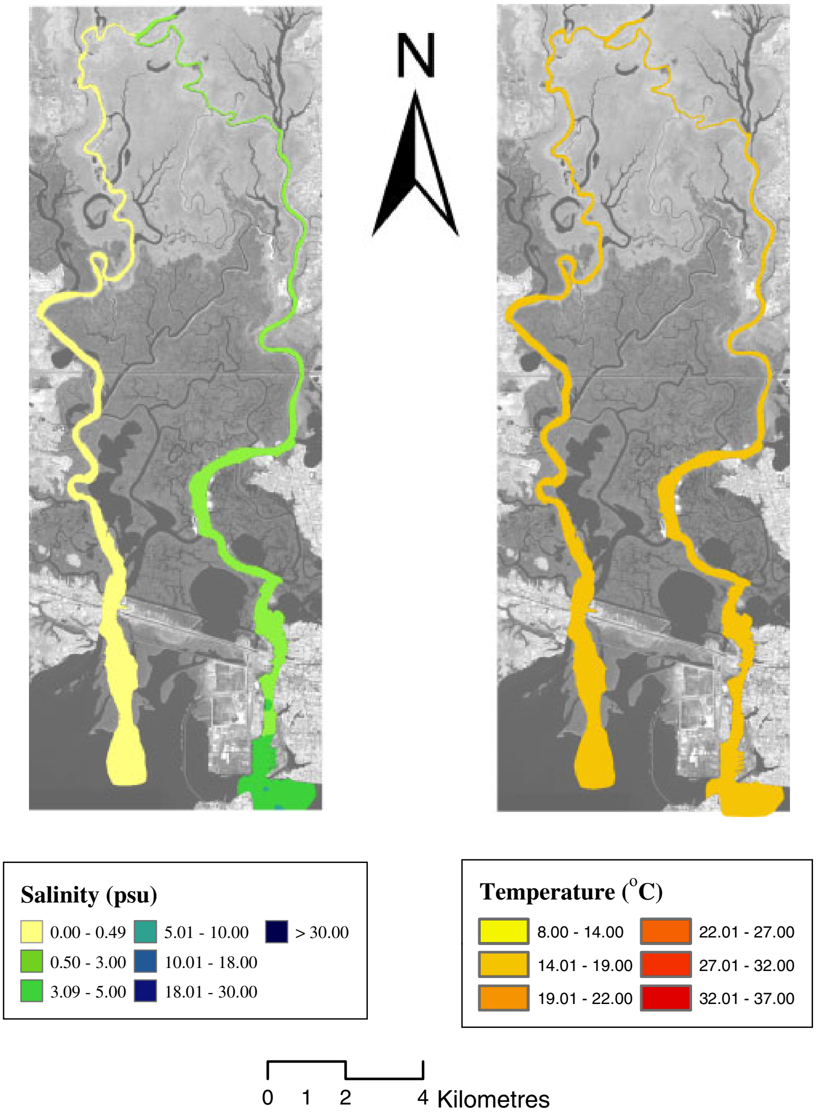

Figure 4. Illustration of the separate water temperature and salinity horizontal profiles for March in the lower Pascagoula River estuary that were integrated to construct the potential growth zones found in Figure 5.

also is enhanced compared to similar towed equipment (Ross and Ott, 2001; Hains and Kennedy, 2002) because of the ability to sample in shallower water and the reduced chance of losing equipment in the towed array approach owing to unseen underwater obstructions. Also, the array is considerably less expensive and more flexible than similar standard oceanographic equipment (Greenstreet *et al.*, 1997; Sieburth and Kester, 1997).

The patterns of dynamic habitat from the six collections suggest that nekton recruiting into either the east or west distributary of the lower Pascagoula River estuary would have a different environmental template within which to carry out that portion of their life history. Additionally, the distance an estuarine-

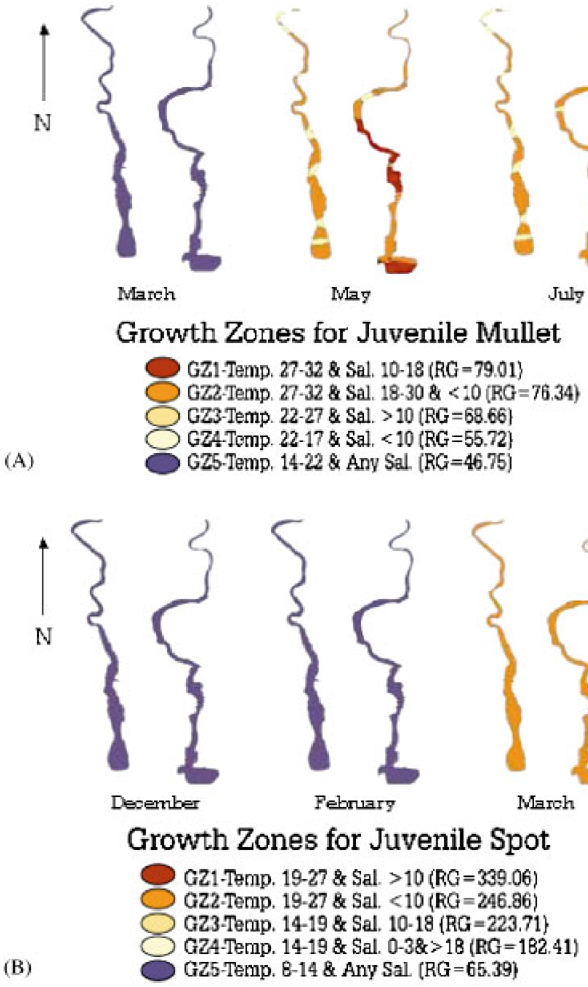

Figure 5. Composite potential growth zone map for both juvenile mullet and spot for each of the months ($n = 3$ each) that the size range of the laboratory specimens occurred in the region.

Table 5. Summary of distributary habitat area (km^2) and area expressed as a percentage (%) where growth zones identified for juvenile spot (Figure 4) overlap low marsh and anthropogenic structure habitats in the east and west distributaries of the lower Pascagoula River estuary, Mississippi

Shoreline habitat	East	West
Low marsh	0.1065 (48.89)	0.0718 (70.62)
Anthropogenic structures	0.0807 (37.04)	0.0276 (27.08)

dependent species might pulse up-estuary would also differ between the two distributaries, with saltier water moving further up-estuary in the eastern compared to the western distributary. Earlier studies (Peterson *et al*., 2000a; 2004) showed how variable abiotic conditions can be useful in developing a more complete understanding of factors influencing recruitment variability. In fact, defining physical–chemical conditions where optimal growth occurs in juvenile fishes is vital to delineating EFH and identifying potential nursery areas. For example, Miller *et al*. (2000) estimated that abiotic differences among estuaries could account for at least a threefold difference in growth rates of juvenile fishes. Because water temperature and salinity can vary within and among estuaries, Peterson *et al*. (2004) suggested that variability in growth for many nekton species is predetermined by these different abiotic conditions.

Similar findings have been reported for juvenile winter flounder (*Pseudopleuronectes americanus*) in New Jersey (Stoner *et al*., 2001; Manderson *et al*. 2002) and postlarval brown shrimp (*Farfantepenaeus aztecus*) in Texas (Clark *et al*. 2004). For winter flounder, it is clear that dynamic estuarine features such as local water temperature and salinity coupled with relatively static sediment organic and macrophyte cover distributions play a critical role in predicting inshore and estuarine nursery areas (Stoner *et al*., 2001). Essential fish habitat for the growth of winter flounder is defined by multiple environmental factors that vary simultaneously in space and time so that the location and suitability of nursery areas can expand, contract, and shift in location over time (Stoner *et al*., 2001; Manderson *et al*., 2002), as is illustrated here for the lower Pascagoula River estuary. Optimal conditions may be more likely to overlap within a specific region of the estuary during spring and summer when winter flounder begin their early juvenile growth phase (Manderson *et al*., 2002). For postlarval brown shrimp, Clark *et al*. (2004) noted that salinity and vegetation work in a complementary fashion to provide a quality habitat in Galveston Bay, Texas. In fact, using simulation models to link habitat features and survival of postlarval brown shrimp, Haas *et al*. (2004) indicated that surviving postlarval brown shrimp grew faster, moved less, spent more time in vegetation, and experienced higher local densities than shrimp that ultimately died. This again suggests that linking stationary habitat within a salinity range is vital to a more complete understanding of identification of critical nursery areas. Finally, these GIS-based models need to be incorporated with more spatially explicit models of growth potential (see review in Demers *et al*. (2000)) because they can integrate the mosaic nature of estuarine landscapes (both biotic and abiotic components) into a single, more meaningful and predictable framework for resource managers.

The lack of difference in the dynamic habitat component (water temperature and salinity) between east and west distributaries within any sampling period created a situation where the predicted growth zones of early juvenile spot did not differ. It is recognized that other water-quality variables like very low DO can markedly influence growth rates in fishes (e.g. McNatt and Rice, 2004); however, all else being equal, the availability of more low marsh habitat along the main channel of the west distributary predicts a greater area of EFH for young juvenile spot during this size-specific period of their life history (Peterson, 2003). Additionally, the reduced fragmentation of the west distributary marsh edge habitat because it is less developed (piers, docks, bulkheads) and the fact that the mouth of the east distributary is almost completely hardened by bulkhead and rip-rap (Partyka 2005), suggests recruit survival would be greater in the west distributary of the lower Pascagoula River estuary.

In contrast to estuarine-dependent nekton that have a strong association with stationary (structural) wetland habitat during their residency in estuaries, other estuarine-dependent nekton are more pelagic and are less associated with stationary (structural) habitat. For example, young juvenile mullet (present study), menhaden, *Brevoortia* spp., (Friedland *et al*., 1996), and numerous flatfishes (Stoner *et al*., 2001; Manderson *et al*., 2002, 2003) have seasonal and nested spatial abundance and growth patterns reflecting mainly the dynamic features of estuaries such as tracking prey fields or other spatially explicit physical features such as slow-changing bottom sediment types associated with different zones of the estuary. Moreover, some species also have an ontogenetic shift from pelagic to benthic habitats prior to settlement (Manderson *et al*., 2002, 2003) and thus may respond differently depending on actual stage of development. These important zones can move owing to seasonal or annual precipitation patterns, or anthropogenic impacts such as dredging or dam-building, both of which influence not only salinity patterns, but also sediment distribution within an estuary.

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Future applications

The importance of the multilayered approach is rooted in the ecological significance of scale. Research objectives must dictate the scale of the variables and habitat types being studied, as examination of different spatial scales can lead to disclosure of different processes and affect the outcome of the model (Wrigley *et al*., 1994). This system is versatile and has many potential uses in estuarine and freshwater assessments. These include (1) classification and inventory of seasonal and spatial water-quality patterns, (2) monitoring of water-quality relative to land-use patterns or changes in those patterns, (3) delineation of EFH and marine protected area placement, (4) projections of species-specific density, growth and mortality patterns of nekton in space and time, (5) monitoring water-quality patterns relative to an endangered species' use of a drainage, (6) with future development of more accurate nutrient sensors on the YSI meter, one can begin to assess nutrient loads in watersheds under different management scenarios and the effect on vital freshwater SAV and seagrass resources, (7) with future development of a chlorophyll *a* sensor on the YSI meter, one can begin to assess phytoplankton fronts or patches in watersheds as they relate to commercially important filter-feeding planktivorous fishes, and (8) development of quantitative real-time tools for use by resource managers in making water-quality and quantity decisions. All of these will require additional assessment-specific sampling at the correct scale.

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