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Habitat and Hydrology: Assessing Biological Resources of the Suwannee River Estuarine System

By Ellen A. Raabe, Randy E. Edwards, Carole C. McIvor, Jack W. Grubbs, and George D. Dennis

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Abstract

The U.S. Geological Survey conducted a pilot integrated-science study during 2002 and 2003 to map, describe, and evaluate benthic and emergent habitats in the Suwannee River Estuary on the Gulf Coast of Florida. Categories of aquatic, emergent, and terrestrial habitats were determined from hyperspectral imagery and integrated with hydrologic data to identify estuarine fish habitats. Maps of intertidal and benthic habitat were derived from 12-band, 4-m resolution hyperspectral imagery acquired in September 2002. Hydrologic data were collected from tidal creeks during the winter of 2002-03 and the summer-fall of 2003. Fish were sampled from tidal creeks during March 2003 using rivulet nets, throw traps, and seine nets. Habitat characteristics, hydrologic data, and fish assemblages were compared for tidal creeks north and south of the Suwannee River. Tidal creeks north of the river had more shoreline edge and shallow habitat than creeks to the south. Tidal creeks south of the river were generally of lower salinity (fresher) and supported more freshwater marsh and submerged aquatic vegetation. The southern creeks tended to be deeper but less sinuous than the northern creeks. Water quality and inundation were evaluated with hydrologic monitoring in the creeks. *In-situ* gauges, recording pressure and temperature, documented a net discharge of brackish to saline groundwater into the tidal creeks with pronounced flow during low tide. Groundwater flow into the creeks was most prominent north of the river. Combined fish-sampling results showed an overall greater abundance of organisms and greater species richness in the southern creeks nominally attributed a greater range in water quality. Fish samples were dominated by juvenile spot, grass shrimp, bay anchovy, and silverside. The short time frame for hydrologic monitoring and the one-time fish-sampling effort were insufficient for forming definitive conclusions. However, the combination of hyperspectral imagery and hydrologic data identified a range of habitat characteristics and differences in tidal-creek morphology. This endeavor related nearshore benthic habitat and hydrologic conditions with habitat suitability and fish assemblages and provides a template for similar applications in shallow and nearshore estuarine environments.

Introduction

Estuarine and nearshore marine environments provide some of the most important and essential habitats for a wide range of commercially, recreationally, and ecologically important species, including many fishes. The degree to which specific areas serve as essential habitat depends on the spatiotemporal juxtaposition of structural and dynamic habitats (Browder and Moore, 1981; Edwards, 1991). Structural, or stationary, habitat includes geomorphic features as well as vegetation. Dynamic habitat is comprised of physiochemical parameters such as temperature, salinity, dissolved oxygen (DO), as well as water depth, flow characteristics, and accessibility, but also includes biota such as plankton, algae and bacteria, and benthic prey. Habitat suitability is determined by the overlap of structural attributes with dynamic hydrologic and biotic resources. Unfortunately, real-time assessment and monitoring of structural habitat and water-column conditions (and therefore suitability of essential habitats) are infeasible using traditional techniques. This is particularly true in the highly variable conditions typical of most estuarine and coastal-marine environments.

Recent advances in remote sensing now offer the possibility of assessing habitat suitability even within dynamic coastal systems. Hyperspectral imaging has been used to separate and map habitat features of intertidal marshes, shallow estuarine and marine systems. Airborne sensors are ideal for this application, providing full areal coverage with no physical impact on sensitive habitats. Hyperspectral imagery improves conventional mapping with objective categories, measures of physiochemical conditions, assessment of ecological function, and evaluation of essential fish habitat. Project results therefore may be used to refine hydrodynamic-flow and salinity models and real-time hydrologic water-quality and flow measurements for the Lower Suwannee and estuary. The report is divided into five sections: introduction, habitat mapping, hydrology, fish ecology, and a discussion section on the integrated-science approach and recommendations for future studies.

Background

The study was conducted in the Suwannee River Estuary System (SRES) in the Gulf of Mexico "Big Bend" region of Florida. The Suwannee River is one of the largest rivers of Florida, includes drainage from Georgia, and flows over karstic topography on the southeastern Coastal Plain (Ewel, 1990). The Suwannee River Basin (SRB) currently represents one of the least human-altered major rivers in the southeast. However, rapidly increasing water demands call for substantial water withdrawals and flow reductions that may potentially impair the ecological function of the system (Katz and DeHan, 1996), especially in the estuary. The Suwannee River exhibits a complex balance of surface and groundwater flow (Crandall et al., 1999) and is currently at an environmental crossroad of major hydrologic alteration, facing exponential growth in urban and agricultural development in the basin.

Suwannee River discharge and seepage from the Floridan aquifer along the coast exert a dynamic influence on the character of emergent and submerged vegetation and ecology of the estuarine benthic and nearshore habitats. The spatial and temporal variability in mixing of freshwater with tidal flow creates a suite of microhabitats suitable as nursery, feeding, and seasonal refuge for fish communities. The identification of these microhabitats, their areal extent, and temporal stability will provide much needed information on the critical component of essential fish habitats.

Compact Airborne Spectrographic Imager (CASI) data have been used to characterize and map shallow and nearshore benthic habitats, differentiating between submerged aquatic vegetation (SAV) and algae (Beazley and Howard, 1997; Virnstein et al., 1997), and quantifying SAV biomass (Mumby et al., 1997; Mumby and Green, 2000). Other characteristics, including approximate depth, water-body characteristics, bottom type, and emergent habitats, are identifiable with airborne multi-spectral data (Borstad Associates, 2000; Rollings et al., 1998; Raabe, unpubl. data).

Water characteristics from *in-situ* surveys are combined with secondary indicators from the airborne sensor, such as vegetation and bottom type, to identify gradients and microhabitats. Vegetation, both submerged and emergent, reflects local environmental variations in hydrology, substrate, and elevation. Whereas factors such as water salinity may be variable in an estuary, vegetation can be a reliable measure of average salinity and flooding patterns. The areal extent of the estuarine mapping effort focuses on the Suwannee Estuary and the tidal creeks to the north and south.

Study area

The Suwannee River watershed drains 28,600 km^2 between southern Georgia and northern Florida (Fig. 1). The hydrology of the river is relatively pristine, unaltered by dams, but human activities and socio-economic factors have had significant impacts on wildlife, habitat, and water quality (Conniff, 1992; Ewel, 1990; Fishburne, 1997). At the end of the 394-km-long drainage is the Suwannee River Estuary, a coastal-plain estuary, situated between Dixie and Levy Counties on a low-energy, shallow, limestone shelf with a tide range of approximately 1.0 m (Fretwell et al., 1996; Montague and Odum, 1997; White, 1958). The estuary is composed of four zones, the tidal river, the intertidal marsh, Suwannee Sound, and the estuarine/marine zone (Fig. 2).

The tidal-river zone (a, Fig. 2) is a freshwater riverine environment with the regular pulse of tidal movement but is only influenced by salinity during low river-discharge conditions or during storm surge. Topographic differences on either side of the Suwannee River are most discernible in the area known locally as the California Swamp. In this area, the 2-m contour extends inland of the intertidal zone into the upland and freshwater swamps. The intertidal-marsh zone (b, Fig. 2) is a coastal arc of mixed fresh and tidal salt-tolerant emergent species established over a depositional environment between terrestrial and marine settings. The tidal cycle, river discharge, groundwater, and surface flow are the major forcing functions in the intertidal marsh, and are manifested in a mosaic of tidal creeks through vast stretches of emergent grasses dominated by black needlerush, *Juncus roemerianus* (Raabe and Stumpf, 1997; Montague and Wiegert, 1990).

The Suwannee Sound (c, Fig. 2) is a nearshore environment partially bounded by oyster reefs and sand deposits. Water from the Suwannee is semi-contained within this arc. Average depth in Suwannee Sound is 2 m and with a tide range of half this depth, tidal flushing of the sound is frequent and mixing is thorough (Orlando et al., 1993). Tides in the sound are often dominated by winds (Orlando et al., 1993). River discharge dominates the salinity regime in the estuary and ranges from low salinity (average 7.7 ppt) and high discharge from February to April to high salinity (average 19.9 ppt) and low discharge from October to December (Orlando et al., 1993). Although base flow in the river is driven by spring discharge from the Floridan aquifer, inter-annual variability in river discharge is closely tied to climate in south Georgia and north Florida, where basin headwaters originate (Orlando et al., 1993; Heath and Conover, 1981). River discharge and wind-dominated tides play a critical role in salinity variability and flooding of the nearshore shallow habitats.

The estuarine-marine zone (d, Fig. 2) includes an area beyond the reefs to approximately 10 m of depth, where river discharge moderates seasonal and inter-annual salinities with a high degree of variation. Circulation along the Gulf Coast varies from northerly in the summer to southerly in the winter. Consequently, the freshened, estuarine conditions influenced by Suwannee River discharge can shift between Horseshoe Beach to the north and Waccasassa Bay to the south.

Coastal forest thrives inland of the tidal marsh, and scattered tree islands, or hammocks, dot the intertidal zone at elevated locations (Raabe et al., 2004; Williams et al., 1999). Pockets of freshwater swamp and cypress stands occupy the delta and riverbanks. The adjacent upland consists of land development, pine plantation, or hydric hammock. The Suwannee is a black-water river, so named for the tannin-laden, or tea-colored, waters. The average annual discharge of the Suwannee River is 10,430 ft^3/s at Wilcox (Tillis, 2000). The river has a relatively low sediment load of 73,000 tonnes (Montague and Odum, 1997).

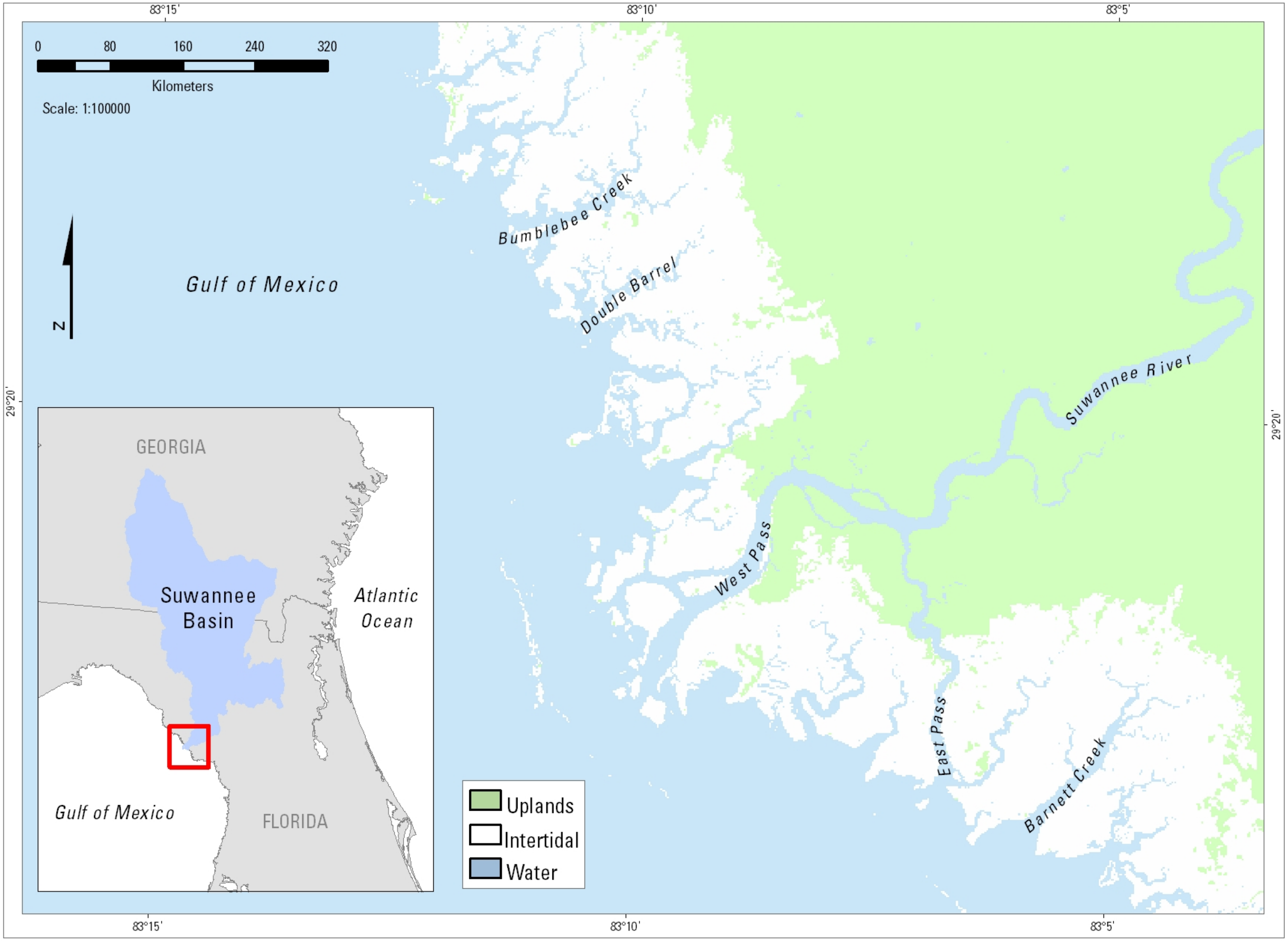


Figure 1. Location of Suwannee River Estuary and tidal creeks.

Figure 2. Zones of Suwannee River Estuary: (a) tidal river, (b) intertidal, (c) Suwannee Sound, (d) estuarine/marine.

Habitat Mapping with Hyperspectral Imagery

Data-acquisition Methods

Multi-spectral imagery was collected for sites on the Florida Gulf Coast under a Florida Department of Environmental Protection (FDEP) contract during the fall of 2002 (Borstad Associates, 2002b). The imagery for the Suwannee River Estuary was flown September 28, 2002. Imagery from the September date supercedes the initial data collection of July 31, 2002, which yielded higher quality data. See Table 1 for details on instrument and flight specifications.

Table 1. Specifications for data acquisition September 28, 2002.

Instrument/sensor	CASI	Compact Airborne Spectrographic Imager
Description	Push-broom manufactured by Itres 1990, s/n 101; modified 1995 for blue sensitivity	
Mode	Spatial	
Image swath	512 pixel	
Altitude	10,800 ft	
Swath width	2 km	
Camera integration	80 msec	
Ground speed	100 kt	
Pixel size	4 m	Across track and approximation for along track with re-mapping to 4x4 m
Lens	35	Narrow angle
Fore-optics	f 5.6 or 4.0	Depending on target and incident light levels
Aircraft position and attitude	Synchronized pulse to auxiliary computer; 2-axis Honeywell gyro mounted on sensor, broadband light sensor, and Leica 940N GPS	
Bands	See Table 2	

Adapted from Borstad Associates, 2002a

The Suwannee flight was conducted in conjunction with other flights along the coast, thereby reducing mobilization costs. Additional flights with varying bandwidths and data-collection parameters were flown for FDEP along river corridors to the north and south. Florida Department of Environmental Protection will use these hyperspectral data to detect and quantify non-point-source impacts, particularly septic-tank effluent, on surface-water quality. Bandwidths for the Suwannee Estuary are shown in Table 2.

Table 2. Band specifications for Suwannee flight September 28, 2002.

Band	Center (nm)	Width	Start	End
1	435.15	33.5	418.4	451.9
2	490.15	21.5	479.4	500.9
3	549.95	18.1	540.9	559.0
4	600.5	12.8	594.1	606.9
5	639.65	12.9	633.2	646.1
6	669.95	12.9	663.5	676.4
7	680.65	9.3	676.0	685.3
8	704.8	11.2	699.2	710.4
9	720.0	13.0	713.5	726.5
10	750.5	9.4	745.8	755.2
11	784.55	12.9	778.1	791.0
12	864.35	21.9	853.4	875.3

Adapted from Borstad Associates, 2002a

Bands for the Suwannee Estuary were adjusted for water-column penetration, separation of upland and emergent spectra, and reduction of signal saturation over bright terrestrial targets. See Table 3 for panchromatic instrument specifics.

Table 3. Specifications for panchromatic data acquisition September 28, 2002.

Instrument/sensor	Panchromatic imagery	
Description	Broadband line-scan camera, Bassler L220	
Image swath	4096-pixel (~10x CASI)	
Altitude	10,800 ft	
Swath width	2 km	
Camera integration	2.4 msec	
Ground speed	100 kt	
Pixel size	~0.4 m	Along-track resolution ~10x CASI
Lens	50 mm	Nikon
Filter	Hoya x1	Green filter to attenuate strong NIR signal
FOV	31	
Fore-optics	f 2.8	
Bands	Visible and NIR	

Adapted from Borstad Associates, 2002b

Start and end points for the flight lines are available in Borstad Associates (2002a). Lines were oriented in an east-west direction to minimize sun glint. Lines 16 and 17 are “tie lines” used as an aid during data processing. Tie lines are oriented perpendicular to the survey lines and are included as an aid to data processing during mosaicking. See Figure 3 for flight lines and orientation. Despite cloud cover, path overlap was sufficient to create an almost cloud-free set of flight lines. A small area around the town of Suwannee and parts of the uplands may be obscured. Where possible, the service provider spliced data from the July 2002 imagery to replace clouded areas. Borstad Associates (2002b) provided flight lines in WGS84, with 2-km swath width and 4-m resolution. The initial July 2002 mosaic was not used for interpretation but served as a guide for ground-truth data collected by field crews. FDEP and USGS teams collected ground data coincident with and subsequent to imagery acquisition. Low-altitude digital photography was also acquired by FDEP and was used for mapping verification.

Contract negotiations caused a delay in imagery acquisition until late July and September, when cloud accumulation and thunderstorms are an almost daily event. Despite unpredictable conditions, the flight paths over the Suwannee were planned with sufficient overlap and time lapse to eliminate most cloud cover in the mosaic. Sun glint was also present but did not pose a significant problem. The September flight was conducted under clearer skies and with the addition of panchromatic imagery.

Borstad Associates (2002b) conducted initial post-processing of the data, including:

1. Radiometric calibration and data-quality assessment
2. Removal of edge brightening due to anisotropic scattering
3. Corrections for aircraft motion and mapping to GPS coordinates
4. Second-stage georectification using ground-control points to reference imagery
5. Creation of a flight-line mosaic and color matching for land features
6. Areas with cloud cover in September were replaced with July imagery where possible
7. Fusion of CASI and panchromatic data at specific locations

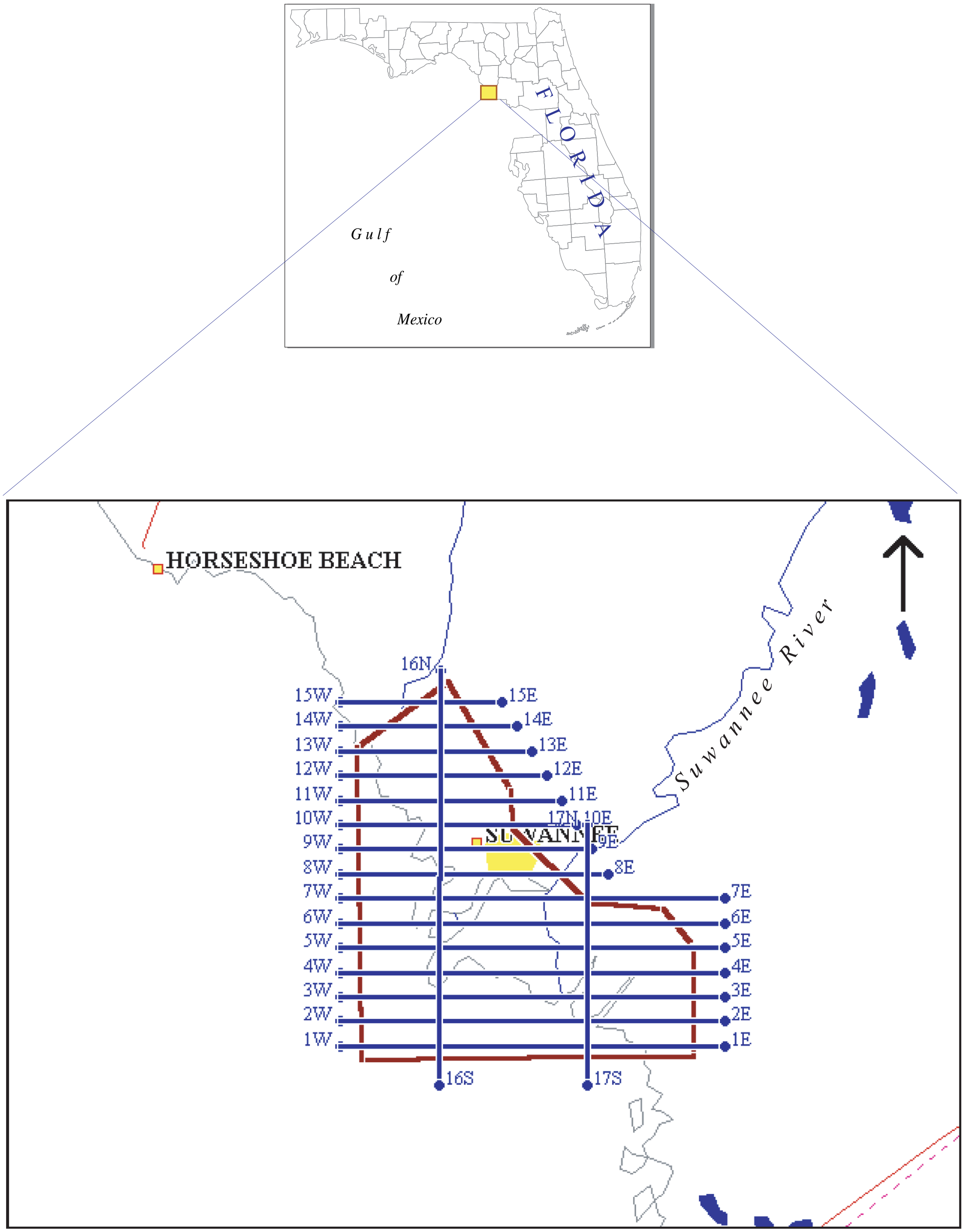


Figure 3. Location of Suwannee River flight lines on the coast of Florida (adapted from Borstad Associates, 2002a).

Mapping methods

Subsequent image processing was conducted at the USGS in St. Petersburg, FL. Two three-band combinations were produced for visualization and identification of general features and field sites. Bands 9, 7, and 5 are shown in Figure 4. The band combination has a false-color appearance, similar to traditional Color Infrared (CIR) photography, showing healthy vegetation in shades of red. Differences in vegetation, submerged features, and basic hydrology are all apparent in this image. Bands 6, 3, and 1 are shown in Figure 5. This band combination has a natural-color appearance and shows additional features, including water bodies, submerged features, and details of tidal-creek hydrology. The service-provider color matched flight lines for land features. As a result, between-flight-line discrepancies appear in the water in the false and natural-color images. Discontinuities from splicing flight lines and cloud cover are visible at locations such as at West Pass and East Pass (Figs. 4, 5).

Image-processing software was applied to the 12 bands of imagery to develop mapping categories suitable to refuge management and habitat monitoring. Land and water masks were developed from Band 12 to separate aquatic features from terrestrial features. The terrestrial layer includes ‘wetted’ portions of the intertidal zone to facilitate categorization of partially vegetated creek banks and low-elevation emergent marsh grass. All features under the terrestrial mask were categorized simultaneously with an unsupervised classification procedure. Separate classifications were conducted line-by-line in the aquatic submerged zone. Categories between lines were matched and mosaicked to obtain consistent mapping of submerged features.

Habitat categories were sieved and filtered for a minimum mapping unit (mmu) of 16 m^2 and to remove noise. Field teams [USGS, FWS, and the Florida Marine Research Institute (FMRI)] provided ground-truth data for interpretation and verification of mapping. Error analysis was performed on 16 basic categories using field-reconnaissance data from over 500 locations.

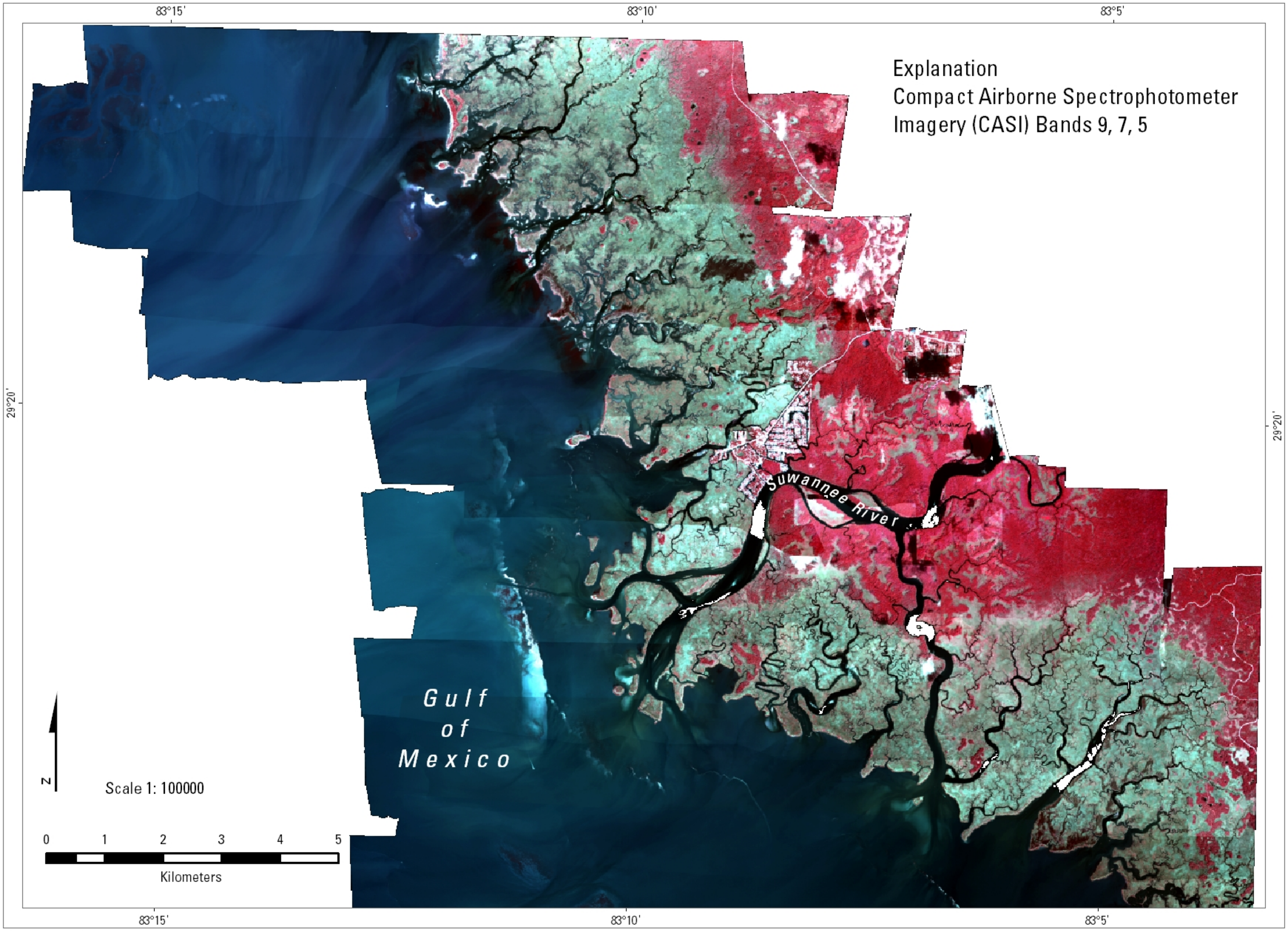


Figure 4. False-color mosaic of Suwannee River Estuary, CASI Bands 9, 7, 5.

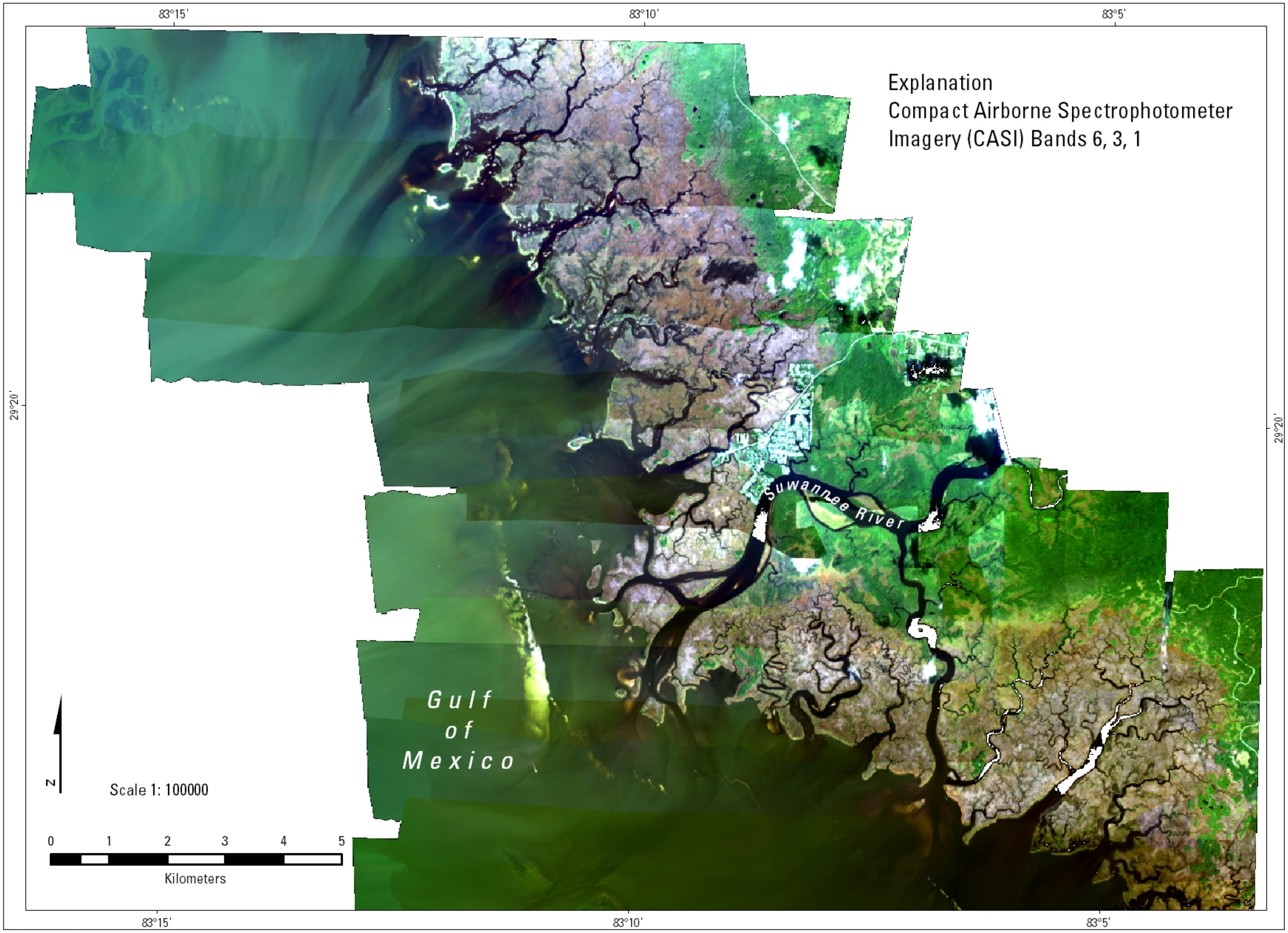


Figure 5. Natural-color mosaic of Suwannee River Estuary, CASI Bands 6, 3, 1.

Results

Habitat Characterization

The band combination, 4-m resolution of the imagery, and processing of 15 flight paths simultaneously allowed the delineation of habitat but not fine detail or individual plant species. Instead, 16 categories were separated by vegetation, flooding regime, elevation, and substrate characteristics (Table 4). Overall map accuracy is 99% as shown in error analysis (Table 5). Features such as game trails and animal wallows, exposed limestone, erosive features, and many plant-community specifics were observed in the field. Such detailed observations, though informative, were not corroborated in the imagery and could not be used in the analysis.

The area covered by the CASI imagery encompasses 7,231 ha of intertidal zone, bordered by marine and upland habitat. Three general categories for submerged, emergent, and upland features were derived from the hyperspectral imagery and were further divided into 16 categories (Fig. 6). Distinctions were made among flooded, saturated or dry, and fresh- or salt-marsh grasses, scrub wetlands and basic forest types. Actual species compositions are suggested but are not defined for habitat categories. Flight-line artifacts are obvious at some locations. Such artifacts generally appear as distinct east/west delineations between two features and may not represent true ground conditions. The artifacts are likely the result of problems in calibration conducted by the service provider.

Table 4. Basic submerged, emergent, and upland categories in Suwannee Estuary.

Category	Category and depth (m)	Notes	Image Value
1	Submerged	Undetermined substrate; includes Suwannee River	4
2	Offshore feature	Hard-packed sand, shell and complex SAV habitat	9
3	Submerged aquatic vegetation (SAV)	Mix of SAV and algae nearshore; includes offshore sand/shell/SAV/algae	15
4	Submerged shell/sand features ≤ 1 m	Varying depths and composition; includes Seven Sisters	21
5	“New mud” ~1 m	Fines with high organic content	24
6	Tidal creek ≥ 1 m	Undetermined substrate	101
7	Intertidal shallow sand/shell & fines	May include sparse grass or algae	106
8	Low marsh with varying canopy	Saturated peat or muddy sediments; cordgrass dominant	109
9	Brackish marsh; mid-marsh	Wet to dry marsh sediments; black needlerush dominant	112
10	Freshwater- dominant marsh	Wet peat or muddy sediments	118
11	Transition; high marsh	Fines/sand or dry substrate; scrub, grass or herbaceous cover	119
12	Mixed scrub habitats; wet & dry soils	Salt scrub, freshwater scrub, cypress	129
13	Coastal forest: oak, sabal palm, cedar	May include thin pine, scrub woodland	132
14	Mixed hardwood and evergreen forest	Magnolia, pine, cedar, large oak & others; full, multi-storied canopy	139
15	Bare; elevated dry sand and/or shell hash	Beaches, barren, dirt roads, clearings	150
16	Development	Structures, paved surfaces	200
NA	Unknown	Cloud, cloud shadow, or image holiday	160

Table 5. Error matrix for map and 16 individual categories, as defined in Table 4.

Field Class	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Total	*User Accuracy
1	20																20	100
2		16															16	100
3			24														24	100
4				21													21	100
5					9												9	100
6						59											59	100
7							29		1								30	97
8							3	108									111	97
9								5	104	1							110	95
10										24		1					25	96
11									2	1	38						41	93
12									1	1		22					24	92
13													25				25	100
14														15			15	100
15															22		22	100
16																14	14	100
Total	20	16	24	21	9	59	32	113	108	27	38	23	25	15	22	14	550	100
****Producer Accuracy**	**100**	**100**	**100**	**100**	**100**	**100**	**90**	**96**	**96**	**89**	**100**	**96**	**100**	**100**	**100**	**100**		**Overall Map Accuracy =99%**

*User accuracy: probability that a category on the map represents a feature on the ground.

**Producer accuracy: probability that a field site is correctly categorized on the map.

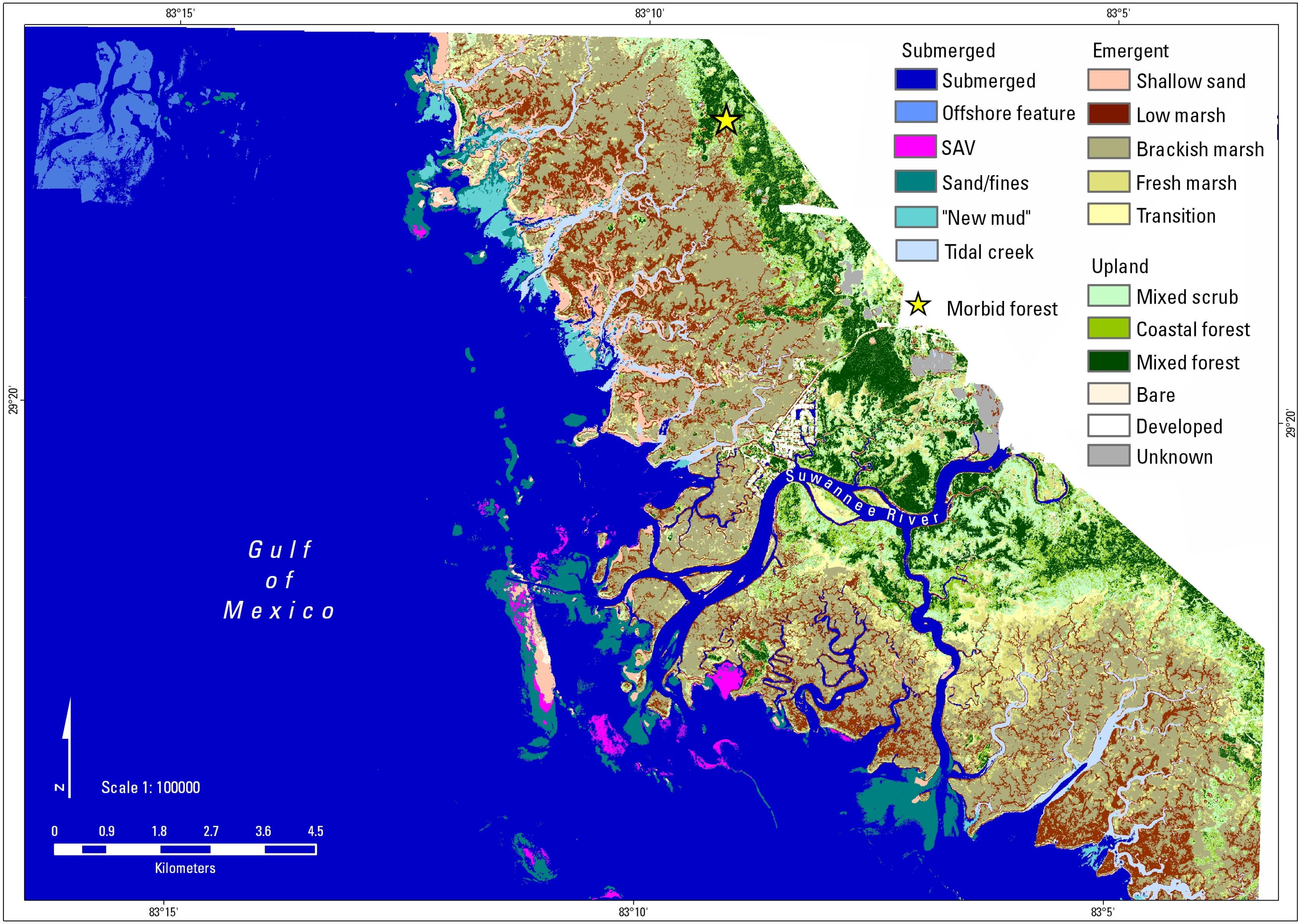


Figure 6. Habitat categories derived from CASI imagery over Lower Suwannee River and Estuary.

Estuary

Shallow submerged features are separated by bottom type and vegetation. Figure 6 simplifies depth characteristics, which are not discernible at a scale of 1:100,000. The main estuarine categories are shallow sand/shell features, shallow fine sediments, shallow ‘new mud’, and submerged aquatic vegetation (SAV). A distinct offshore feature was captured by several flight paths extending to the west of Bumblebee Creek, having characteristics consistent with relict-channel morphology. Field reconnaissance confirmed deep channels (> 2 m), hard-packed sand and shell deposits, and complex SAV habitat.

Tide levels were falling during over-flight, and significant flow from the tidal creeks was mixing in the estuary. Observable fronts and mixing of water bodies were identifiable in the imagery (Figs. 4, 5). Although potentially useful for identification of tidal or estuarine fronts, the mixing zone can be visually confusing to the casual observer and was eliminated from the mapped categories. Outgoing tides commonly carry a film of detritus from the marsh, making it possible to separate marsh outflow from marine and river-dominated fronts. Three water bodies were identified: marine, tidal creeks, and tannin-colored Suwannee River water.

Intertidal Zone

Categories of submerged and emergent features were identified within the intertidal zone. Submerged intertidal represents the flooded portion of the intertidal zone, delineating permanent aquatic habitat available to mobile and sessile organisms. The submerged zone is accessible to plankton and nekton during all phases of the tidal cycle. Throw-trap and seine-net sampling techniques were conducted in the submerged zone of the tidal creeks.

Submerged sand, shell, and shallow fine substrates were distinguishable with the imagery. These bottom types represent coarser substrates that may be favored by various benthic organisms. Field reconnaissance confirmed the presence of additional substrate and structure in the tidal creeks that were not distinguishable with the acquired imagery. These included submerged exposed limestone, submerged tree trunks, and *Vallisneria* beds (eelgrass), a freshwater SAV.

Emergent habitat in the intertidal zone is flooded for periods during the tidal cycle. Low marsh includes vegetated, partially vegetated, and bare portions of the intertidal zone that are subject to both exposure and flooding during a normal tidal cycle. Soils in this zone are typically saturated and may be flooded for an extended period during a normal tide cycle. If vegetated, the low-marsh zone is dominated by *Spartina alterniflora* (cordgrass), although in freshened areas, *Scirpus* spp. (bulrush), *Cladium jamaicense* (sawgrass), or other freshwater species may also be present.

Low marsh is accessible to planktonic organisms and free-swimming nekton (fish, crabs, shrimp) during flood and high tide. Marsh rivulets, utilized for rivulet-net sampling, are located in this zone. The low marsh provides feeding and refuge area for small mobile organisms during rising tides. Transients leave this zone with the falling tide or risk being stranded. Discontinuous impoundments and depression habitat may serve as refuge or as traps for estuarine plankton and nekton. Anecdotal evidence regarding redfish in the California Swamp (Fig. 2) indicates that estuarine fish may become stranded and thrive in interior impoundments following storm-surge or high-tide events.

Brackish marsh refers to mid-elevations in the emergent zone dominated by *Juncus roemerianus* (black needlerush) and is infrequently flooded, as little as 5% of the time (Stout, 1984). Depending on location, the mid-marsh may include a mix of salt and freshwater species, *Acrostichum* (leatherfern), *Borrichia* spp. (seaoxeye), or *Distichlis spicata* (saltgrass). This zone includes a range of elevation categories, from wetted to increasingly drier areas. The mid-marsh is temporarily accessible to plankton and nekton during rising tides and storm events. The vegetative cover provides refuge, and the shallow waters are inaccessible to larger predatory species. Rivulets serve as tidal conduits from low marsh to mid-marsh during rising tides and subsequently drain the marsh surface during falling tides. The marsh surface, whether at low or intermediate elevations, supports a rich assemblage of benthic micro-algae, bacteria, detritus, and other food organisms. Drainage during a falling tide facilitates the export of material from the marsh surface to the estuary.

Freshwater marsh includes *C. jamaicense, Scirpus* spp., and other species, and may occupy fresher as well as more interior portions of the intertidal emergent zone. The freshwater marsh may receive river discharge from overland flow in addition to tidal flow and may be more frequently wetted than the mid-marsh zone. Nekton requiring low-salinity conditions are likely to thrive in these tidal creeks and marshes. In addition, estuarine organisms with high-salinity requirements are unlikely to compete for resources in these locations except during periods of low river flow. Freshwater wetland scrub and swamp species such as *Taxodium* (cypress) and *Salix* (willow) adjoin the freshwater marsh in the southern tidal tributaries, where surface overflow from river discharge is more pronounced.

Marsh-to-forest transition and upland habitats

At the interior of the emergent intertidal zone are marsh-to-forest-transition plant communities that occupy zones beyond the reach of normal tide range. Transition habitat may be tidally flooded during the highest spring tides and storm events. This zone will typically occur at the marsh interior, adjacent to the tree line. Species composition will vary depending on elevation and proximity to the river or the Gulf of Mexico but will be dominated by grass, shrubs, and herbaceous species. The substrate may be dry, sandy, or include exposed limestone outcrop. The vegetation in this transition zone may include *D. spicata, Borrichia, Sagittaria* (arrowhead), *Solidago* (goldenrod), *Ipomoea* (morning glory), *Iva* (marshelder), *Baccharis* (falsewillow), *Amaranthus* (pigweed), *Yucca* (yucca), *Spartina, Juncus, Batis* (saltwort), and *Salicornia* (pickleweed) species, among others.

Scrub habitat includes various salt or freshwater scrub, prairie wetlands, and thin-canopy woodland habitats. Typical scrub habitat includes herbaceous or grass cover in addition to scattered scrub and small trees. In a freshened environment, scrub may include *Persea palustris* (swamp bay), *C. jamaicense*, *Solidago, Magnolia* (magnolia), *Sambucus* (elderberry), *Scirpus* spp., *Taxodium*, and others. In a more saline location, such as a tidal-creek levee, scrub habitat may include *Iva, Baccharis, Amaranthus, Yucca, Spartina, Juncus, Sabal palmetto* (cabbage palm), *Juniperus silicicola* (southern red cedar), and others. In both tidal and freshwater environments, the substrate may be wetted or dry.

The coastal forest has a thin tree canopy dominated by *Sabal palmetto* and *J. silicicola* (Raabe and Stumpf, 1997). The forest may include *Quercus* spp. (oak), *Pinus elliottii* (slash pine), *Magnolia*, *Serenoa repens* (saw palmetto), and various shrub, herb, and grass species. Isolated stands are found at elevated locations within the intertidal zone itself and along the coastal margins of interior forests. Often called hammocks, the stands are typically open canopies with a low herbaceous understory. At some locations, the coastal-forest habitat is categorized as wet scrub and exhibits characteristics common to tidally induced tree morbidity at these places. Characteristics of a morbid coastal forest include lack of tree regeneration, few live trees, many standing dead trunks, the establishment of salt-tolerant grass and scrub, and the initiation of tidal flooding in the area (Williams et al., 1999). An example can be found at the head of South Bumblebee Creek, where tidal flow has entered the coastal forest and surface elevation has dropped since these trees were first established (Fig. 6). A tidally encroached morbid forest is illustrated in Figure 7. A visible lowering of the ground surface apparently occurred along with colonization of the substrate by salt- and flood-tolerant vegetation.

The mixed-forest category is a multi-storied forest with a full canopy and larger stature trees than the coastal forest. Both broadleaf and evergreen species are present, and the understory may be well developed. Canopy species include but are not limited to *Quercus virginiana* (live oak), *P. palustris*, *Magnolia*, *Celtis laevigata* (hackberry), *Zanthoxylem clava-herculis* (prickly ash), *P. elliottii*, *J. silicicola*, *Sabal palmetto*, and others. Infrequently sampled classes, such as the forest categories, may have inadequate representation in the error analysis (Table 5). A comprehensive stratified random-sampling scheme was not feasible on this study.

Two types of barren features have been identified in the imagery: natural (exposed sand, shell hash, and barrens) and man-made features (pavement and buildings). Mapped features delineate general habitat types, and areas of pronounced freshwater influence and illustrate geomorphologic and flooding characteristics of the intertidal zone.

Flight-line artifacts can be observed in the true- and false-color mosaics and to a lesser degree in the categorized maps. Refinements in data collection, calibration, and mosaicking techniques will help eliminate the artifacts in future mapping efforts. Bandwidths based on spectrophotometry of specific community characteristics might better resolve plant species, soil saturation, or substrate type.

Figure 7. Coastal forest: bases of still-living trees are ~0.60 m above present ground surface, Bumblebee Creek, Dixie County, Florida.

Tidal-flood zones

Variations in water penetration and substrate wetness provided an opportunity to map tidal-flood zones. Nine tidal zones were interpreted from the imagery and are depicted in Figure 8, showing tidal-flood stages.

Zone 1 represents the submerged estuarine and riverine zone with indeterminate depths. Zone 2 represents shallow submerged estuarine features generally less than 2 m in depth. These features include shoals, flats, and SAV. Zone 3 represents the submerged tidal creeks. Zone 4 represents creek and shoreline shallows, primarily sand/shell, and is located almost exclusively north of the river mouth. Zone 5 represents the low-tide flood zone, a vegetated zone with saturated soils flooded regularly during every tidal cycle. Zone 6 represents the mid-tide flood zone, a vegetated zone flooded regularly for a shorter duration during mid- to high tides. Zone 7 represents the high-tide flood zone, a vegetated zone flooded only during normal or extreme high tides. Zone 8 represents a zone beyond the reach of normal tidal flow, frequently characterized by salt or freshwater scrub. Zone 9 represents an elevated zone beyond the reach of normal tidal flow and may include forest, urban development, and other elevated features. Zones 7, 8, and 9 do not have consistent elevations, but a combination of distance from the Gulf, the strength of freshwater influences, and elevation protect these zones from normal tidal influence to varying degrees.

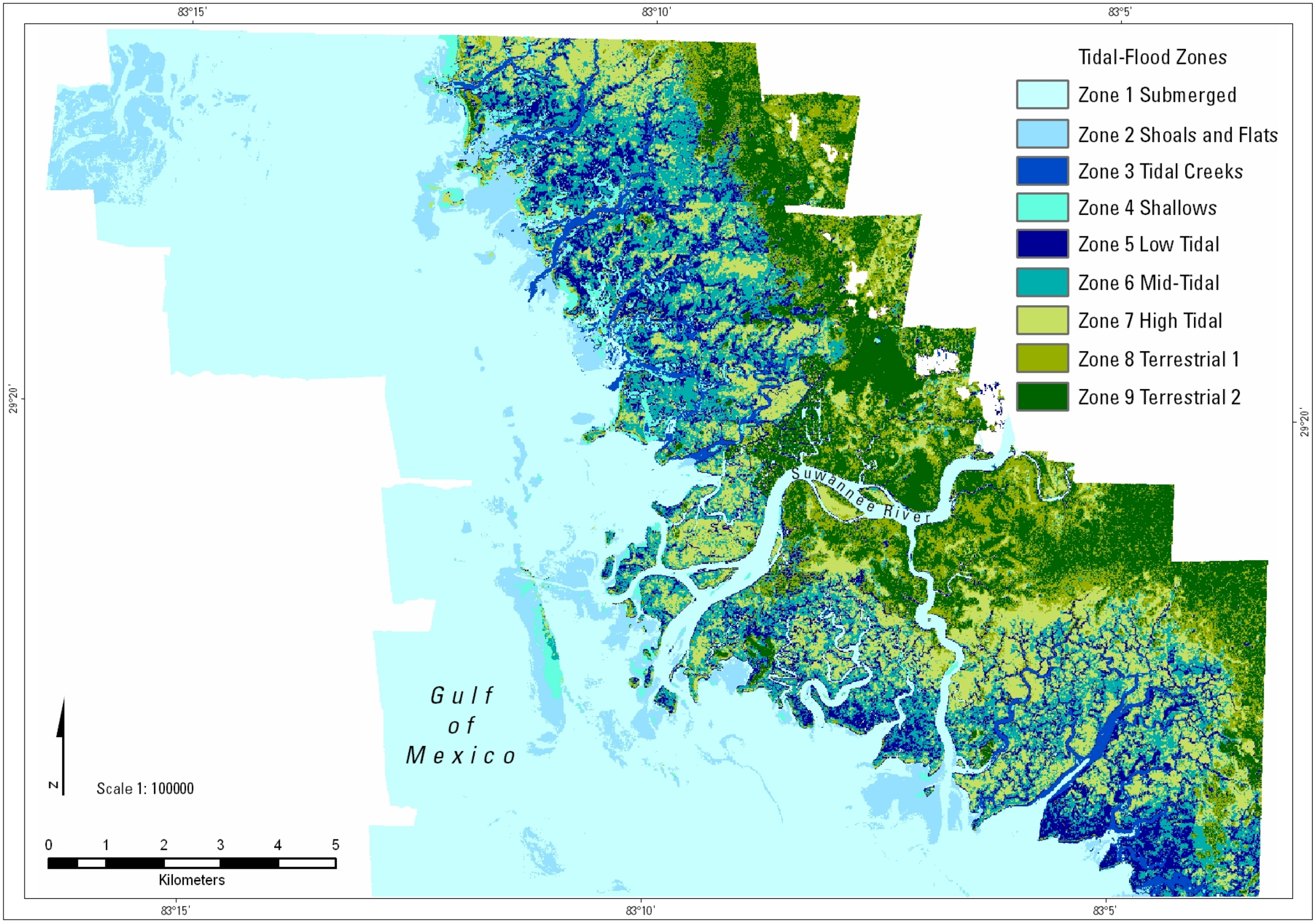


Figure 8. Suwannee River Estuary tidal-flood zones derived from 2002 hyperspectral imagery.

Derived Metrics for Tidal Creeks

The intertidal zone was the focus of more detailed analysis to forge a link between mapping, hydrologic-data collection, and fish collection in the tidal creeks. This section presents an evaluation of sampled tidal creeks based on intertidal habitats and derived metrics. The intertidal zone was divided into creek and sub-creek watersheds. Figure 9 depicts tidal-creek watersheds north and south of the Suwannee River overlaid on marine, emergent-intertidal, and upland zones.

Water monitoring and fish sampling were confined to selected creeks north and south of the river, as highlighted in Figure 9. Tidal creeks used for fish sampling were further divided into lower and upper branches, labeled L (lower), N (north), and S (south). Bumblebee Creek and Double Barrel Creek are both north of the river. Barnett Creek is south of the river. Historical naming conventions labeled the northern branch of Barnett Creek "McCormick". Although treated elsewhere as separate tidal creeks, McCormick and Upper Barnett are both tributaries to Lower Barnett Creek.

Tidal-creek habitat characteristics

Habitat characteristics and area in hectares are presented in Table 6 for each sampled creek. The proportion of each habitat category was calculated as a percent of the intertidal zone for each tidal creek or sub-basin. Submerged, low-marsh, mid-marsh, freshwater-marsh, and transitional habitat are discussed in more detail in an earlier section of the report.

Table 6. Intertidal habitats of tidal-creek watersheds and sub-basins.

Tidal Creeks and Sub-basins	Watershed (ha)	Submerged Intertidal (%)				Low marsh (%)	Mid-marsh (%)	Freshwater marsh (%)	Upland & transition (%)
		Total	Unknown	Fines	Coarse				
Lower Bumblebee	263	34	19	11	4	28	30	4	4
North Bumblebee	270	5	4	1	0	17	64	5	9
South Bumblebee	263	6	4	1	1	22	51	1	20
All Bumblebee	**796**	**15**	9	4	2	**22**	**49**	**4**	**10**
Lower Double Barrel	200	35	12	17	6	30	28	3	4
North Double Barrel	282	9	5	3	1	27	58	2	4
South Double Barrel	296	12	7	4	1	25	45	3	15
All Double Barrel	**778**	**17**	7	7	3	**28**	**43**	**3**	**9**
Lower Barnett	427	28	28	0	0	17	48	6	1
McCormick	264	5	5	0	0	7	41	22	25
East Barnett	336	7	7	0	0	15	46	16	15
All Barnett	**1026**	**15**	15	0	0	**14**	**46**	**13**	**12**

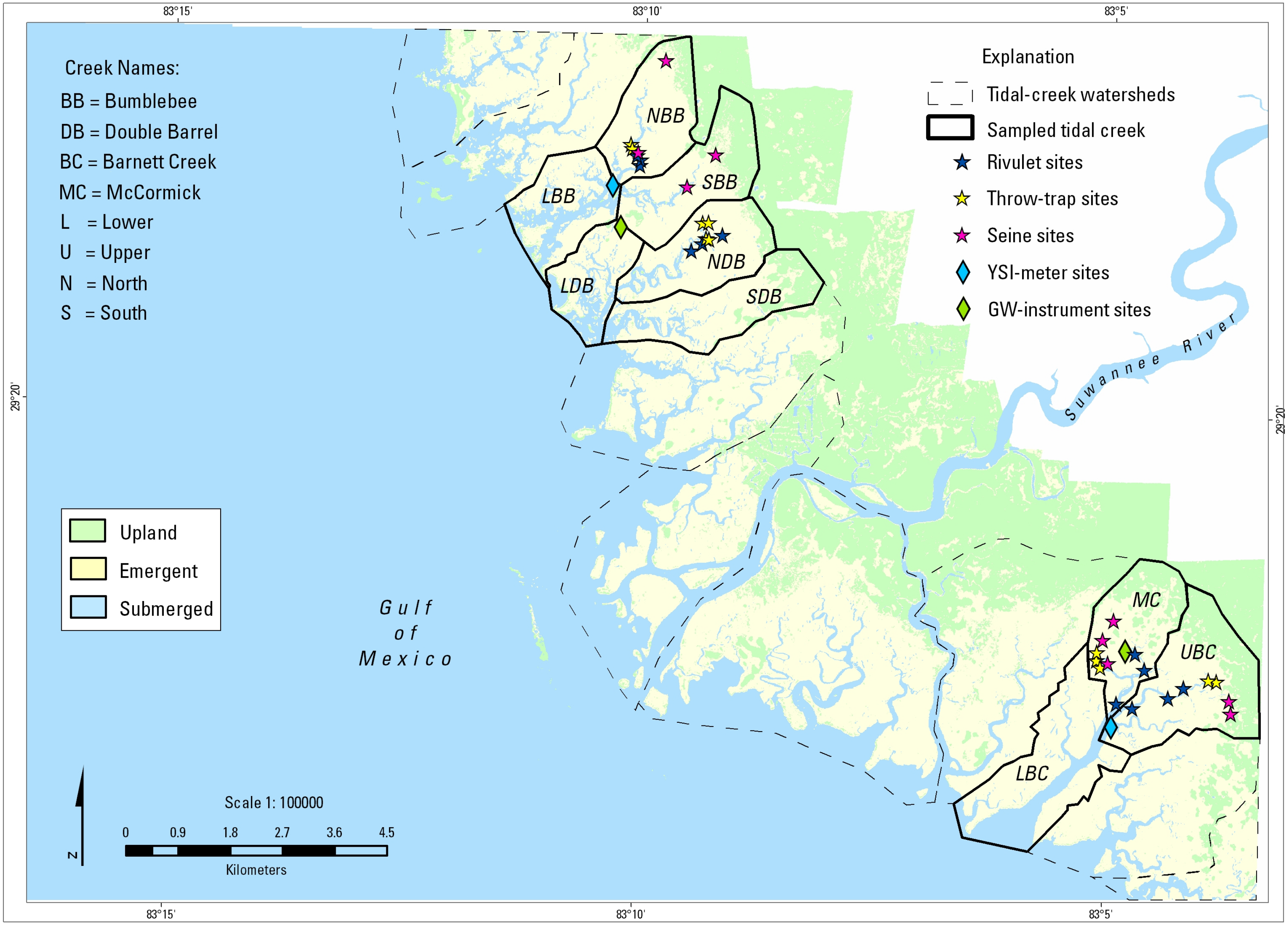


Figure 9. Tidal-creek watersheds and sampling locations for water and fish investigations.

Intertidal habitat was evaluated by calculating the percentage of submerged, low-marsh, mid-marsh, fresh-marsh, and marsh-to-forest-transition categories in each sub-basin. In brief:

- Percent submerged (Table 6) includes tributaries and meanders that remain inter-connected at low-water levels. Inter-connectivity provides access and departure routes for mobile species. Percent sand/shell and percent fines (Table 7) are subsets of the total submerged category.
- Percent of low marsh (Table 6) gives relative measure of regularly flooded marsh habitat. This area is regularly accessible as shallow refuge for opportunistic mobile species during flood tides.
- Percent mid-marsh is a relative measure of the area flooded during rising tides and storm events. The mid-marsh, though less frequently accessible, serves as a food source via the production and export of detritus, bacteria, and benthic algae.
- Percent fresh marsh is an important parameter in the tidal creeks because this type of marsh provides a relative measure of the areal extent of persistent freshened conditions in the intertidal zone.
- Percent marsh-to-forest transition is a relative measure of habitat within the intertidal zone that may support upland or dry-land plant species and refuge for birds, mammals, and reptiles. This category includes high marsh, scrub habitat, exposed sand/shell barrens, and coastal-forest hammocks.

Tidal-creek geomorphology

Tidal creeks north and south of the river were evaluated for measurable geomorphic variables derived from the remotely sensed imagery. A low-water line was generated from Band 12, approximating low-tide levels. This linear feature was used to estimate creek edge along the length of the creek until the line was broken toward the marsh interior. Drainage metrics derived from the imagery that may play a role in determining habitat characteristics are sinuosity, drainage density, entrenchment, bed material, stream order, and vegetation. These parameters are presented in Table 7 for each creek basin.

Table 7. Image-derived metrics of tidal-creek watershed and sub-basin geomorphology.

Tidal Creeks and Sub-basins	Area (km^2)*	Creek (m)*	Valley (m)*	Sinuosity*	Dd*	E*	Percent Fines*	Percent Coarse*	Order*
Lower Bumblebee	2.63	4930	1945	2.5	0.19	1.8	11	4	3
North Bumblebee	2.7	4570	2380	1.9	0.18	4.3	1	0	2
South Bumblebee	2.63	5970	1730	3.5	0.23	4.9	1	1	2
All Bumblebee	**7.96**	**15470**	**6055**	**2.6**	**0.19**	**2.5**	**4**	**2**	
Lower Double Barrel	2.0	5890	1820	2.5	0.29	1.9	17	6	3
North Double Barrel	2.82	4570	2380	1.9	0.16	4.1	3	1	2
South Double Barrel	2.96	9650	2860	3.4	0.33	3.1	4	1	2
All Double Barrel	**7.78**	**20110**	**7060**	**2.8**	**0.26**	**2.7**	**6**	**3**	
Lower Barnett	4.36	5160	2960	1.7	0.12	1.5	0	0	3
McCormick	2.64	3435	1390	2.5	0.13	2.5	0	0	2
East Barnett	3.36	3960	2225	1.8	0.12	3.2	0	0	2
All Barnett	**10.36**	**12555**	**6575**	**1.9**	**0.12**	**1.9**	**0**	**0**	

*Terms are defined in section on Tidal-creek geomorphology, pg. 22.

A description of the tidal-creek drainage parameters are:

- Intertidal (Area) is the full extent of the intertidal zone in km^2. The area includes tidal creeks, emergent vegetation, and transitional habitat.
- Creek edge (Creek) is the length of low-water line along the main tributaries in meters.
- Valley length (Valley) is the 'straight-line' valley length in meters from the head of the creek to the mouth of the creek or to the junction with the next tributary.
- Sinuosity is the ratio of creek edge to valley length. A straight creek has a sinuosity value of 1. Increasing values represent increased sinuosity. Sinuosity is directly related to meander characteristics and provides a relative measure of available creek edge and an indirect measure of the presence of habitat forms, such as meanders and alternating deeper erosional and shallow depositional banks. Sinuous creeks provide more edge habitat and decreased velocity. Lower energy may offer stability for sediment-dwelling organisms. Straighter creeks, closer to "1", may show increased velocity and greater motility for small organisms "riding" the tide.
- Drainage density (Dd) is a measure of stream-channel length (Creek) per unit area (Area). High values indicate increased basin dissection, low absorption, and faster hydrologic response, whereas low values indicate high absorption and slower hydrologic response. Our measurement of stream length is limited to the main tidal-creek tributaries and may present an underestimate of Dd compared to other studies. However, the values serve as a relative measure among selected creeks within this study. The lower estimates for Dd may prove to be acceptable. Yildiz (2004) showed that an increase in resolution for calculating Dd can increase Dd for a given basin and can overestimate stream discharge.
- Decreased drainage is linked to increased storage capacity and lower runoff rates. Under low-drainage conditions, water may be retained and slowly released from the sediments, providing prolonged or lagged outflow from the peat during falling tides and may positively affect the retention or survival of small organisms within the tidal-creek system.
- Entrenchment (E) is calculated as the ratio of flood width/bankfull width. In this study, the submerged class represents bankfull area, and low marsh plus the submerged zone represents full-flood area. Entrenchment is a measure of stream incision and floodplain development. Entrenchment values of less than 1.4 are deeply incised; values of 1.4 to 2.2 are moderately entrenched; values greater than 2.2 are slightly entrenched with increasingly well-developed floodplains.
- E = (low marsh + submerged)/submerged.
- Bed material is estimated by calculating percent of submerged sand/shell or fines within the submerged zone of each tidal creek. The ratio gives a relative measure of coarse substrate material available in the sampled creeks. It might also serve to address riffle/pool-sequence development in the creeks. Other bed characteristics currently rely on field descriptions of SAV, submerged logs, and other features in each sampled creek.
- Order is the stream order based on the work of Horton (1945) and Strahler (1957). Typically, tidal creeks in the Big Bend region enter the Gulf of Mexico as third-order streams or less. Creek order is determined in a manner similar to river-drainage basins. Many small rivulets combine in the interior of a basin to form permanent streams. We count, as first-order creeks, the tidal creeks in which permanent submerged area is indicated by the 'low-water' line as derived from the hyperspectral imagery. Smaller tributaries are ranked zero. From there, a second-order creek is formed where two or more first-order tributaries meet, and so on. The result is that the creeks, as they meet the Gulf, are generally ranked as third order. For comparison, the Mississippi is a tenth-order stream, and the Suwannee, a sixth-order stream.

Note: Estimates of width: depth ratio, water-surface slope, and velocity were not derived from the imagery for this study but may be developed in conjunction with hydrologic monitoring in the tidal creeks.

Comparison of creeks

Flooding, vegetation, and other metrics in the intertidal zone permit comparisons among tidal creeks. These characteristics can be used to evaluate intertidal habitat and potential use by aquatic species.

Bumblebee Creek had moderate area and stream length with relatively high sinuosity throughout. The upper reaches show strong floodplain development and moderate permeability. Oyster bars and submerged coarse substrate were identified, especially in the lower reach. The interior basins were dominated by brackish marsh, while the lower basin had a larger proportion of submerged habitat. Field reconnaissance revealed the presence of submerged logs and limestone in the first-order creeks and a preponderance of game trails and hog wallows within the marsh itself.

Double Barrel Creek had a shorter valley length but similar overall size to Bumblebee, and was highly sinuous in the interior basins while having a short, broad lower reach. The interior basins had well-developed floodplains but decreased permeability and increased runoff potential compared to Bumblebee Creek. Substantial submerged coarse substrate was present throughout the creek basins. The lower and southern reaches each had a large fraction of low marsh. Both Bumblebee and Double Barrel Creeks had low representation of freshwater-marsh habitat.

The lower branches of Bumblebee, Double Barrel, and Barnett Creeks are all moderately entrenched. Upper reaches of Bumblebee and North Double Barrel Creeks are only slightly entrenched with more developed floodplains than the other tributaries. Vegetation has an increasing influence on channel stability with increasing entrenchment values. The upper reaches of the northern tidal creeks can be expected to be more sensitive to loss of creek-bank vegetation resulting from storm, fire, game wallows, or forest morbidity.

The Barnett/McCormick Creek system was somewhat different from the northern creeks. This system was considerably larger in area and in valley length than either of the two northern creek systems, only moderately sinuous throughout, and Lower Barnett, with E=1.5, was the most deeply entrenched of all the sub-basins. Current velocity may be increased in less sinuous channels. If mobile or sessile species are attracted or repelled by stronger currents, preference could be apparent in faunal assemblages between the southern and northern tidal creeks. Potential for water absorption or storage was greater in the southern creek systems, and runoff is expected to be lower or exhibit a time lag. McCormick Creek showed a remarkably small proportion of low marsh, and the southern creeks also lacked coarse bed material in the submerged zone. Data acquisition at the beginning of the falling tide and deeper water may account for less distinction of submerged features observed in the southern creeks.

The interior reaches of Barnett and McCormick had substantially higher proportion of freshwater marsh. Adjoining the McCormick Creek interior is a broad expanse of cypress and willow swamp. Field reconnaissance identified extensive SAV beds of *Vallisneria* in the first-order tributaries of McCormick and Barnett Creeks. The SAV beds were not identified in the imagery, but the combination of freshwater marsh, interior freshwater scrub, and the presence of freshwater SAV together indicate a more prolonged and persistent freshened environment than in the northern creeks.

In summary, the northern creeks provide more flooded low-marsh area accessible to small mobile organisms, more creek edge, and more coarse substrate than the southern creeks. Portions of the northern creeks and the entire Barnett system may have low runoff rates and prolonged discharge during low tide. Barnett Creek and its tributaries are straighter, fresher, and deeper than the northern creeks. The southern creeks may have less coarse substrate and low marsh but deeper submerged habitat. Distinct differences in habitat composition within the intertidal zone exist north and south of the Suwannee River. The habitat differences point toward significant differences in tidal and freshwater hydrology and geomorphology and accompanying differences in potential fish habitat.

Tidal-Creek Monitoring in Conjunction with Fish Sampling

Introduction

The Suwannee Estuary is a complex and dynamic water body governed by several forcing factors, including tidal flow, marine storm surge, input from precipitation, and freshwater discharge from the Suwannee River. Groundwater, as seepage from the Floridan aquifer, also makes a contribution to the salinity regime and hydrology of the area. The estuary lacks an enclosed embayment or protecting barrier islands but is protected in part by an arc of oyster reefs and in part by a broad and shallow offshore shelf.

A three-dimensional model was developed to evaluate the effects of changes in freshwater flow on salinity in the Suwannee Estuary (Bales et al., 2006). The model was calibrated and tested using data collected during 1999-2000, a period of extremely low flows in the Suwannee. Streamflow data indicated there could be a substantial contribution of groundwater to the river between river mile 33 and the head of the estuary. Analysis of data and model-simulation results also indicate that some flow may be bypassing the delta region and flowing southeast across the marsh directly to the Gulf of Mexico.

Hydrodynamics in the estuary are further influenced by the geomorphology of tidal creeks and local topography and bathymetry. Seasonal and inter-annual fluctuations in sea level and tidal flow as well as river discharge affect water level, salinity, and other water-quality parameters.

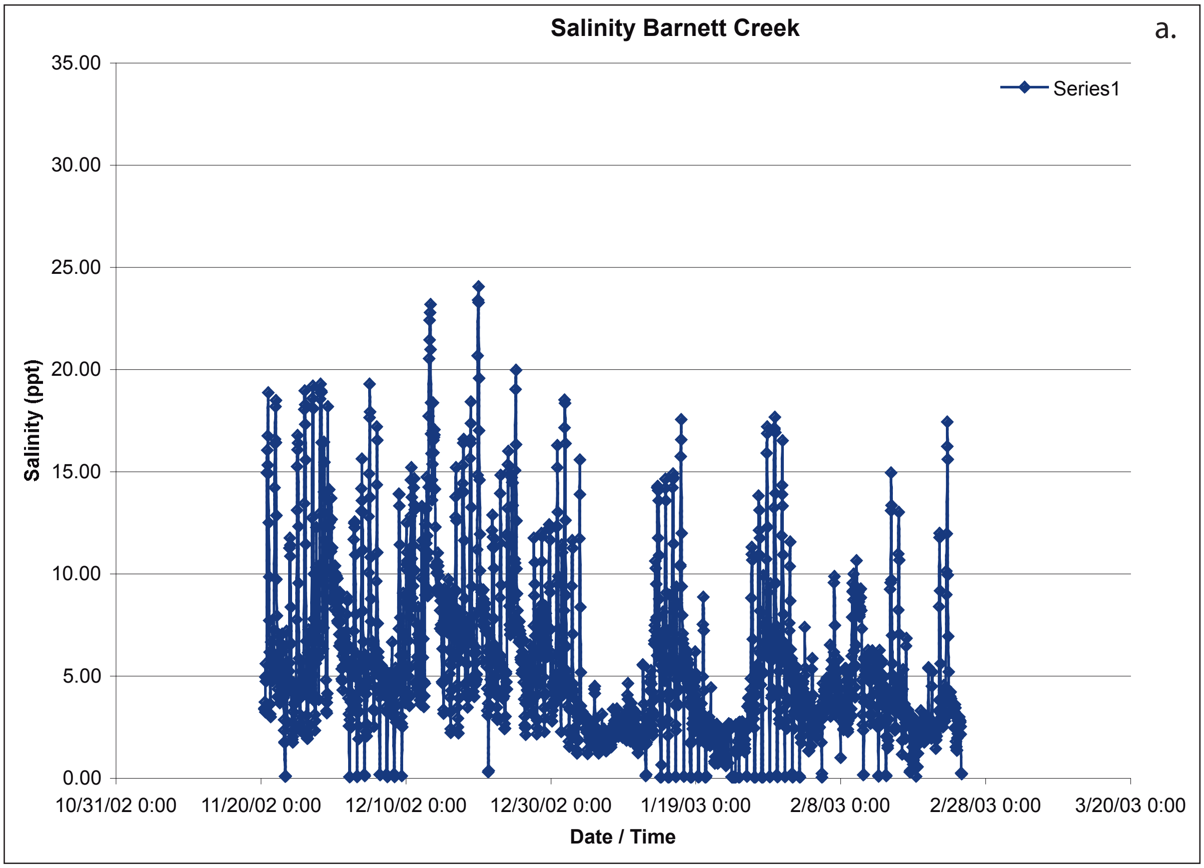
Methods

Water level and water-quality parameters were monitored to characterize and differentiate tidal-creek hydrology. Single-data recorders (YSI) collected temperature, salinity, pH, and relative water levels in each of two creeks, Bumblebee Creek to the north, and Barnett Creek to the south (Fig. 9). Length of record for this preliminary study covered three months of tidal patterns in the winter of 2002-2003. Though the records are brief, they provide the basis for evaluation of creek characteristics and potential sampling methods for the future.

Results

Records showed distinctly different patterns in each creek. In Barnett Creek, a strong diurnal tidal influence on water depth and salinity was observed (Figs. 10a, 10b). High and low water levels were regularly spaced over time, and salinity levels seemed to follow the same pattern. Relative water levels ranged from 0 to 1.5 m in depth. This range was 0.5 m greater than the tide range. Salinity frequently dropped to 0 ppt, indicating a strong freshwater influx, but rose to 24 ppt during high tides. pH rarely varied from 7.7 to 7.8, with one obvious drop in late January that coincides with a prolonged period of low-salinity conditions (Fig. 10c). An anomalous drop in temperature occurred on 01/25/03 (Fig. 10d).

Salinities in Bumblebee Creek range from 3 to 26 ppt but do not coincide with the diurnal tidal cycle (Fig. 11a). A period of low salinities, 8 to 12 ppt, occurred from 12/25/02 to 01/05/03, coinciding with a period of elevated water levels in the creek (Fig. 11b) and with two precipitation events. Precipitation at Cross City, Florida, was recorded as 0.74 inches of rain on December 24 and 1.62 inches on December 31. Cross City is inland of Bumblebee Creek and within the California Swamp drainage area (see Fig. 2).



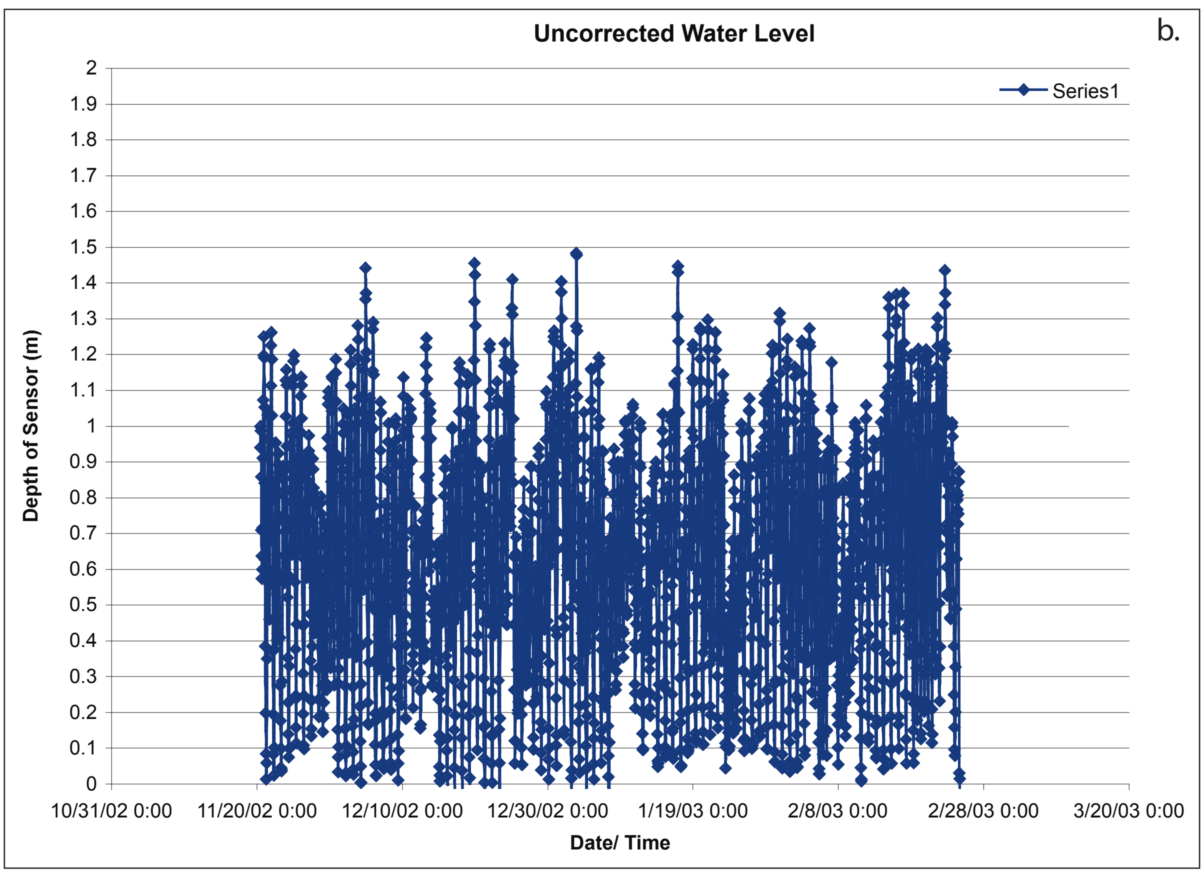
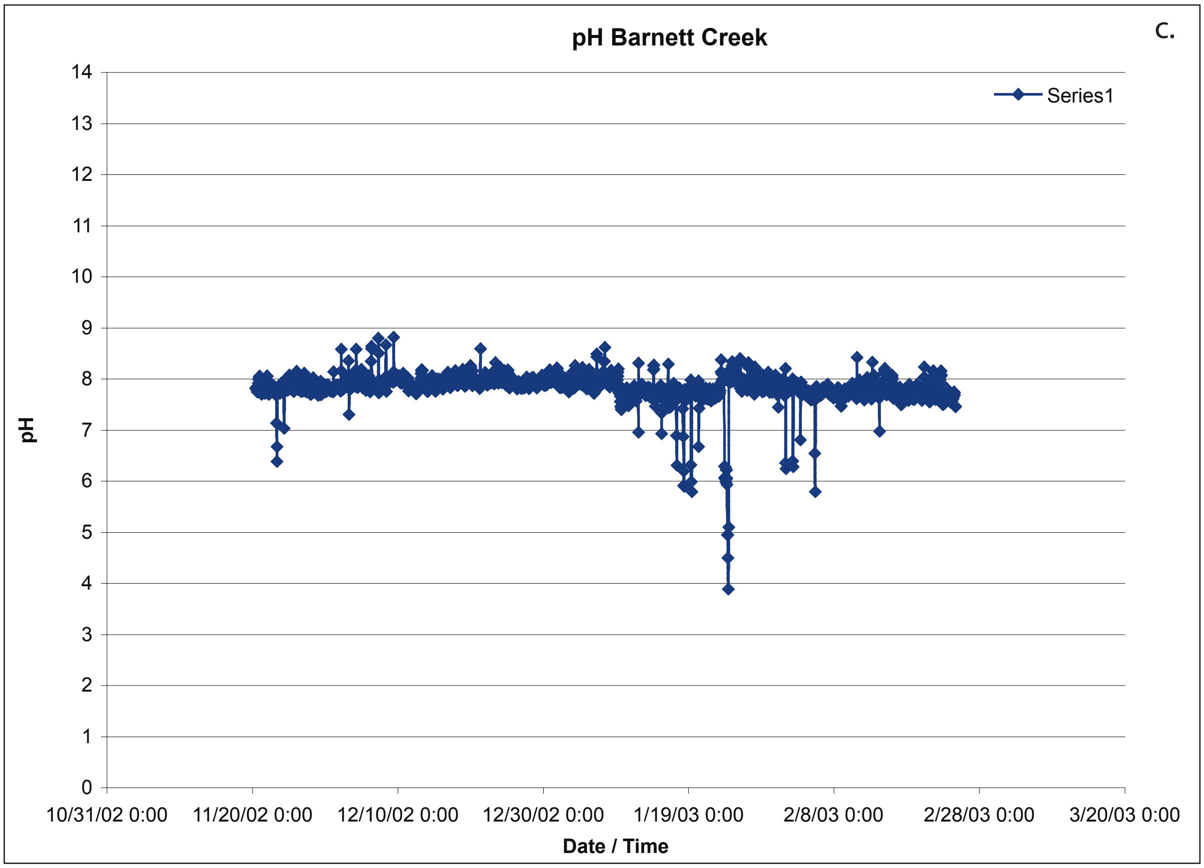


Figure 10a, b. Salinity and uncorrected water depth at Barnett Creek, 2002-2003.



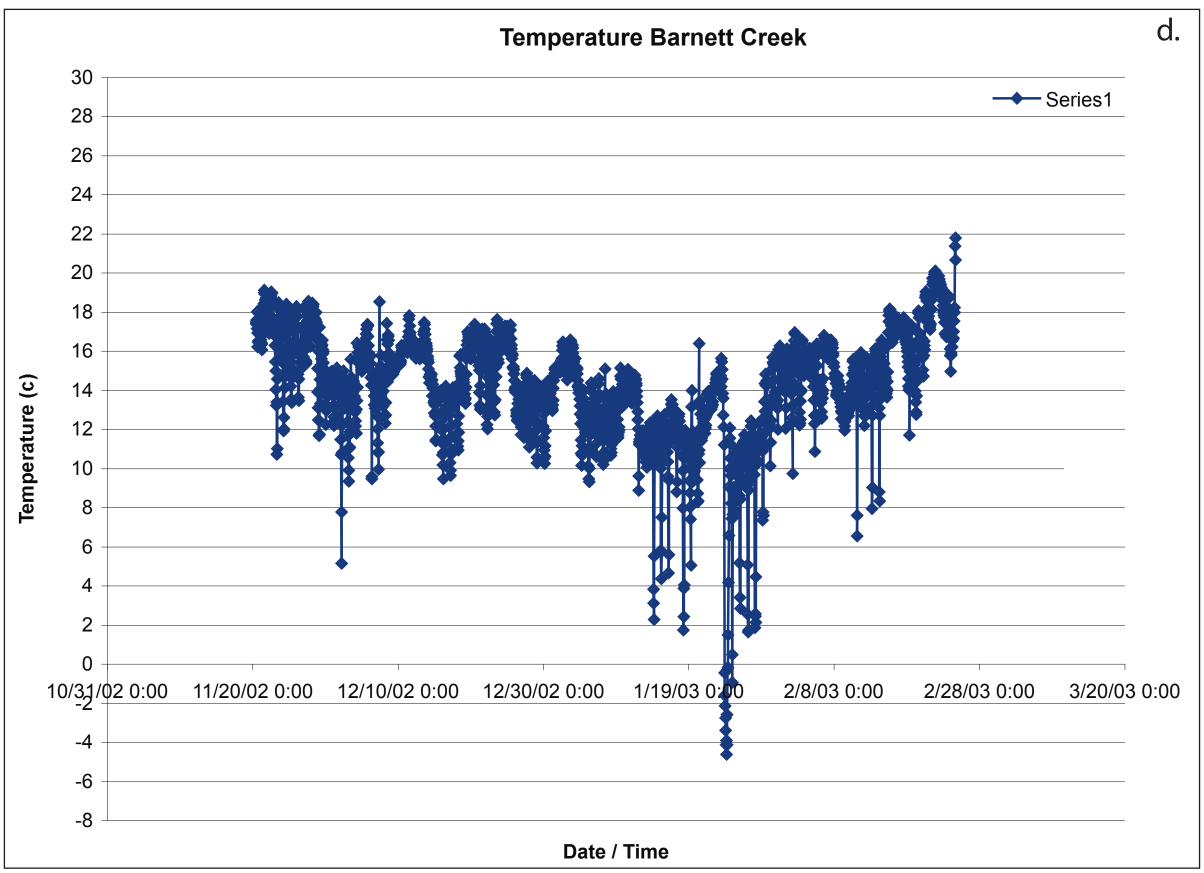


Figure 10c, d. pH and temperature at Barnett Creek, 2002-2003.

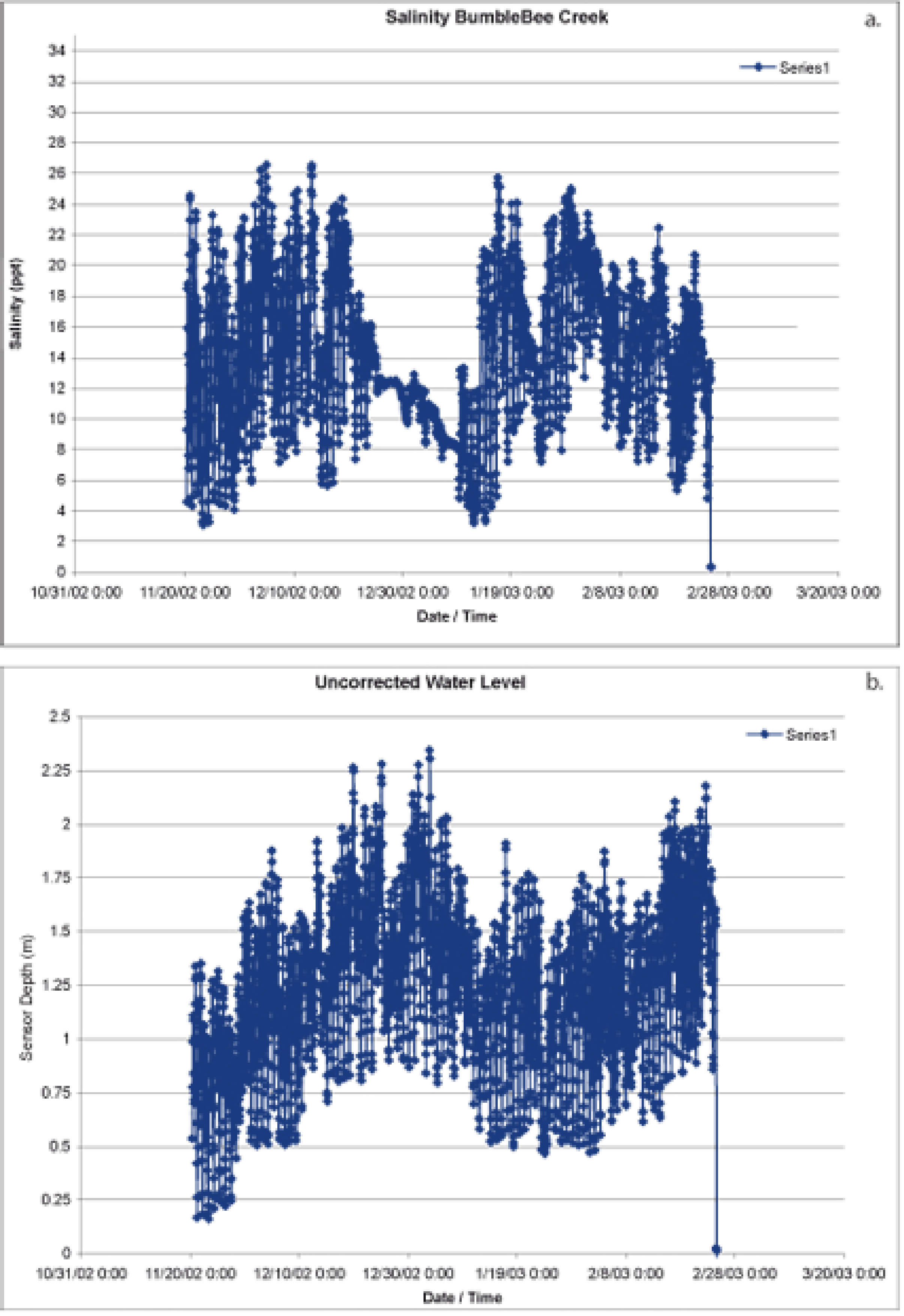


Figure 11a, b. Salinity and sensor depth at Bumblebee Creek, 2002-2003.

Discussion

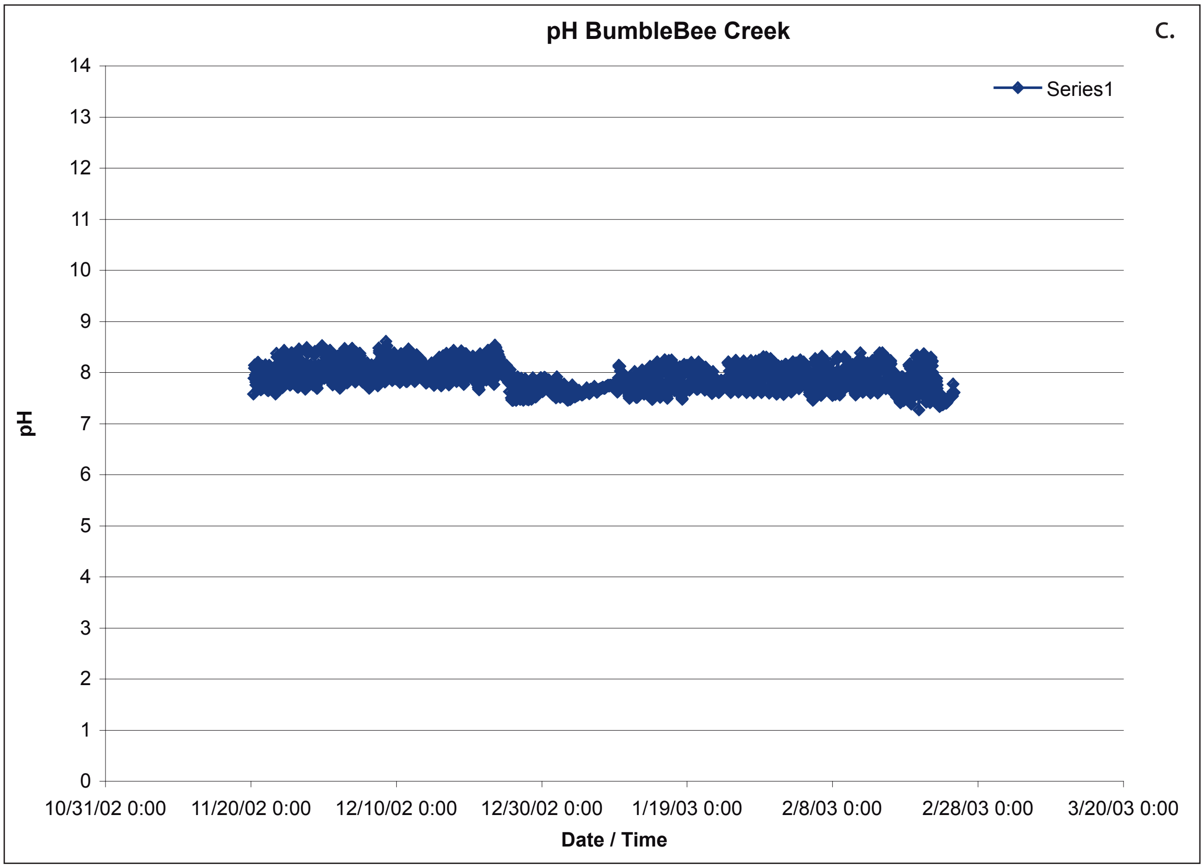
Relative water levels in Bumblebee Creek are much more variable than in Barnett Creek with a full range in excess of 2 m (Fig. 11b). This range exceeds local tide range by 1 m. Although a diurnal cycle can be discerned, there is another pattern in water level that is longer than the lunar tide cycle and may be related to precipitation events or flow from the California Swamp (see Fig. 2). pH in Bumblebee rarely departs from around 8.0 but exhibited a temporary drop to approximately 7.7 at the same time that the creek had low salinities and higher water levels (Fig. 11c).

The only temporally common element between the records of the two creeks is temperature. Temperatures in Bumblebee Creek dropped precipitously in mid-January (Fig. 11d), and the general temperature pattern compares well with that shown for Barnett Creek. Low creek temperatures coincide with an almost record low of -6ºC on January 14, 2003, at Cross City, and for a period of time afterward.

Since fish sampling was to take place during low tide, it was necessary to know how well the predicted tides coincided with actual water levels in the tidal creeks. A comparison between predicted tides and creek water levels indicated a considerable lag to low water in the creeks (Fig. 12). Taking into account wind speed and direction:

- When wind was less than 13 mph, low tide occurred about 1 hour 37 minutes after predicted time.
- When wind was greater than 13 mph, especially from the south or southwest, low tide occurred 2 hours 11 minutes after predicted time.

These data indicate a longer period of monitoring is needed with recorders distributed on transects from the Gulf, along tidal creeks, and extending to sites on the inland side of refuge roads. A spatially distributed arrangement of data recorders can illuminate components of tidal hydrology and water sources. A longer temporal record can clarify seasonal, event-driven, and inter-annual influences.



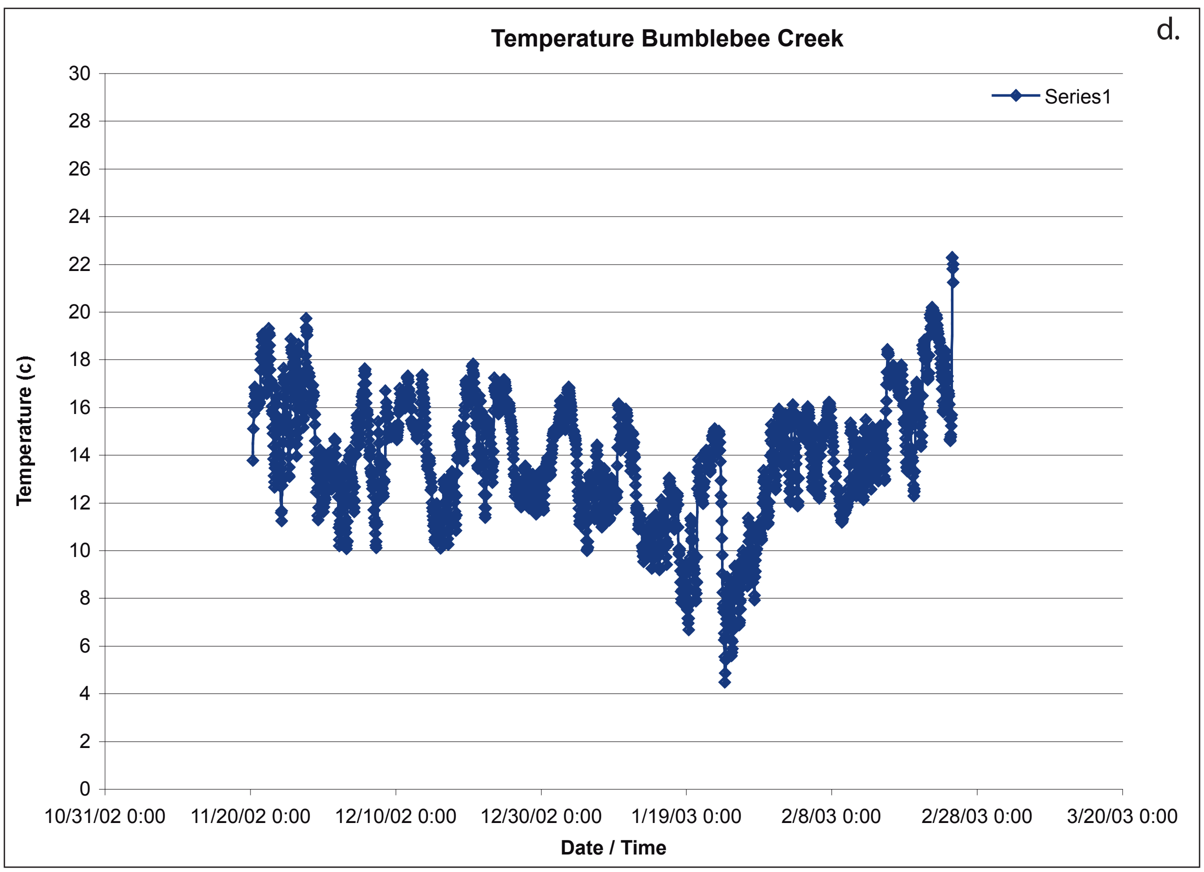


Figure 11c, d. pH and temperature at Bumblebee Creek, 2002-2003.

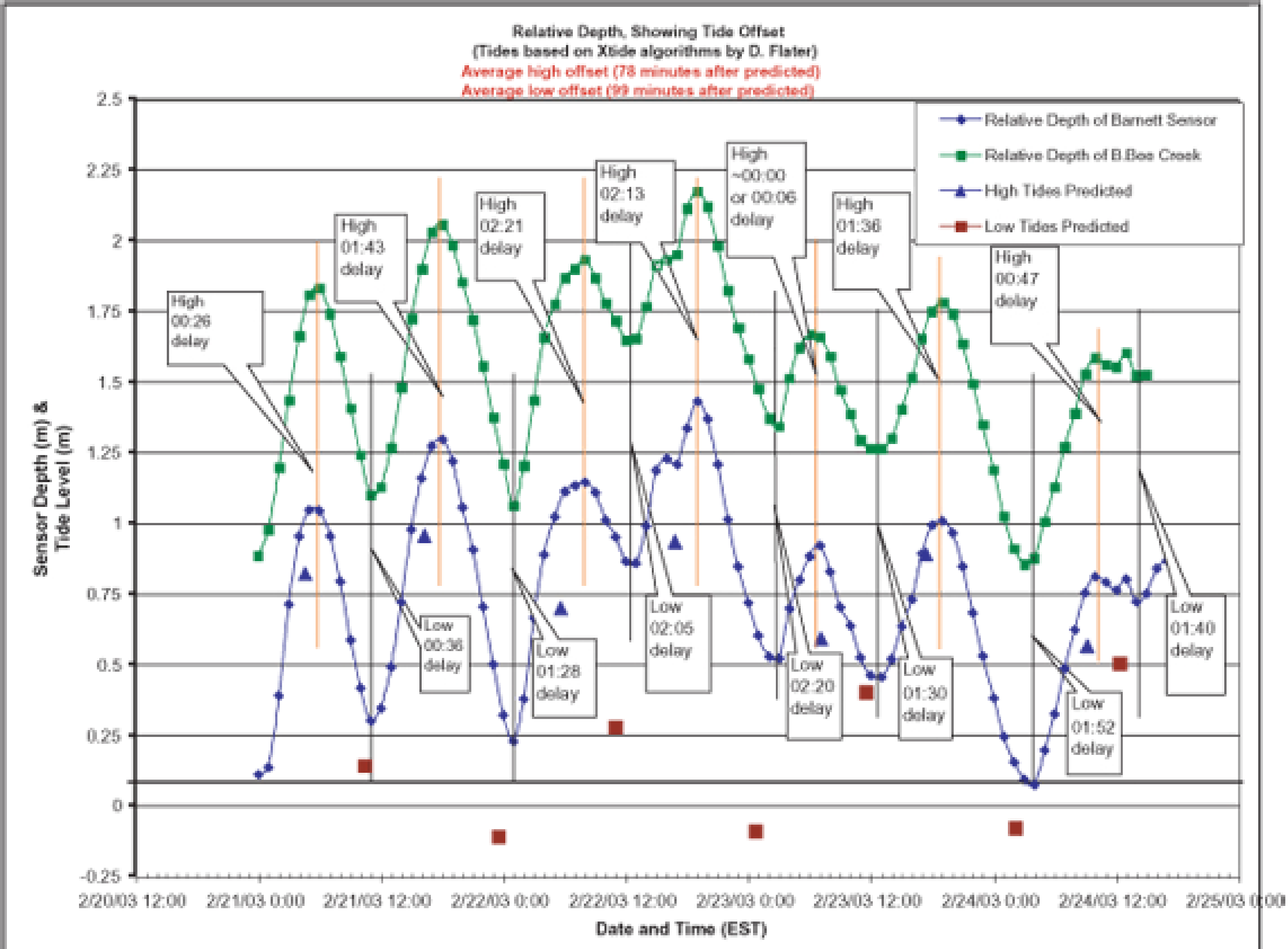


Figure 12. Relative depth, showing high- and low-tide offset at Barnett and Bumblebee Creeks.

Surface-Subsurface Water Exchanges at Tidal-Creek Sites

Estimates of groundwater fluxes to coastal areas of the Lower Suwannee River Basin are needed to quantify freshwater inflows to the coastal marshes and estuary. Freshwater inflows influence water-column and shallow-subsurface salinity in the river basin. Delineation of the location and character of the zone of mixing of fresh and salty subsurface water may also improve our understanding of the groundwater-flow system, which is the dominant source of water for drinking, irrigation, and the maintenance of river and spring flows in the basin. To date, very few measurements of coastal fluxes of groundwater have been made in Suwannee tidal creeks. The objective of this portion of the study was to estimate the magnitude, direction, and salinity characteristics of surface-subsurface water exchanges at two tidal-creek sites adjacent to the Suwannee River Estuary by measuring water levels, temperature, and electrical conductance in the creeks and shallow subsurface.

Methods

Two techniques were used to estimate groundwater seepage to tidal creeks. The first was based on water-pressure measurements that were made above and below the sediment/water interface, which were used to calculate the magnitude and direction of the hydraulic-head gradient across the interface. The gradient information was then used (with Darcy's Law) to estimate the magnitude and direction of water seepage between the creek and the underlying sediments at a given location. Electrical-conductance sensors were co-located with the pressure sensors to evaluate the surface and subsurface salinities at each site.

The second technique employed an array of temperature sensors deployed at various depths within the water column and creek-bed sediments (Lapham, 1989). Relatively simple methods of calculating the seepage rate are possible, such as those described in Bredehoeft and Papadopulos (1965), if suitable conditions are met. This second technique provided an alternative approach for quantifying groundwater seepage, one benefit being the lower cost of the sensors employed.

The two techniques were implemented by installing a set of instruments (GW) at sites north and south of the Suwannee River (see Fig. 9). The first site was located in a tributary to Barnett Creek, approximately 8,075 m inland. The second site was located in Bumblebee Creek, approximately 4,800 m inland. Distance given is linear creek-edge distance from the Gulf of Mexico.

At each site, temperature, electrical conductance, and pressure sensors were deployed near the creek bottom, and at 1.2 to 1.3 m below the creek bottom. Three additional subsurface temperature sensors were also placed at approximately 0.25-m intervals above the deepest sensor at each site (Figs. 13, 14). Pressure, temperature, and conductance measurements began on June 20, 2003, at the Barnett Creek site and on July 3 at the Bumblebee Creek site. Conductance measurements ceased on July 18, 2003, at the Bumblebee Creek site and on September 8 at the Barnett Creek site. Collection of pressure and temperature data was completed at both sites on December 8, 2003.

At both creeks, sediments near the surface of the creek bed consisted of loosely cemented oyster shells that were either exposed or overlain by a very fine, organic-rich muck with a very small fraction of fine silt. The muck layer was about 0.5-1 m thick at the Barnett Creek site. The muck layer was the only lithology encountered during installation of the sensors at the Bumblebee Creek site and, therefore, extended at least 1.6 m below the creek bottom.

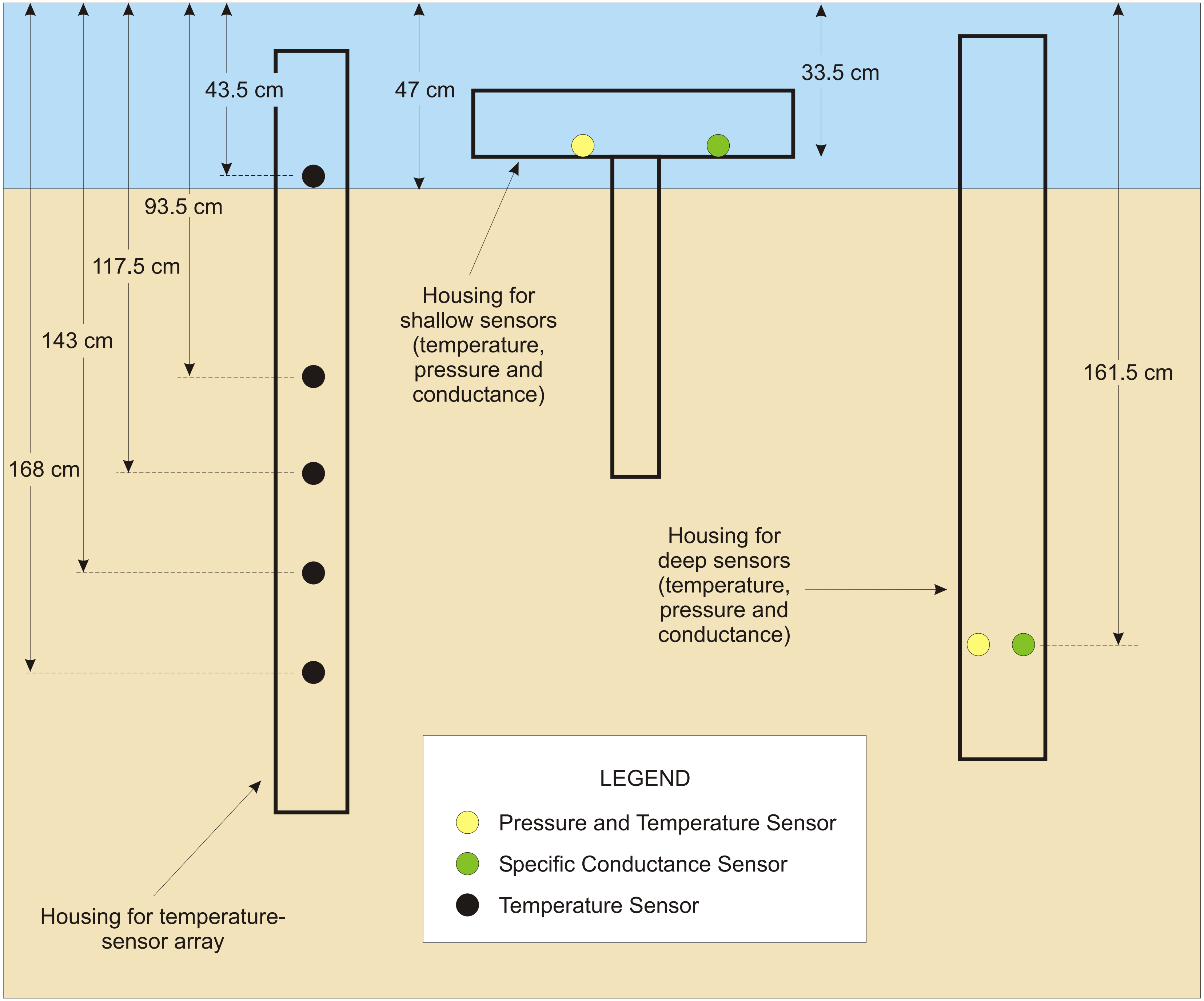


Figure 13. Barnett Creek sensor depths 12/08/03, 11:55 pm, Eastern Standard Time.

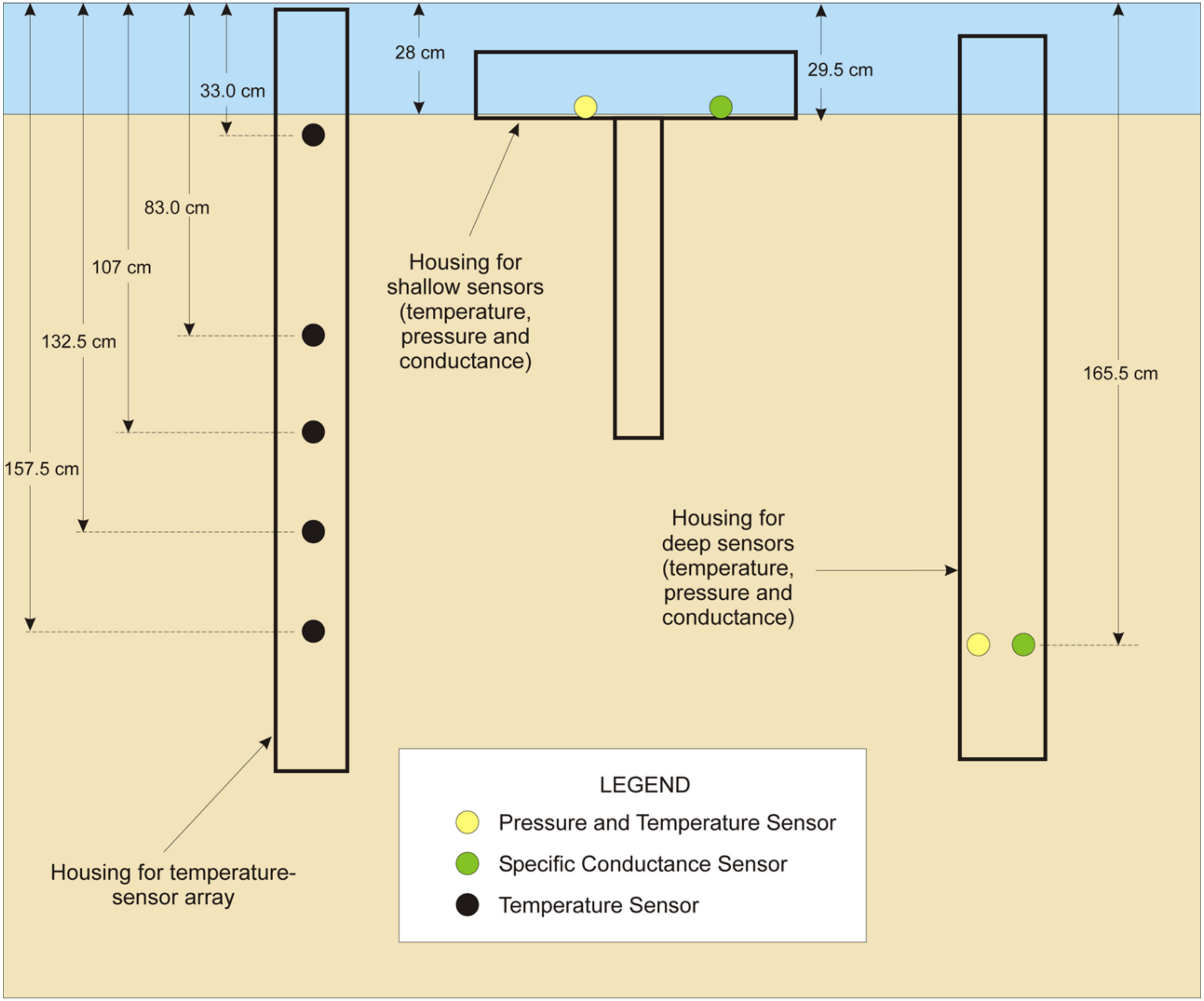


Figure 14. Bumblebee Creek sensor depths 12/08/03, 14:40 pm, Eastern Standard Time.

Results

Inferences from hydraulic-head data

At both sites, water levels computed from the pressure measurements exhibited a mixed-tide pattern, two high and two low tides per tidal day, with successive high or low tides having unequal heights. At the Barnett Creek site, the pressure data indicated that creek levels typically varied over a range of about 0.8 to 1.1 m during a tidal day, from higher-high tide to lower-low tide (Fig. 15). The pressure measurements also indicated that the creek bed at the Barnett Creek site was not submerged at all times during the study. At the Bumblebee Creek site, the creek-level range varied from about 0.5 to 1 m (Fig. 16). The upper pressure sensor at the Bumblebee Creek site was exposed during the lowest tides on about 25% of the days. This reading indicated that the creek bed was exposed at least part of the day during about 25% of the study period.

The pressure data from both sites indicated a consistent pattern of seepage from the subsurface into each creek. At Barnett Creek, the median hydraulic-head difference (deep minus shallow head) was 0.05 m, which is equivalent to a median hydraulic-head gradient of about 0.04 (dimensionless). At Bumblebee Creek, the median hydraulic-head difference was 0.08 m, which is equivalent to a median hydraulic-head gradient of about 0.06. Estimates of an upper limit of seepage at these sites is possible using Darcy's Law, which states that the flow rate per unit area through a porous medium is equal to the product of the hydraulic conductivity of the medium and the hydraulic-head gradient. Substituting a value of 0.06 for the hydraulic-head gradient and a value of 10-2 m/day for the upper limit of hydraulic conductivity of the organic-muck sediments at both sites yields an upper limit for the seepage rate of about 0.2 m per year.

At both sites, temporal variations in the hydraulic-head gradient followed similar patterns. The gradient was typically at a maximum near lower-low tide and then decreased to a minimum halfway between lower-low and the following high tide. The gradient then increased gradually until about halfway through the recession from higher-high to lower-low tide, when the gradient then increased sharply as it approached another maximum near lower-low tide. At the Barnett Creek site, the maximum gradient during a tidal day was typically about 0.08, which was 2 times greater than the typical minimum gradient of 0.04. At the Bumblebee Creek site, the maximum gradient during a tidal day was typically about 0.11, which was 2.75 times greater than the typical minimum gradient of 0.04. Note that the range of variation at both sites is probably slightly underestimated because the shallower pressure sensors at these sites were not submerged during the lowest tides at least 25% of the time. These results indicate that subsurface seepage to both creeks varied by a factor of two or more at both sites during a typical day.

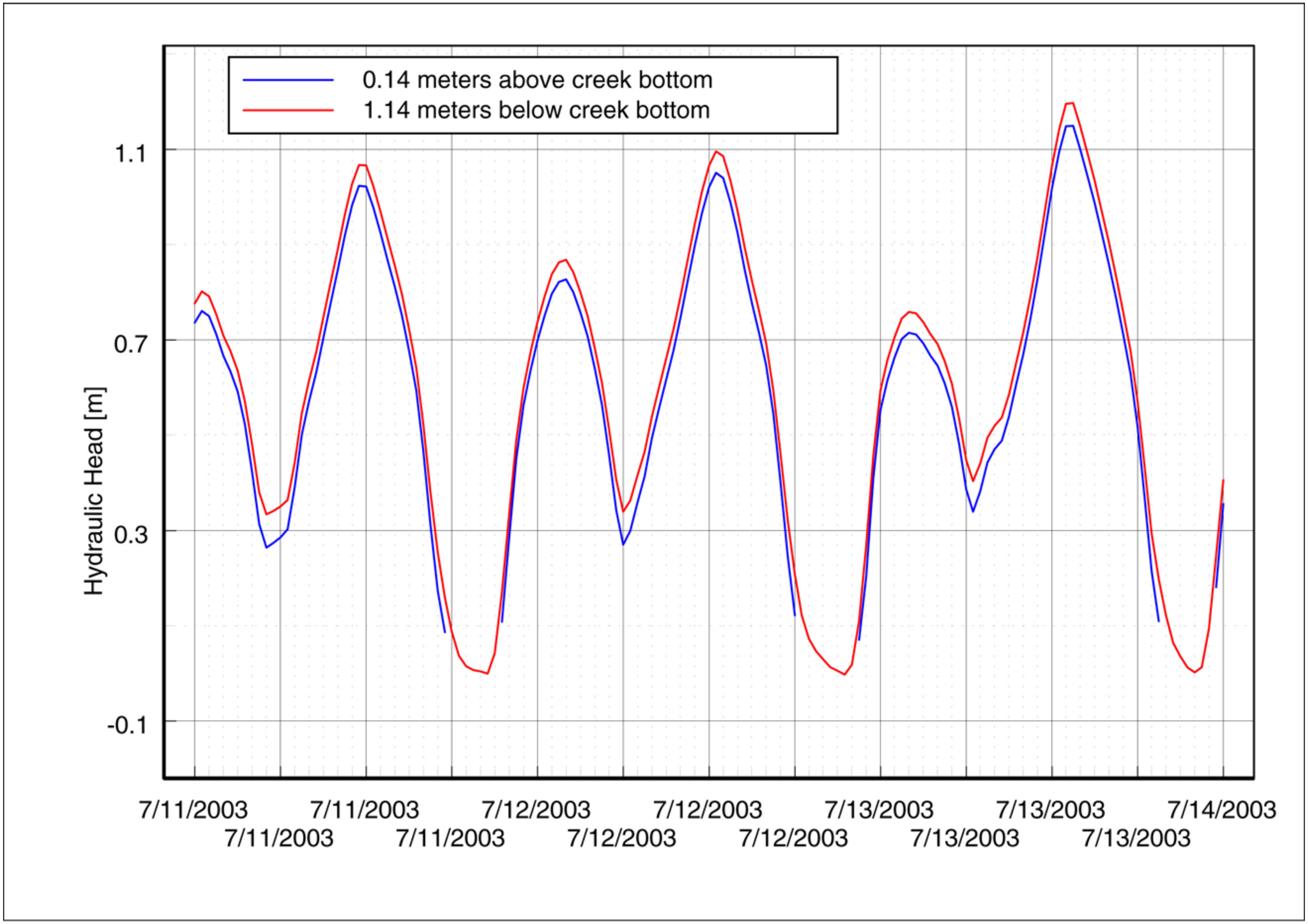


Figure 15. Hydraulic-head (water-level) time series at Barnett Creek seepage-measurement site.

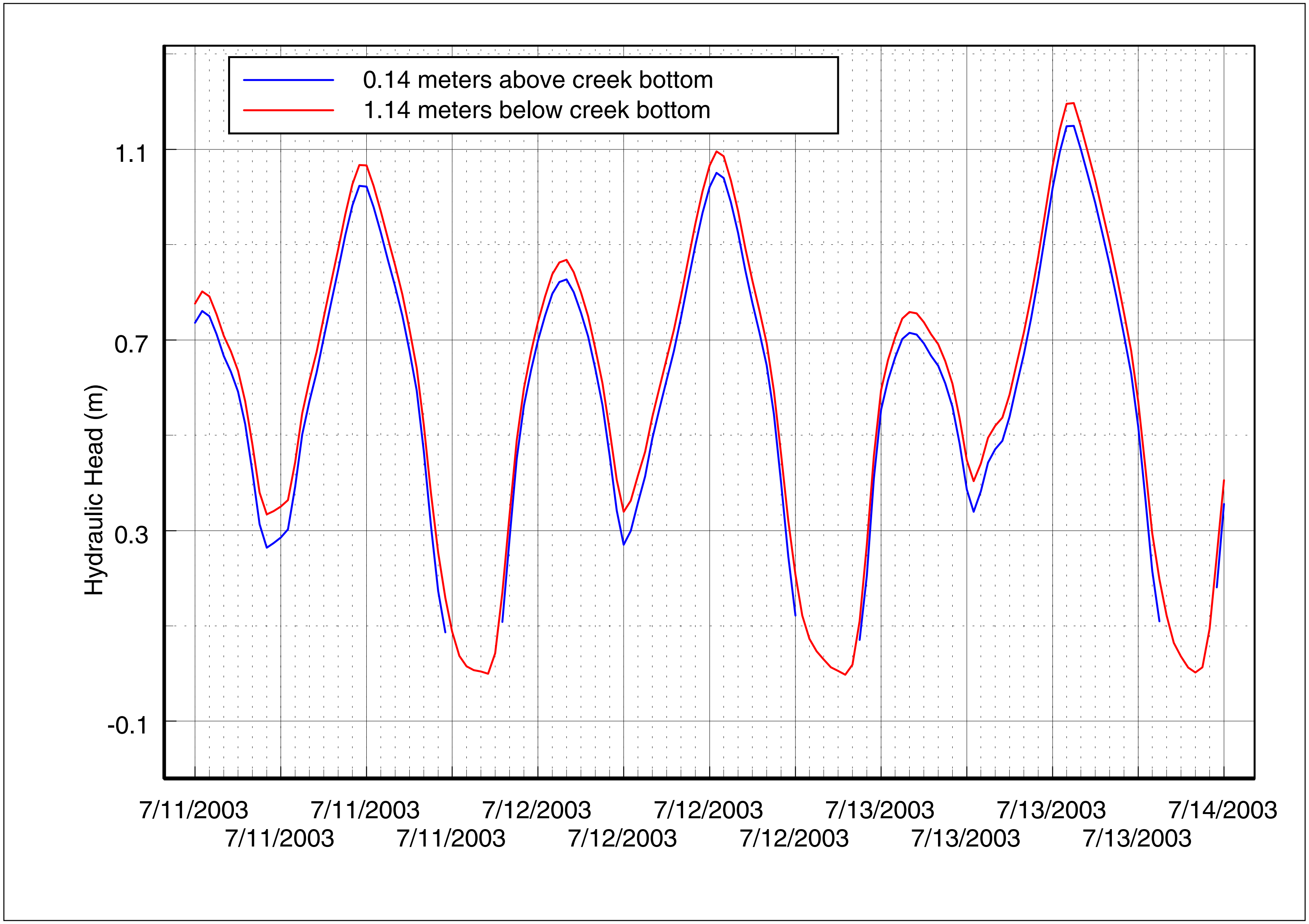


Figure 15. Hydraulic-head (water-level) time series at Barnett Creek seepage-measurement site.

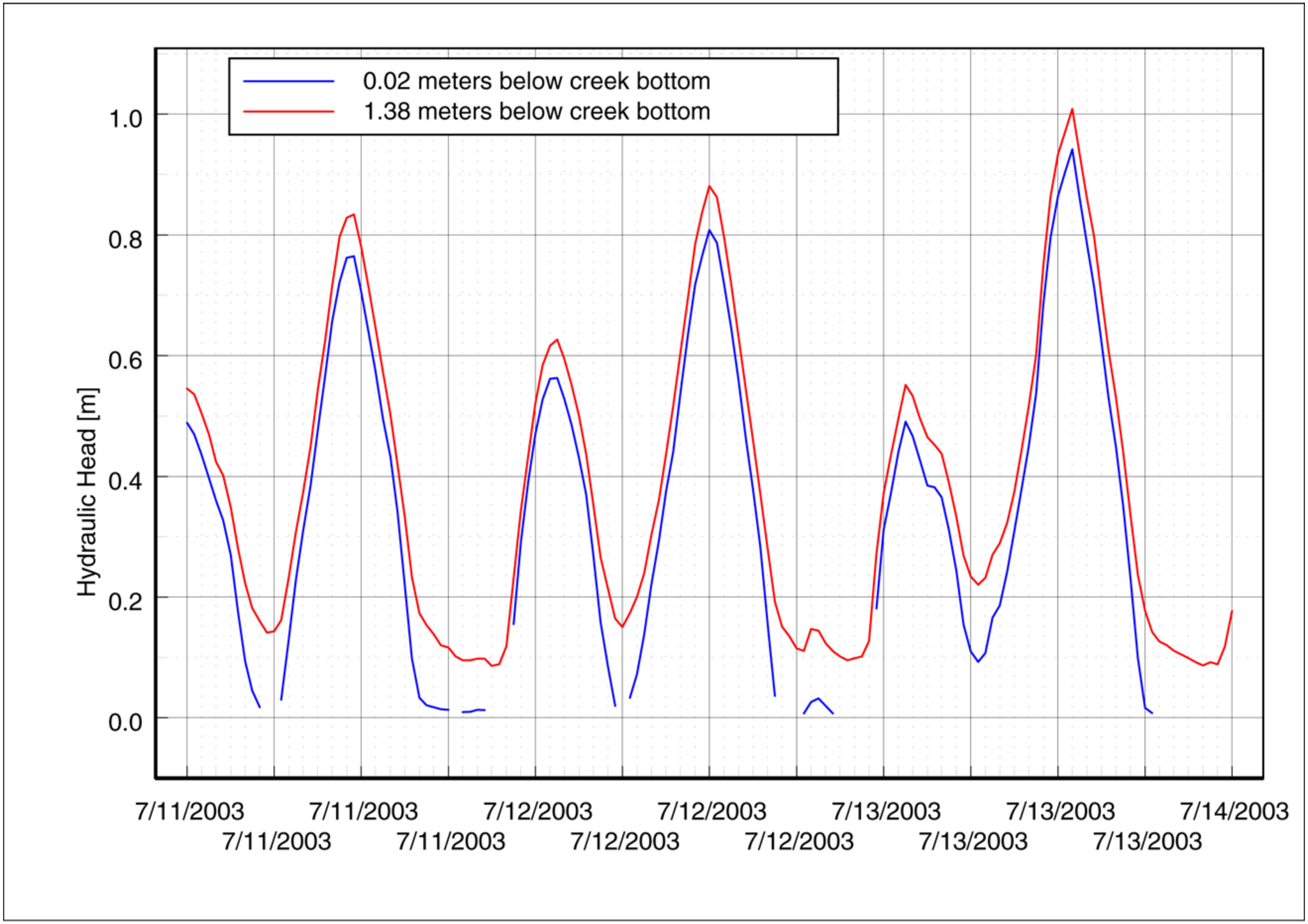


Figure 16. Hydraulic-head (water-level) time series at Bumblebee Creek seepage-measurement site.

Inferences from specific-conductance measurements

The specific (electrical) conductance measurements at both sites indicated that the pore water in the subsurface, below the creek bed, was saltier than the overlying creek water (Figs. 17, 18). At the Barnett Creek site, the specific-conductance values measured by the subsurface sensor were influenced by the injection of fresher creek water that occurred during site construction. This effect gradually diminished over the first month of deployment. After that time, the subsurface conductance was fairly steady: the median value was about 8.8 milliSiemens (mS), and the lower and upper quartile were 8.7 and 8.8 mS, respectively. Measurements made at the sensor deployed in the creek (above the creek bed) were fresher and more variable: the median value was 2.5 mS, with a lower and upper quartile of 1.5 and 3.3 mS, respectively. Lower (fresher) values typically occurred near low tide, and higher (saltier) values typically occurred near higher-tide conditions (Fig. 19). This relation between salinity and tide level was also observed at the Bumblebee Creek site.

The specific conductance of subsurface pore water at Bumblebee Creek was also affected by the injection of fresher creek water that occurred during site construction. This effect diminished considerably toward the end of the deployment of the conductance sensors at Bumblebee Creek, when specific conductance appeared to ‘level off’ at a value of about 26 mS. This value is probably very close to the value that would have been measured if the deployment of the conductance sensors had been extended, since the conductance measured at the Barnett Creek site two weeks after site construction was within 10% of the value that was measured four weeks after construction. In addition, much more surface water was injected at the Barnett Creek site to place deep sensors within the oyster-shell beds.

Like Barnett Creek, measurements at the sensor deployed in Bumblebee Creek (above the creek bed) were fresher than the subsurface measurements: the median creek conductance was 16.9 mS, with a lower and upper quartile of 14.4 and 18.6 mS, respectively. Note that the median creek (surface water) value at Bumblebee Creek is nearly 7 times the median surface-water value (2.5 mS) measured at the Barnett Creek site. This difference may arise because of the influence of fresher inflows of water from one or more tributaries that connect Barnett Creek with the East Pass of the Suwannee River.

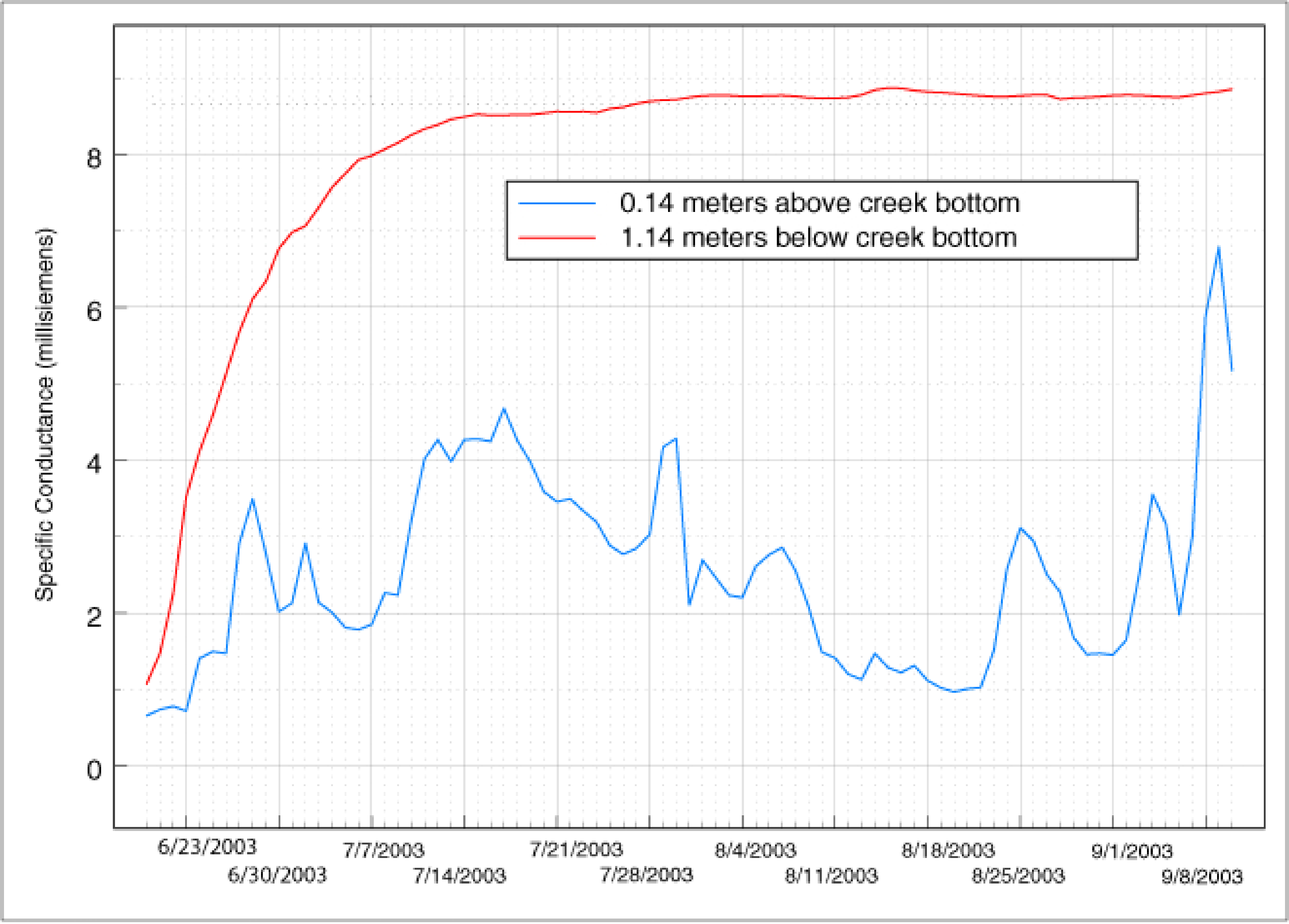


Figure 17. Time series of daily mean specific conductance at Barnett Creek seepage-measurement site.

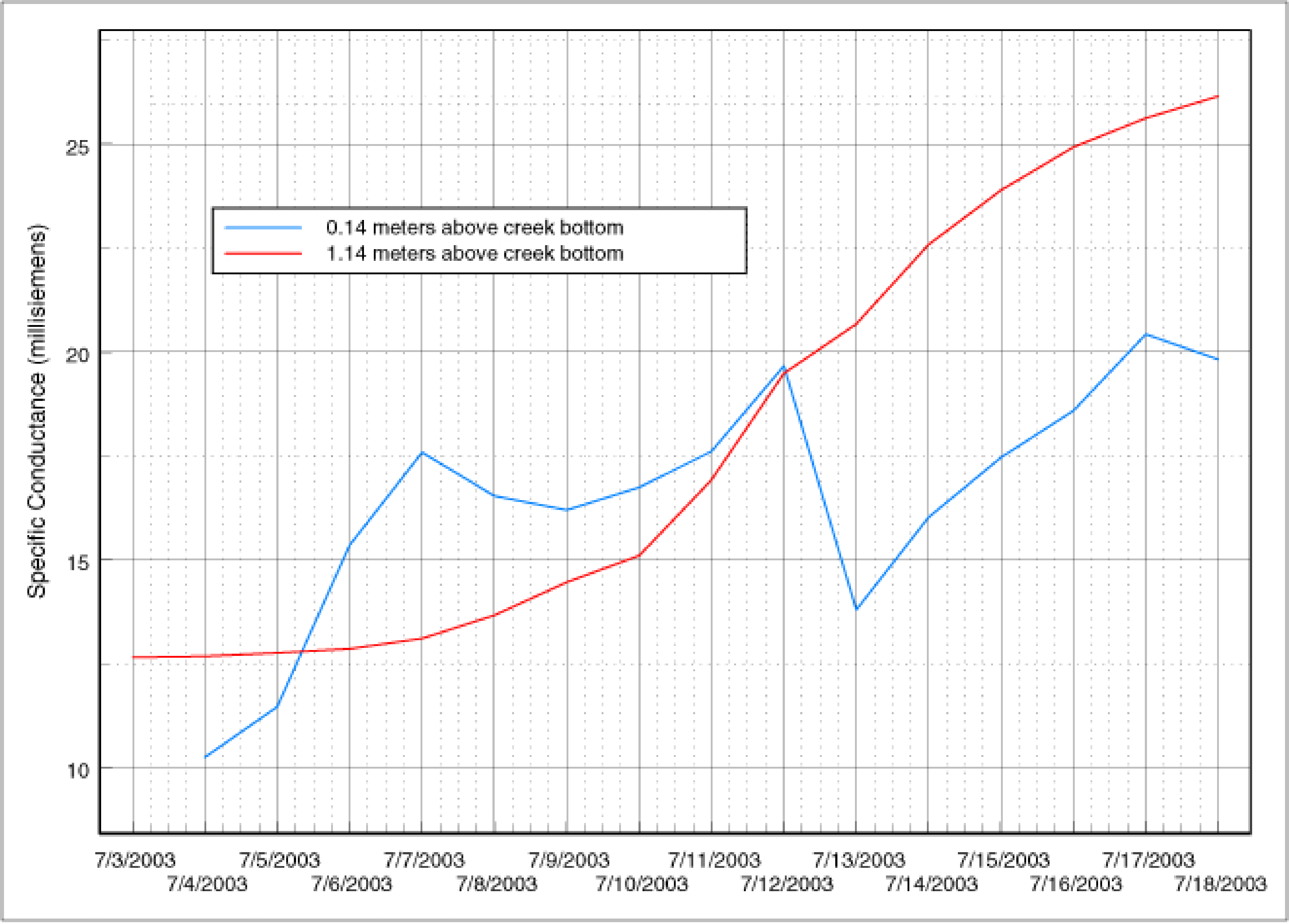


Figure 18. Time series of daily mean specific conductance at Bumblebee Creek seepage-measurement site.

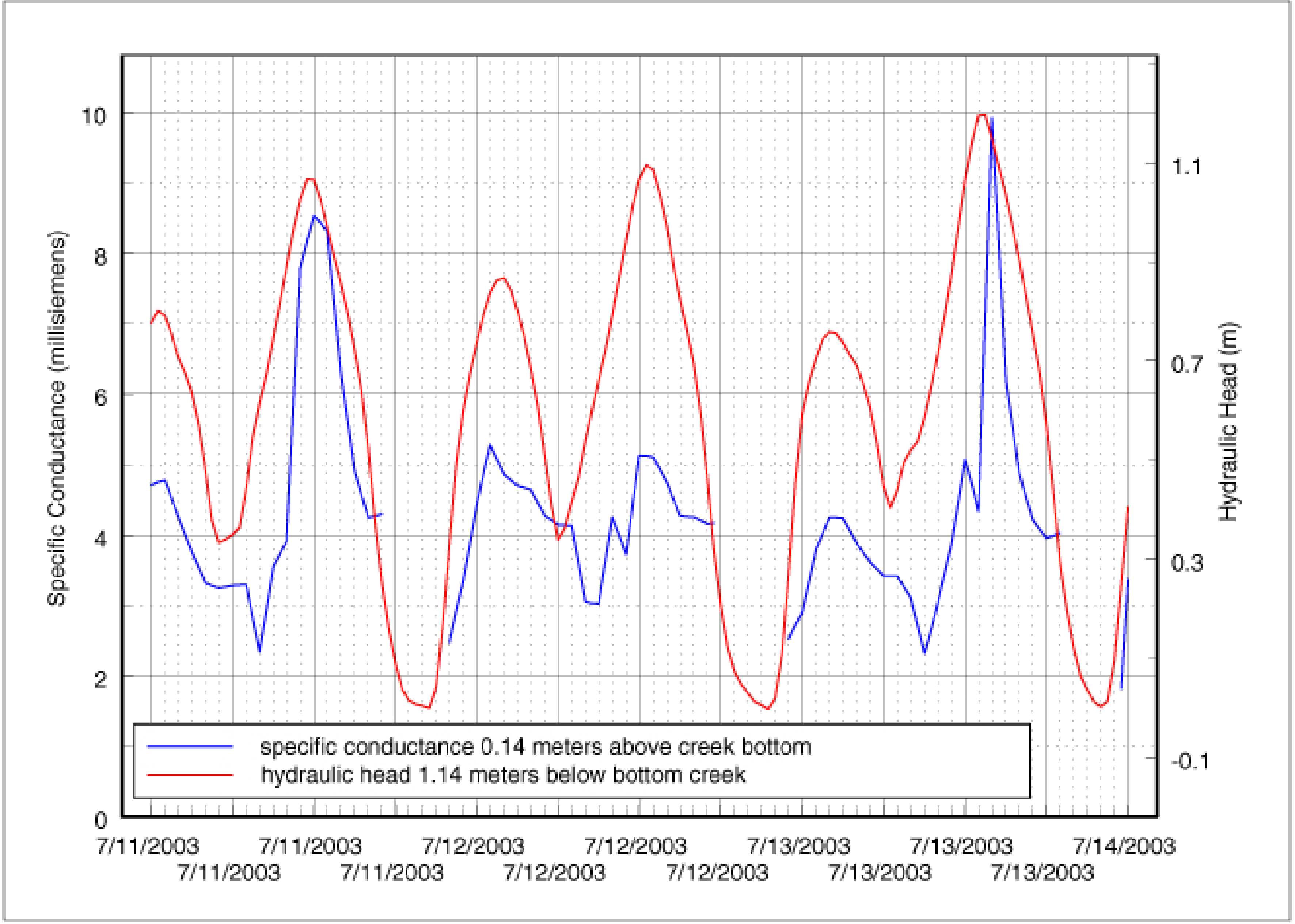


Figure 19. Time series of specific conductance and hydraulic-head (water-level) measurements at Barnett Creek seepage-measurement site.

Inferences from temperature measurements

Temporal patterns in subsurface temperature measurements were fairly similar at both sites. Over monthly and longer time scales, temperature changes reflected seasonal changes in surface temperatures. Temperatures gradually increased from the beginning of the deployment, peaked between the beginning of September and the end of October, and then declined with the onset of cooler surface temperatures during the following months (Figs. 20, 21). Shorter-term temporal variations, on the order of a few days or less, at various depths were consistent with patterns typically observed in the shallow subsurface, with shallower depths exhibiting wider diurnal temperature swings and a more rapid response to surface-temperature changes. The chief difference in the temporal patterns observed at the two sites was the more rapid response of subsurface temperatures during November and December. This difference is probably caused by the exposure of the creek bed at the Barnett Creek site at lower tides during those months. Some of the short-lived upward temperature spikes were created by injection of surface water during installation of the temperature sensors and their retrieval for data download. These spikes occurred on June 20 and September 8 at the Barnett Creek site, and on July 3 and July 18 at the Bumblebee Creek site.

Spatial patterns in the subsurface temperature measurements were also fairly similar at both sites. During the first half of the study period, there was a strong, downward temperature gradient, indicating a flux of heat from the surface into the subsurface. Reversal of the temperature gradient (and therefore direction of heat flux) began near the middle part of October at both sites. By the middle of November, this reversal was essentially complete and temperatures consistently increased with depth. The primary difference in spatial patterns at the two sites was the warmer temperatures that were measured in the deeper subsurface sensors. For example, temperatures measured at the deepest subsurface sensors were 0.5 to 1ºC warmer at the Barnett Creek site than at the Bumblebee Creek site from the beginning of the deployment through early September. The differences occurred even though surface temperatures were often similar or slightly warmer at the Bumblebee Creek site. Lower subsurface temperatures indicate that the rate of groundwater-to-creek seepage may be greater at the Bumblebee Creek site, since the low temperatures more closely approximate the temperature (22ºC) of groundwater in this region (SRWMD 2007). Quantification of the seepage-rate differences was not attempted because of the apparently low rates and unsteady nature of the seepage, as indicated by the pressure data, and the fact that the profiles were neither linear nor exponential in shape. Thus, simpler approaches for calculating seepage rates, such as methods described by Bredehoeft and Papadopulos (1965) and Land and Paull (2001), are not appropriate. Instead, the more complicated numerical approaches described by Land and Paull (2001) and Constantz et al. (2002) are required.

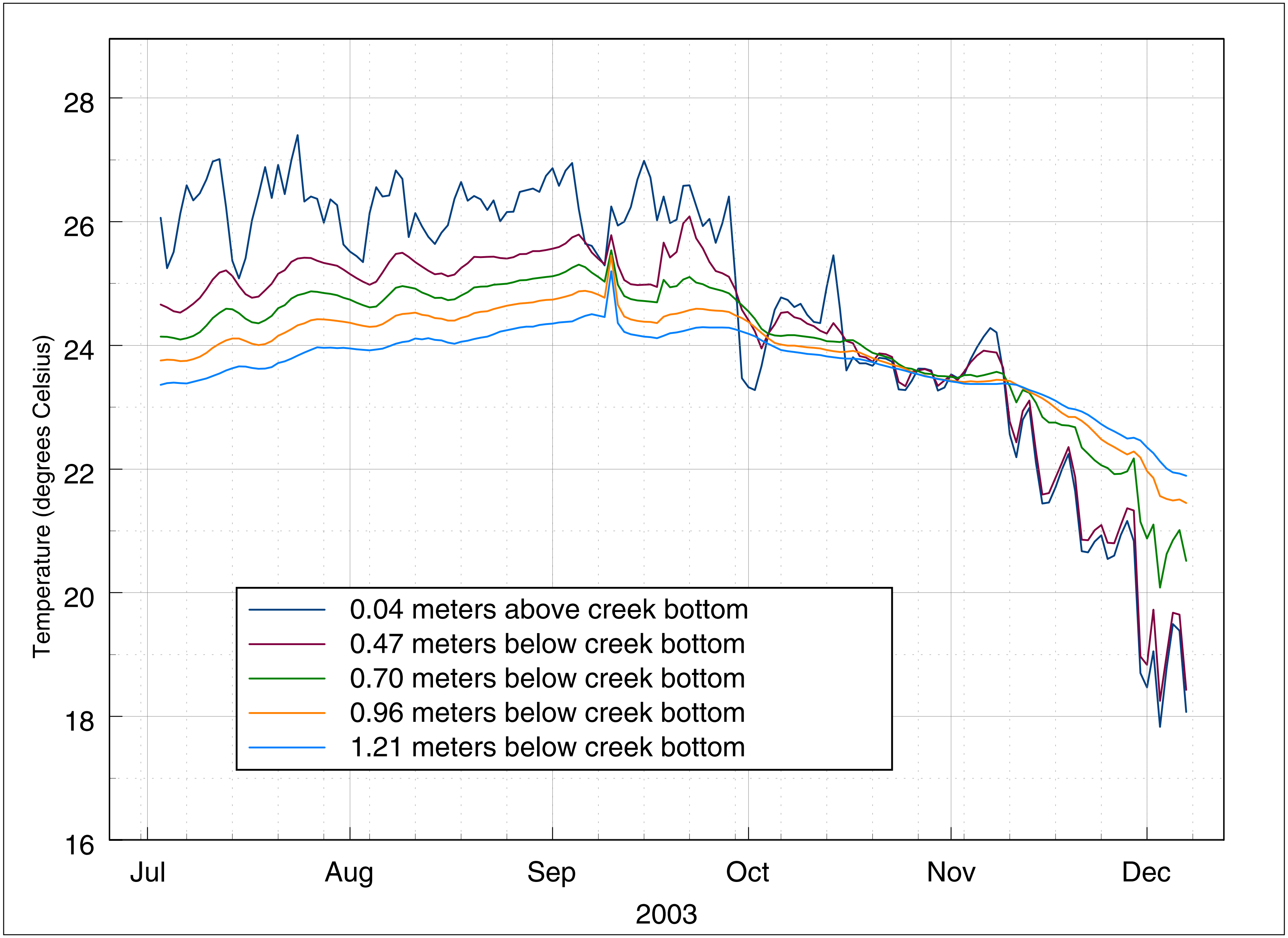


Figure 20. Time series of daily mean temperature profiles at Barnett Creek seepage-measurement site.

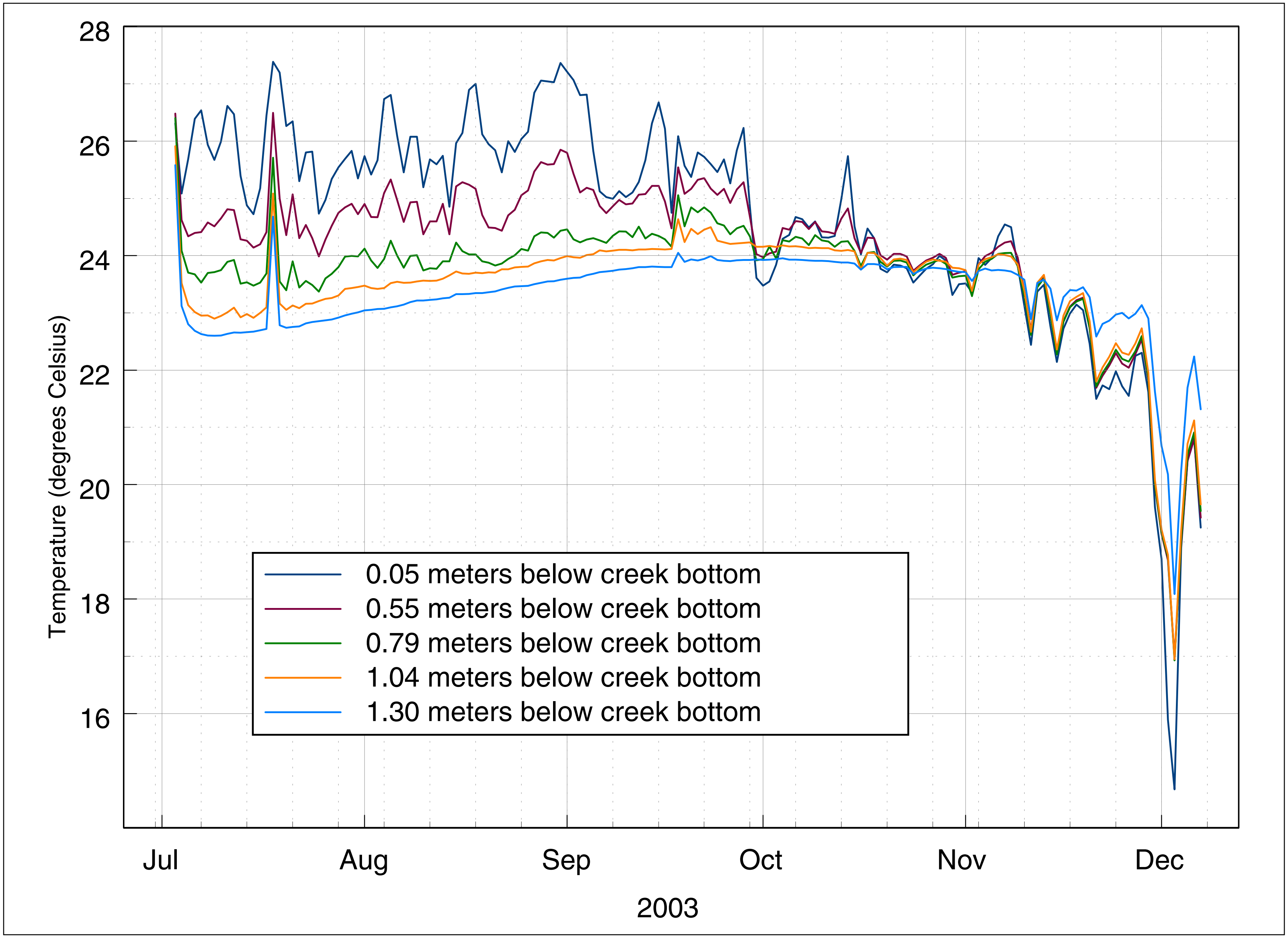


Figure 21. Time series of daily mean temperature profiles at Bumblebee Creek seepage-measurement site.

Discussion

Water-level data at both tidal-creek sites indicate a consistent pattern of upward seepage from the subsurface into the creeks. Over a tidal day, seepage rates typically vary by a factor of 2 to 3 at these sites. Seepage rates are typically at a maximum near lower-low tide and decrease to a minimum halfway between lower-low and the following high tide. Seepage rates are underestimated because both sets of recording instruments were installed in shallow sections of the creek bed that were exposed frequently during regular tidal cycle.

Vertical hydraulic-head gradients indicate that the upper limit for the seepage rate is about 0.2 m per year at both sites. Electrical-conductance measurements at both sites indicate that the pore water in the subsurface (below the creek bed) was saltier than the overlying creek water. When coupled with water-level observations, these data indicate a consistent pattern of upward-seeping, brackish groundwater. Thus, both sites appear to be located in a zone of mixing between upwelling salt- and freshwater. Temperature measurements followed seasonal patterns of surface temperatures, with temperature profiles showing typical patterns of dampened fluctuations with increasing depth. Temperatures measured in the deepest subsurface sensors were 0.5 to 1ºC cooler at the Bumblebee Creek site, which indicates that the seepage rate is probably greater at this site. The cooler Bumblebee Creek site is considerably closer to the Gulf of Mexico, 4,800 m up creek, than the Barnett Creek site, 8,075 m up creek. Distance from the Gulf of Mexico may be an influence.

Use of the temperature data to quantify site differences, as well as the magnitude of seepage at the individual sites, was not attempted during this study, in part because of the unsteady nature and relatively low rates of seepage. Quantitative seepage estimates are possible using the temperature data if numerical-modeling approaches are used. Estimates of seepage over a larger area should also be possible if more instruments are deployed, especially if combined with areally extensive measurements of heat fluxes.

Tidal-Creek Fish Ecology

Background

The Suwannee River Estuary System (SRES) is a large, relatively unaltered and natural system that includes large areas of estuarine habitat for many ecologically important and valued fish species. The system also provides critical essential habitat for the largest population of the threatened Gulf sturgeon (*Acipenser oxyrinchu, desotoi*). Despite the obvious value and importance of the SRES in terms of essential fish habitat (Williams et al., 1990), only a few studies (Mattson and Krummrich, 1995; Tsou and Matheson, 2002; Tuckey and Dehaven, 2006) have been conducted in the system. Florida Marine Research Institute (FMRI) runs a Fisheries Independent Monitoring Program to monitor the relative abundance of fishery resources in major estuarine systems in Florida. This monitoring is done by using statistically valid sampling designs in particular estuarine systems to sample juvenile and adult fishes. The FMRI Laboratory in Cedar Key conducts the monitoring program in the Suwannee River Estuary.

Salinity, along with temperature and dissolved oxygen, are the primary physicochemical factors determining fish-habitat suitability (Miller et al., 2000). Because water-column characteristics can vary rapidly in time and space, they are sometimes termed dynamic habitat (Browder and Moore, 1981). Food/prey availability is the primary biotic-habitat factor, although predation also can be important. Accessibility to habitat can also pose constraints. Routes to intertidal habitat may be narrow, shallow, and temporary. Specific requirements related to type and size of organism may limit the number actually accessing these environments. Additionally, many species require or survive and grow best in certain stationary or structural habitats such as seagrass beds, oyster bars, shallows, and small creeks (Browder and Moore, 1981; Edwards, 1991).

Large areas of the SRES may undergo transition from marine or estuarine conditions to freshwater conditions and back again in a matter of weeks or months. Such transitions greatly alter the fish communities, but little is known about these transitions and their impacts on fish and fisheries. A shift in salinity has two potentially important indirect impacts on fish nursery-habitat suitability. First, transition from higher salinity to freshwater conditions (or vice-versa) can have an ecological effect that is analogous to fire in terrestrial systems. Either transition results in “resetting” of ecological succession, with new communities of benthic plants and organisms becoming established. The new communities may include productive prey organisms that support high productivity of juvenile fishes. Second, salinity transition to freshwater or an oligohaline condition provides juvenile fishes with refuge from marine predators that tend to be much less tolerant of low salinity. The timing and magnitude of salinity transitions can therefore determine the productivity of the system with regard to habitat for ecologically and economically important fish species.

Even small fishes have substantial mobility and can move away from areas with unsuitable conditions. Many estuarine fishes are physiologically able to acclimate to and tolerate a wide range of physical conditions, especially variations in salinity. Many of the prey resources supporting small and juvenile estuarine fishes are benthic, sessile, and less able to tolerate extreme changes in physical factors such as salinity. Overall habitat suitability, therefore, is determined by the combination, interaction, and overlap in time and space of dynamic (physical), structural, and biotic factors (Browder and Moore, 1981; Edwards, 1991). Understanding these factors is essential for understanding the ecological functioning of a system.

Fish-collection methods

Preliminary fish samples were collected during the initial transition from low river flow to high river flow 17-19 March 2003 (Fig. 22).

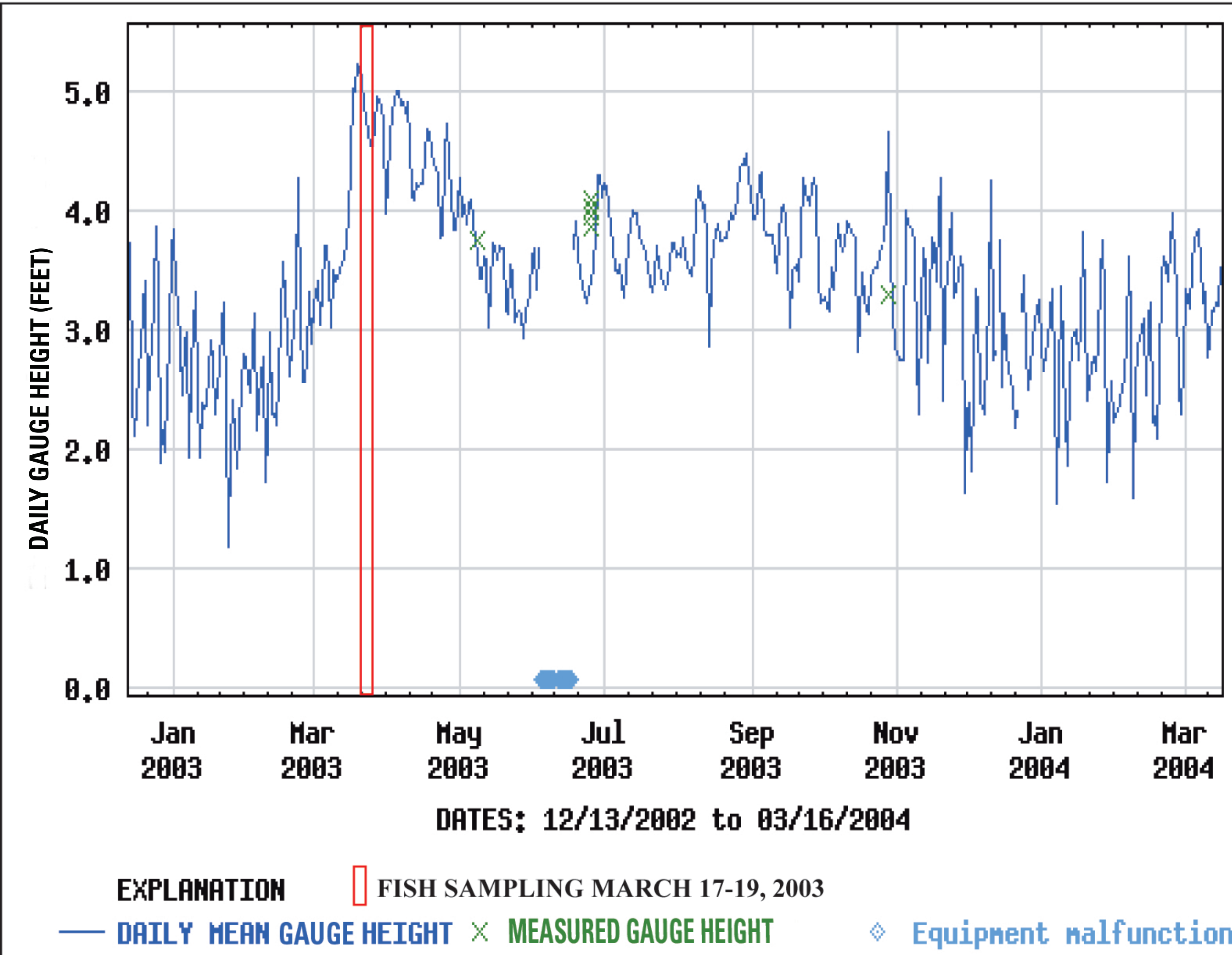


Figure 22. Water level at Gopher River gauge, near Suwannee, FL, during fish sampling.

Gauge height (USGS recording station 02323592) more than approximately 1.2 m results in overtopping of adjacent marshes and outflow of freshwater over marsh surface to the tidal tributaries (Clewell et al., 1999). The transition from tidal to freshwater dominance in the tidal creeks arises from a seasonal increase in Suwannee River level that can result in sheet flow from the lower river across marshes and tributaries, primarily south and southeast of the lower river near East Pass.

Replicate fish samples were taken in two representative tidal-marsh habitats: (1) intertidal rivulets draining the flooded marsh surface using rivulet nets (Rozas et al., 1988), and (2) permanent subtidal creeks with seine nets and throw traps. Fish data were analyzed for species composition, overall abundance, and spatial patterns. Variables identifiable or derived from the imagery were considered for their value in identifying fish habitats.

Fish were collected from flooded marshes with rivulet nets, and from tidal creeks with throw traps and seine nets (see Fig. 9 for sample locations). Rivulet nets were used during a falling tide. The low marsh offers protection to nekton within the grass canopy and access to high food production on the surface of marsh sediments. Fish that have been utilizing the marsh surface exit the marsh interior primarily via small drainage features called rivulets (Rozas et al., 1988). Depending on water levels, the area flooded and utilized by organisms may include low marsh and portions of the higher marsh. Rivulet nets are the block-net portion of the flume net described by McIvor and Odum (1986). Placed at the low to mid-marsh interface and centered over the rivulet at the peak of high tide, the net passively samples fish and decapod crustaceans leaving the marsh surface for the permanent waters of the subtidal creek during the subsequent falling tide.

One-square-meter throw traps were used to collect fish in the subtidal creek bed at low tide (Rozas and Odum, 1987) from three strata: vegetated creek, unvegetated creek, and shoreline. Water-column parameters recorded at rivulet and throw-trap sites include dissolved oxygen, salinity, depth, pH, and tide level.

Seine samples were collected on March 18-19 from two major southern tributaries, Barnett Creek and McCormick Creek, and from one major northern tributary, Bumblebee Creek. The seines measured 10 m or 20 m long, 2 m deep (2 x 2 m bag), with 3-mm (square) mesh. The larger seine was used where possible, and the small seine was used in tight quarters where snags, rocks, or deep water prevented deployment of the larger seine. All fish were identified, counted, measured, and released alive. Seine nets were used to collect fish within subtidal creeks and larger tributaries in the upper reaches of the creeks.

Seine samples could not be taken in a manner that would provide quantitatively comparable samples because of extreme geomorphologic heterogeneity: oysters, rock outcroppings, snags, extremely soft sediments, and lack of suitable shallow bank against which to land the seine. Therefore, the objective of seine sampling was to sample the fish qualitatively rather than to attempt a replicate sampling approach. Another goal was to identify community structure caused by recent declines in salinity that in turn were caused by recent increases in Suwannee River levels (Fig. 22). To accomplish this, seine samples were taken from approximately mid-creek to as far up each creek as was passable by small boat (Fig. 9). Analysis of the seine data consisted of identifying freshwater/oligohaline species (0-5 ppt) and stenohaline (limited to saline waters) marine species whose presence or absence could be affected by reduced salinity.

Parameters that may affect presence/absence of nekton include:

- Site-specific structural characters: local microhabitat characteristics may be relatively permanent but may represent a small portion of the creek habitats.
- Time-specific dynamic parameters: dissolved oxygen, salinity, pH, water depth, tide phase, and temperature. Thresholds and ranges are more important than time and location-specific measurements, since mobile organisms may adjust.
- General creek characteristics: freshwater influx, productivity, depth and velocity, habitat complexity, and access.

Fish-data summaries

Dynamic conditions within Suwannee River tidal creeks were characterized from measurements taken at sites during the 3-day sample period, from 17-19 March 2003 (Table 8). Mean water-quality values, depth, and substrate characteristics were estimated from collection-site measurements. Relative substrate composition is described as soft or firm and by bottom type as sand, mud, or mix, as estimated from field observations. These descriptions reflect local conditions, but not necessarily creek-wide conditions. General creek characteristics derived from the imagery are described in Tables 6 and 7.

Species composition of fishes and selected invertebrates was summarized for comparison by type of collection gear used and by location north and south of the river. The term "sample" represents the catch from a single rivulet net, throw trap, or seine net. The term "frequency" refers to the number of samples (single net) containing that species. Further analysis of faunal groups (i.e., fishes, crabs, shrimp) from throw traps was conducted on samples pooled by creek and habitat stratum (i.e., unvegetated bottom, vegetated, and shoreline). Further quantitative analysis and comparisons could not be made due to differences in gear used, low number of samples, and short sampling time frame.

Table 8. Dynamic conditions during fish sampling.

Creek	Mean depth	Substrate description	pH (range)	Salinity ppt (range)	Temperature C (range)	DO* mg/l (range)
Bumblebee	~ 0.5m	Firm sand mix	7.4-7.6	3.1-8.4	20.5-24.0	5.1-5.7
Double Barrel	< 0.5 m	Firm sand and sand mix	7.2-7.4	7.4-9.2	22.9-23.8	5.1-5.4
McCormick	~ 0.5 m	Soft mud mix	7.2-7.9	0.1-1.2	20.9-24.4	5.2-6.1
Barnett	> 0.5 m	Soft sand mix	7.1-7.4	0.2-0.8	22.1-23.4	5.1-6.4

*DO = dissolved oxygen

Study creeks

Bumblebee and Double Barrel Creek sample sites, north of the Suwannee River (Fig. 9), are located farther from the Gulf of Mexico than the southern sites and are characterized by shallower depths, higher sinuosity, firm sand-mud bottoms, and higher mean salinities (Table 8). McCormick and Barnett Creek sites, south of the Suwannee River, are characteristically deeper, less sinuous, with soft mud or mud-sand bottoms, and lower mean salinities. The lower salinities may be related to proximity to the Suwannee River and the general flow patterns that transport large volumes of freshwater into the creeks. Mean temperature, pH, and dissolved oxygen exhibited a small range and were similar among the four creeks during the 3-day sampling period (Table 8).

Rivulet nets

Twenty-eight species of fishes and selected invertebrates, consisting of 4,258 individuals, were collected from 12 rivulet-net samples in tidal creeks north and south of the Suwannee River (Tables 9, 10). Organisms captured were dominated by grass shrimp, *Palaemonetes* spp.; early-juvenile spot, *Leiostomus xanthurus;* and bay anchovies, *Anchoa mitchilli*. Also in high abundance were menhaden, *Brevoortia* spp.; blue crabs, *Callinectes sapidus*; pinfish, *Lagodon rhomboides*; and silversides, *Menidia* spp.

Interestingly, diamond killifish *Adinia xenica* occurred at all six sites in southern creeks but were absent from all but one collection site in the north. Conversely, sailfin mollies, *Poecilia latipinna*, occurred at five of six northern creek sites but were absent from southern creek sites. Greater than 95% of all *Gobionellus boleosoma*, the most abundant goby collected, was taken from southern creeks, and none was captured from Double Barrel Creek sites, the sites with the sandiest substrate.

Table 9. Rivulet-net results: Northern Creeks.

Creek Name	Bumblebee	Double Barrel	Total	Frequency
No. of Samples	3	3		
Taxa	13	14	**17**	
Leiostomus xanthurus	287	184	**471**	6
Anchoa mitchilli	77	238	**315**	4
Brevoortia spp.	28	56	**84**	4
Poecilia latipinna	10	3	**13**	5
Lagodon rhomboides	1	9	**10**	2
Menidia spp.	6	4	**10**	4
Adinia xenica	5	0	**5**	1
Fundulus grandis	4	1	**5**	3
Gambusia holbrooki	0	4	**4**	1
Fundulus confluentus	2	1	**3**	2
Cynoscion arenarius	0	2	**2**	1
Bathygobius soporator	0	1	**1**	1
Gobionellus boleosoma	1	0	**1**	1
Mugil cephalus	1	0	**1**	1
Paralichthys albigutta	0	1	**1**	1
Total Fish	**422**	**504**	**926**	
Callinectes sapidus	25	8	**33**	5
Palaemonetes spp.	108	612	**720**	6
Total Individuals	**555**	**1124**	**1679**	

Differences in fish-community structure were observed among south creeks with Barnett Creek having a distinct community characterized by greater abundances of *A. xenica*, mosquitofish, *Gambusia holbrooki*; and lesser abundances of *A. mitchilli* and *Brevoortia* spp. In terms of fish-community structure, replicate sites within southern creeks at McCormick and Barnett were generally more similar to one another, though this was expected given the close proximity of the six southern sites and a common lower creek basin. Northern creek replicates showed greater variability from one site to another. Fish communities in southern creeks were distinct from those in northern creeks due to the notably greater abundance of *L. rhomboides*, *Menidia* spp., mullets, *Mugil* spp., and darter goby, *G. boleosoma* (Tables 9, 10). Fish species typical of freshwater habitats, least killifish (*Heterandria formosa*), warmouth (*Lepomis gulosus*), and spotted sunfish (*Lepomis punctatus*), were collected solely in southern creeks and at the most upstream sites, though in low abundance.

Table 10. Rivulet-net results: Southern Creeks.

Creek Name	Barnett	McCormick	Total	Frequency
No. of Samples	**3**	**3**		
Taxa	17	18	**25**	
Leiostomus xanthurus	281	782	**1063**	6
Anchoa mitchilli	69	177	**246**	6
Lagodon rhomboides	40	48	**88**	6
Brevoortia spp.	0	59	**59**	3
Gambusia holbrooki	59	0	**59**	3
Menidia spp.	10	44	**54**	6
Adinia xenica	23	9	**32**	6
Gobionellus boleosoma	9	16	**25**	3
Bathygobius soporator	6	1	**7**	2
Mugil cephalus	3	1	**4**	4
Paralichthys lethostigma	2	1	**3**	2
Clupeidae	0	2	**2**	1
Elops saurus	0	2	**2**	2
Fundulus grandis	2	0	**2**	1
Fundulus confluentus	0	1	**1**	1
Gobiosoma spp.	0	1	**1**	1
Heterandria formosa	1	0	**1**	1
Lepomis gulosus	0	1	**1**	1
Lepomis punctatus	1	0	**1**	1
Microgobius gulosus	1	0	**1**	1
Mugil gyrans	0	1	**1**	1
Mugil spp.	1	0	**1**	1
Syngnathus scovelli	0	1	**1**	1
Total Fish	**524**	**1147**	**1655**	
Callinectes sapidus	16	71	**87**	6
Palaemonetes spp.	401	436	**837**	6
Total Individuals	**925**	**1654**	**2579**	

Species in bold are freshwater affinity

Throw traps

Eighteen species of fishes and selected invertebrates, consisting of 455 individuals, were collected from 56 throw traps in tidal creeks north and south of the Suwannee River (Tables 11, 12). Throw traps were deployed within three strata: vegetated, unvegetated, and shoreline. Distribution of samples within strata was uneven, with eight samples from each of three strata in southern creeks and 16 samples from two strata each, unvegetated and shoreline, in northern creeks. *Vallisneria americana* grass beds were not readily located by field crews in the northern creeks. Young-of-the-year *L. xanthurus* was the most frequently collected species (73% of the total hauls), while *Callinectes* spp. was collected in 37% and *L. rhomboides* in 35% of the total hauls. *Palaemonetes* spp. was also frequently collected, especially in Bumblebee Creek (56%) and Barnett Creek (42%).

Throw-trap samples from creeks north and south of the Suwannee River were dominated by *Palaemonetes* spp. and newly recruited young-of-the-year *L. xanthurus*, the same two species that dominated the rivulet samples. Also in greater abundance were *L. rhomboides, Callinectes* spp. (likely young-of-the-year blue crabs), and striped anchovies, *Anchoa hepsetus*. Overall, communities were more similar between adjacent creeks than between northern and southern creeks. Differences can probably be explained by higher overall abundances in northern creeks compared to southern creeks but also by differences in species richness and composition. Thirteen species were collected in both Bumblebee and Double Barrel Creeks, 10 of which were observed in both creeks. Seven species that were absent from southern creeks were present in northern creeks, though not in any significant abundance. *Elops saurus, A. mitchilli*, *G. holbrooki*, and clupeids were all found in northern creek samples but were absent from southern creeks. Both northern creeks had higher mean abundances of *L. xanthurus* but lower mean abundances of *Callinectes* spp.

In contrast, samples from McCormick and Barnett Creeks each contained nine species, with seven of those species present in both. Only two species, consisting of two individuals, were present in southern creeks that were absent from northern creeks. As was the case with rivulet-net samples, goby species, *Microgobius gulosus* and *Gobiosoma robustum*, were collected in all creeks except Double Barrel, which had a characteristically sandy substratum. Bumblebee Creek was observed to be the most productive creek, having the highest mean faunal abundance (Fig. 23a). Mean fish abundance was also highest in Bumblebee Creek; however, mean crab and shrimp abundances were highest in Barnett Creek.

Fish assemblages differed statistically among the three strata (ANOSIM; p=0.003). Non-shoreline creek sites containing submerged aquatic vegetation possessed a higher mean abundance of shrimp and portunid crabs, whereas shoreline sites produced the highest mean abundances of fishes (Fig. 23b). Unvegetated sites yielded the lowest mean faunal abundance of all strata, with only the unvegetated Bumblebee Creek sites having more than five species/sample. Although the lack of vegetated sample sites on northern creeks may bias the results, the pattern of vegetated sites containing more individuals than unvegetated ones is a pattern commonly observed in estuarine studies. Such results generally imply that vegetated areas provide food and shelter for small individuals (Bell and Pollard, 1989; Ferrell and Bell, 1991). The shoreline of Bumblebee Creek may provide similar resources for small organisms, perhaps due to sinuosity or other characteristics.

Table 11. Throw-trap results: Northern Creeks.

Station	Bumblebee 1	Bumblebee 2		Bumblebee 3	Double Barrel 1		Double Barrel 2		Total	Freq.
Habitat Type	UV N=4	S N=4	UV N=4	S N=4	S N=4	UV N=4	S N=4	UV N=4		
Taxa	10	7	5	4	6	0	11	3	**16**	
Leiostomus xanthurus	17	10	13	27	7	0	20	4	**98**	**7**
Lagodon rhomboides	2	3	1	12	6	0	1	0	**25**	**6**
Anchoa hepsetus	5	4	0	0	3	0	4	1	**17**	**5**
Anchoa mitchilli	3	0	3	0	0	0	4	0	**10**	**3**
Clupeidae	1	4	0	0	0	0	1	0	**6**	**3**
Microgobius gulosus	3	0	1	0	0	0	0	0	**4**	**2**
Myrophis punctatus	0	0	0	0	0	0	2	0	**2**	**1**
Menidia spp.	0	0	0	1	0	0	1	0	**2**	**2**
Elops saurus	0	1	0	0	1	0	0	0	**2**	**2**
Gambusia holbrooki	0	1	0	0	1	0	0	0	**2**	**2**
Gobiosoma robustum	1	0	0	0	0	0	0	0	**1**	**1**
Citharichthys sp.	1	0	0	0	0	0	0	0	**1**	**1**
Fundulus grandis	0	0	0	0	0	0	1	0	**1**	**1**
Lepomis gulosus	0	0	0	0	0	0	1	0	**1**	**1**
Lepomis marginatus	0	0	0	0	0	0	0	0	**0**	**0**
Opsanus beta	0	0	0	0	0	0	0	0	**0**	**0**
Total Fish	**33**	**23**	**18**	**40**	**18**	**0**	**35**	**5**		
Palaemonetes spp.	2	30	1	34	0	0	28	0	**95**	**5**
Callinectes spp.	5	0	0	0	3	0	1	4	**13**	**4**
TOTAL	**40**	**53**	**19**	**74**	**21**	**0**	**64**	**9**	**280**	

Notes: Shore (S), Vegetated (V), Unvegetated (UV)

Table 12. Throw-trap results: Southern Creeks.

Station	**McCormick 1**	**Barnett 1**		**McCormick 2**	**Barnett 2**		**McCormick 3**			**Total**	**Freq.**
Habitat Type	S N=1	V N=2	UV N=4	S N=2	S N=4	V N=2	S N=1	V N=5	UV N=3		
Taxa	2	4	2	3	7	6	2	8	4	**11**	
Leiostomus xanthurus	0	0	1	7	9	1	4	5	5	**32**	**7**
Lagodon rhomboides	0	5	0	0	1	1	0	6	0	**13**	**4**
Anchoa hepsetus	10	0	0	5	0	0	0	0	0	**15**	**2**
Microgobius gulosus	0	1	0	0	2	0	0	1	1	**5**	**4**
Myrophis punctatus	0	0	1	0	0	0	0	8	7	**16**	**3**
Menidia spp.	0	0	0	0	2	0	0	0	0	**2**	**1**
Gobiosoma robustum	0	0	0	0	1	1	0	4	0	**6**	**3**
Lepomis marginatus	0	0	0	0	0	1	0	0	0	**1**	**1**
Opsanus beta	0	0	0	0	0	0	0	1	0	**1**	**1**
Total Fish	**10**	**6**	**2**	**12**	**15**	**4**	**4**	**25**	**13**	**91**	
Palaemonetes spp.	0	12	0	0	6	39	1	5	0	**63**	**5**
Callinectes spp.	1	3	0	2	2	6	0	6	1	**21**	**7**
TOTAL	**11**	**21**	**2**	**14**	**23**	**49**	**5**	**36**	**14**	**175**	

Notes: Shore (S), Vegetated (V), Unvegetated (UV)

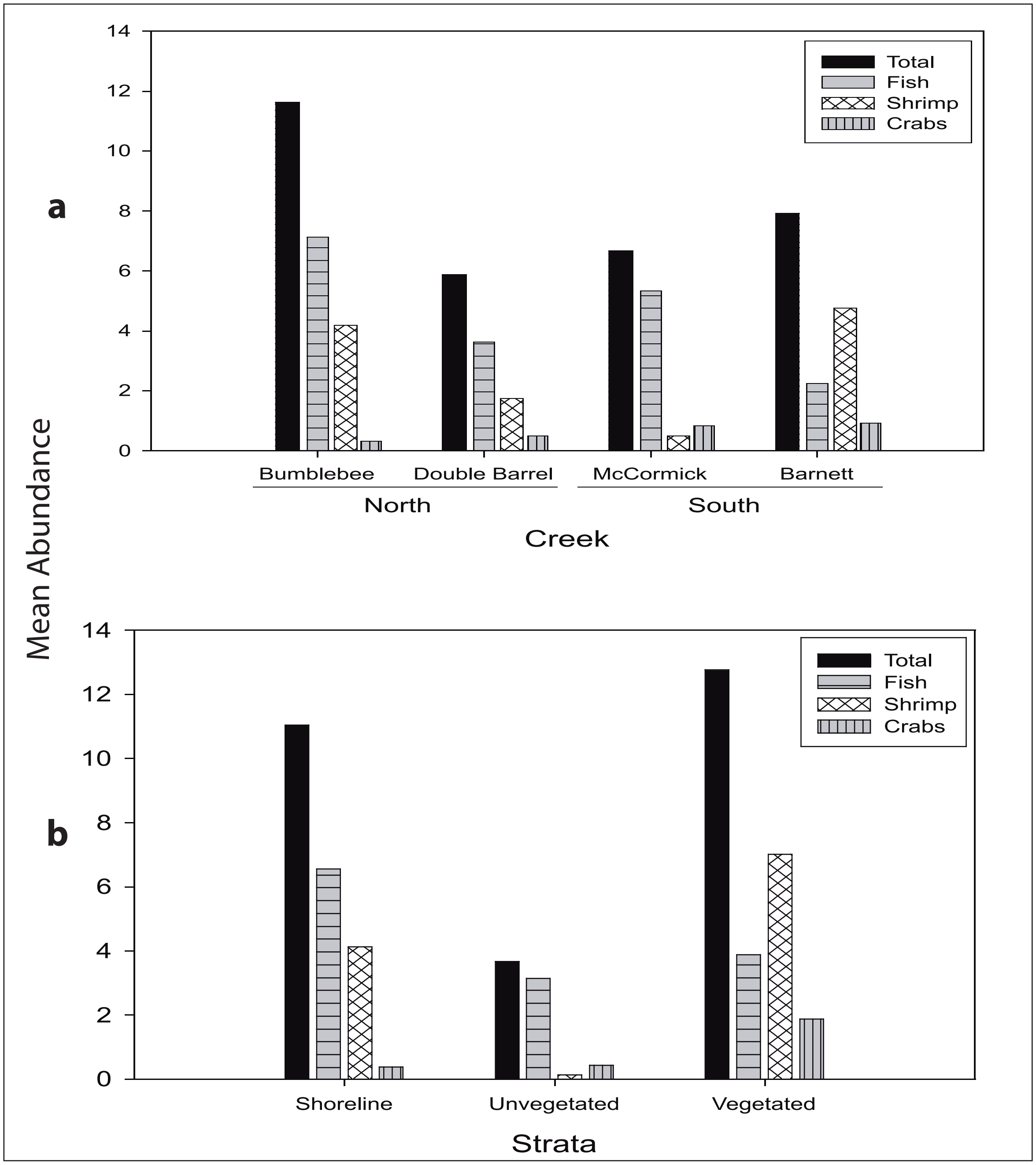


Figure 23. Mean abundances of estuarine fauna in throw-trap samples, (a) tidal creeks, (b) over various substratum.

Seine Samples

Seine sampling focused on the upper reaches of the tidal creeks. Twenty-one fish species and two macro-invertebrate species were collected by seine (Tables 13, 14). Early juvenile spot (*L. xanthurus*) was the most abundant species and was the only species collected at all stations. Three most abundant species, juvenile spot, along with silversides and grass shrimp, account for 89% of seine results. Freshwater species (*Micropterus salmoides, Lepomis microlophus,* and *Lepomis macrochirus*) were collected only in Barnett Creek in very low salinities (0.2-0.5 ppt).

Seines captured a total of 1,636 individuals. In the south, Barnett Creek had fewer individuals than McCormick Creek, but Barnett had a large contribution from grass shrimp. Although total numbers of taxa were similar north and south, substantially fewer individuals were collected in the northern creeks. Twenty of the 23 species occurred in the southern creek (Barnett and McCormick) samples, and 14 occurred in the northern creek (Bumblebee) samples. However, only four stations were sampled in the latter and five in the former. Three species were collected solely from the northern creeks, and nine were collected solely from the southern creeks.

Dissolved-oxygen and salinity values were well within the tolerance ranges for estuarine species. As with the rivulet-net analysis, there is a need for a larger dataset to describe the relationship better between faunal communities and the water-column parameters in which communities exist. There may be a correlation between distance to the Gulf of Mexico and fish abundance since the Bumblebee Creek sites were closest to the Gulf and had the highest mean faunal abundance, whereas Double Barrel Creek sites were farthest from the Gulf and contained the lowest mean faunal abundance.

Table 13. Seine results: Northern Creeks.

Creek & Station	Bumblebee 1	Bumblebee 2	Bumblebee 3	Bumblebee 4	Total	Frequency
Taxa	4	11	8	5	**14**	
Leiostomus xanthurus	37	113	173	5	**328**	4
Menidia spp.	0	15	27	7	**49**	3
Trinectes maculatus	1	1	2	0	**4**	3
Lagodon rhomboides	0	3	0	0	**3**	1
Microgobius gulosus	0	1	2	0	**3**	2
Anchoa mitchilli	0	0	0	3	**3**	1
Bothidae	0	1	1	0	**2**	2
Fundulus grandis	0	1	0	0	**1**	1
Gobiosoma bosc	0	0	1	0	**1**	1
Poecilia latipinna	1	0	0	0	**1**	1
Clupidae	0	0	1	0	**1**	1
Dasyatis spp.	0	1	0	0	**1**	1
Total fish	**39**	**136**	**207**	**15**	**397**	
Palaemonetes spp.	0	38	0	7	**45**	2
Callinectes sapidus	1	4	1	2	**8**	4
Total individuals	**40**	**178**	**208**	**24**	**450**	

Table 14. Seine results: Southern Creeks.

Creek & Station	McCormick 1	McCormick 2	McCormick 3	Barnett 1	Barnett 2	Total	Frequency
Taxa	6	8	10	13	5	**20**	
Leiostomus xanthurus	109	117	142	92	18	**478**	5
Menidia spp.	0	50	145	29	96	**320**	4
Lagodon rhomboides	0	21	18	17	0	**56**	3
Lucania parva	0	0	4	11	0	**15**	2
Microgobius gulosus	0	10	0	0	0	**10**	1
Gambusia holbrooki	0	0	6	1	0	**7**	2
Cyprinodon variegatus	0	0	1	4	0	**5**	2
Lepomis macrochirus	0	0	0	5	0	**5**	1
Fundulus grandis	0	2	2	0	0	**4**	2
Mugil cephalus	1	2	0	0	0	**3**	2
Sciaenops ocellatus	0	0	3	0	0	**3**	1
Syngnathus scovelli	0	0	1	1	1	**3**	3
Gobiosoma bosc	2	0	0	0	0	**2**	1
Trinectes maculatus	0	0	0	2	0	**2**	1
Bothidae	1	0	0	0	0	**1**	1
Lepomis microlophus	0	0	0	1	0	**1**	1
Micropterus salmoides	0	0	0	0	1	**1**	1
Poecilia latipinna	0	0	0	1	0	**1**	1
Total fish sampled	**113**	**202**	**322**	**164**	**116**	**917**	
Palaemonetes spp.	24	14	0	200	0	**238**	3
Callinectes sapidus	17	8	3	1	2	**31**	5
Total individuals	**154**	**224**	**325**	**365**	**118**	**1186**	

Collective Sample Results

Forty-five species were collected with three different sampling gears over the course of approximately three days in tidal creeks north and south of the Suwannee River (Table 15). Data given in Table 15 represent relative abundance as percentage of all individuals captured, and frequency-of-occurrence, as number of individual samples containing that species. Forty-one species were collected in the south creeks. These samples were dominated by juvenile spot, grass shrimp, silverside, and anchovy. Eleven species accounted for 99% of the 3,940 individuals collected. Four species collected in the north creeks were not found in the southern creeks.

Thirty species were collected in the northern creeks. The samples were dominated by juvenile spot, grass shrimp, and bay anchovy. Nine species account for 99% of the 2,409 individuals collected. Fifteen species collected in the southern creeks were not collected in the northern creeks.

Table 15. Collective sample results from all tidal creeks.

South Creeks			North Creeks		
Total 41 Taxa	Total 3940 Individuals		Total 30 Taxa	Total 2409 Individuals	
Taxa	**% of total**	**Freqency**	**Taxa**	**% of total**	**Frequency**
Leiostomus xanthurus	40	15	*Leiostomus xanthurus*	37	15
Palaemonetes spp.	29	12	*Palaemonetes* spp.	36	12
Menidia spp.	10	11	*Anchoa mitchilli*	14	8
Anchoa mitchilli	6	6	*Brevoortia* spp.	3	4
Lagodon rhomboides	4	12	*Menidia* spp.	3	9
Callinectes sapidus	3	11	*Callinectes sapidus*	2	9
Gambusia holbrooki	2	5	*Lagodon rhomboides*	2	8
Adinia xenica	1	6	*Poecilia latipinna*	1	6
Callinectes spp.	1	5	*Anchoa hepsetus*	1	4
Brevoortia spp.	1	3	*Callinectes* spp.	1	3
Gobionellus boleosoma	1	3	*Fundulus grandis*	<1	5
Mugil cephalus	<1	6	Clupeidae	<1	4
Microgobius gulosus	<1	5	*Microgobius gulosus*	<1	4
Syngnathus scovelli	<1	4	*Gambusia holbrooki*	<1	3
Fundulus grandis	<1	3	*Trinectes maculatus*	<1	3
Myrophis punctatus	<1	2	*Fundulus confluentus*	<1	2
Anchoa hepsetus	<1	2	Bothidae	<1	2
Lucania parva	<1	2	*Elops saurus*	<1	2
Bathygobius soporator	<1	2	*Adinia xenica*	<1	1
Gobiosoma robustum	<1	2	*Cynoscion arenarius*	<1	1
Cyprinodon variegatus	<1	2	*Myrophis punctatus*	<1	1
Paralichthys lethostigma	<1	2	*Bathygobius soporator*	<1	1
Elops saurus	<1	2	*Citharichthys* spp.	<1	1
Lepomis macrochirus	<1	1	*Dasyatis* spp.	<1	1
Sciaenops ocellatus	<1	1	*Gobionellus boleosoma*	<1	1
Clupeidae	<1	1	*Gobiosoma bosc*	<1	1
Gobiosoma bosc	<1	1	*Gobiosoma robustum*	<1	1
Trinectes maculatus	<1	1	***Lepomis gulosus***	<1	1
Bothidae	<1	1	*Mugil cephalus*	<1	1
Fundulus confluentus	<1	1	*Paralichthys albigutta*	<1	1
Gobiosoma spp.	<1	1	*Syngnathus scovelli*	0	0
Heterandria formosa	<1	1	*Lucania parva*	0	0
Lepomis gulosus	<1	1	*Cyprinodon variegatus*	0	0
Lepomis marginatus	<1	1	*Paralichthys lethostigma*	0	0
Lepomis microlophus	<1	1	*Lepomis macrochirus*	0	0
Lepomis punctatus	<1	1	*Sciaenops ocellatus*	0	0
Micropterus salmoides	<1	1	*Opsanus beta*	0	0
Mugil gyrans	<1	1	*Lepomis marginatus*	0	0
Mugil spp.	<1	1	*Micropterus salmoides*	0	0
Opsanus beta	<1	1	*Gobiosoma* spp.	0	0
Poecilia latipinna	<1	1	***Heterandria formosa***	0	0
Cynoscion arenarius	0	0	*Lepomis microlophus*	0	0
Citharichthys spp.	0	0	***Lepomis punctatus***	0	0
Dasyatis spp.	0	0	*Mugil gyrans*	0	0
Paralichthys albigutta	0	0	*Mugil* spp.	0	0

Results from the three types of sampling gear are not directly comparable but may provide complementary information. Major differences between the collection methods include duration of collection, total area covered by sampling technique, and geographic location within the intertidal zones.

1. Duration of sample: Rivulet nets passively sample for up to 6 hours during a falling tide. Seine nets take 5-15 minutes to complete a sample, and throw traps enclose a sample in a second.

2. Sampling area covered: Rivulet nets are set to collect all animals leaving the marsh at a particular point during a falling tide. The exact outflow, unless measured, is unknown, but may constitute hundreds of cubic meters of water and reflect habitat use of hundreds of square meters of marsh surface. A 20-m seine net traps animals across 20 linear meters of submerged bottom: total area sampled depends on method of deployment and site characteristics. On the other hand, the 1-m throw trap samples a maximum of one-cubic-meter of water and one-square-meter of submerged bottom.

3. Geographic locations: Intertidal rivulets of the correct size (1-1.5m width) and accessibility for rivulet-net sampling gear typically drained the marshes in the upper half of the tidal creeks sampled in this study (see Fig. 9). These nets capture animals utilizing vegetated intertidal marsh-surface habitat. The seine nets were deployed in the upper reaches of the tidal creek across the continuously submerged zone. The throw traps were consistently deployed in the mid- to upper portions of the creeks and also collected animals in the submerged zone.

Discussion

Fish assemblages caught indicate that decreasing salinity had not yet had great effect on fish communities in the tributaries. Freshwater species (bluegill, *Lepomis macrochirus;* redear sunfish, *Lepomis microlophus*; and largemouth bass, *Micropterus salmoides*) were collected at the upper Barnett Creek stations, but freshwater species were not collected elsewhere. Fishes were dominated by early-juvenile spot (*Leiostomus xanthurus*), a species that is ubiquitous in most Gulf of Mexico estuaries. Juvenile spot are known to inhabit tidal freshwater zones of estuaries as well. Therefore, spot are unlikely to provide much information about the overall fish-community response to freshwater influx. Interestingly, pipefish (*Syngnathus scovelli*) were found at the same sites as the freshwater species. Pipefish are less able to tolerate low and variable salinity and would probably have been affected soon by the declining salinity.

As of the fish-sampling dates, gauge height at the Gopher River gauging station had been above 1.2 m continually for only about 3-4 days (Fig. 22). Had it been possible to collect fish a week or two later, salinity probably would have been low enough for a sufficient period (ca. one week) to have caused larger changes in species distribution.

This pilot project has provided a brief temporal snapshot of fish assemblages from two of the habitats in the SRES: flooded marsh surfaces, and permanently flooded subtidal creek beds. Hyperspectral imagery of the intertidal zone reveals sinuosity of tidal creeks, presence of coarse substrate or SAV, and location of intertidal marsh subject to frequent interior (as opposed to shoreline) flooding. Areas of interior flooding are often associated with intertidal rivulets, demonstrated "hot spots" for access and egress of small fishes, grass shrimp, and swimming crabs to the flooded intertidal marsh (Rozas et al., 1988).

Due to the small number of samples, the brief duration of sampling, and differences in sampling gear and techniques, a definitive interpretation or correlation between habitat characteristics and fish-community structure was not undertaken. The narrow ranges of temperature and pH observed during this study are well within known tolerance limits for most estuarine species. Substrate type is often a good predictor of fish-community composition and is attributed to differences in organic content, benthic habitat, and prey resources. Factors such as distance from the Gulf, creek width and depth, tidal velocity, vegetation, and other metrics may be used in a thorough analysis of habitat and fish assemblages.

The fish data can be considered to be at best a snapshot of species composition and habitat use within a larger time frame. Nonetheless, results show: (1) the selected sampling techniques are effective, and each may contribute significantly to an overall evaluation of fish communities. (2) Certain common estuarine species dominate all samples regardless of gear. (3) There are assemblage differences that may be related to hydrologic and geomorphic factors such as position in the intertidal zone, distance from the Gulf, and creek depth. (4) Some of the hydrologic and geomorphic factors may be related to creek location north and south of the river. Other differences not noted in the pilot study include seasonal and interannual biases, time of day, effect of storm surge, river discharge, precipitation, and fluctuations in water quality and clarity.

Fish and water-sampling efforts in this study were limited in time and location, with a focus on mid-to-interior zones of the tidal creeks and marsh. Further sampling during different seasons, flow conditions, and in different intertidal zones may clarify habitat use and function, as well as quantification of taxa caught with different sampling gear. Dynamic water-quality parameters varied across the width and length of sites sampled, but were generally within the tolerance range of estuarine species and cannot be used to establish definitive thresholds. A tenuous link between fish assemblages and tidal-creek characteristics was noted and deserves further investigation.

Summary

The objectives of this study were to characterize and map the shallow and nearshore benthic and intertidal habitats of the SRES and to identify relations between benthic habitat, hydrology, and ecological function using airborne hyperspectral imagery. The final product uses spatially explicit hyperspectral imagery to characterize and interpret nearshore estuarine environments and establish a critical link between river discharge, aquifer seepage, and tidal flow on aquatic and emergent habitats, and faunal utilization in the SRES.

Preliminary tidal-flood zones were identified, providing a detailed view of the geomorphology of the nearshore and intertidal environments. The 4-m resolution and band selection of the imagery posed constraints on identifiable features, including SAV beds within the tidal creeks and vegetation-species composition within the emergent zone. Positive identification of freshwater-marsh zones, low marsh, and the derivation of creek sinuosity and other geomorphic parameters provided comparable habitat characteristics between creek and sub-creek watersheds.

Offshore geomorphic features include SAV beds, oyster reefs, and submerged sand bodies as well as sediments high in organic material, “new mud”. The prominent submerged estuarine features were mapped directly west and north of the mouth of the Suwannee River. During image acquisition, the broad swath of the Suwannee River discharge flowed south to Cedar Key. The dark-water plume from the river may have masked submerged features to the south and east. Also, high river discharge may scour and move bed material, reworking submerged features from the nearshore southeast of the river mouth.

In general, the southern tributary creeks are less sinuous than the northern creeks, have a greater proportion of freshwater marsh, and less low marsh or coarse substrate. While not identified in the imagery, field reconnaissance indicates that SAV beds of *Vallisneria* are also larger and more common in the southern creeks. The northern creeks are more sinuous, presenting more edge habitat, and have relatively larger zones of low marsh and submerged coarse substrate. The submerged portion of these creeks is relatively small compared to the deep, broad character of Barnett Creek. All creeks, north and south, enter the Gulf of Mexico as third-order streams. Each offers a different set of aquatic habitats. While the southern creeks provide habitat suitable for species requiring a fresher environment or the submerged cover of SAV beds, the northern creeks provide a greater range of habitat resources.

Based on the demarcation between fresh and brackish marsh zones, the intertidal zone (Fig. 2) can be divided into two zones: the delta marsh and the intertidal marsh (Fig. 24). The delineation was determined by the distribution of vegetation zones shown in Figure 6. The concept is corroborated by the work of Clewell et al. (1999) and Coultas and Lasley (2001).

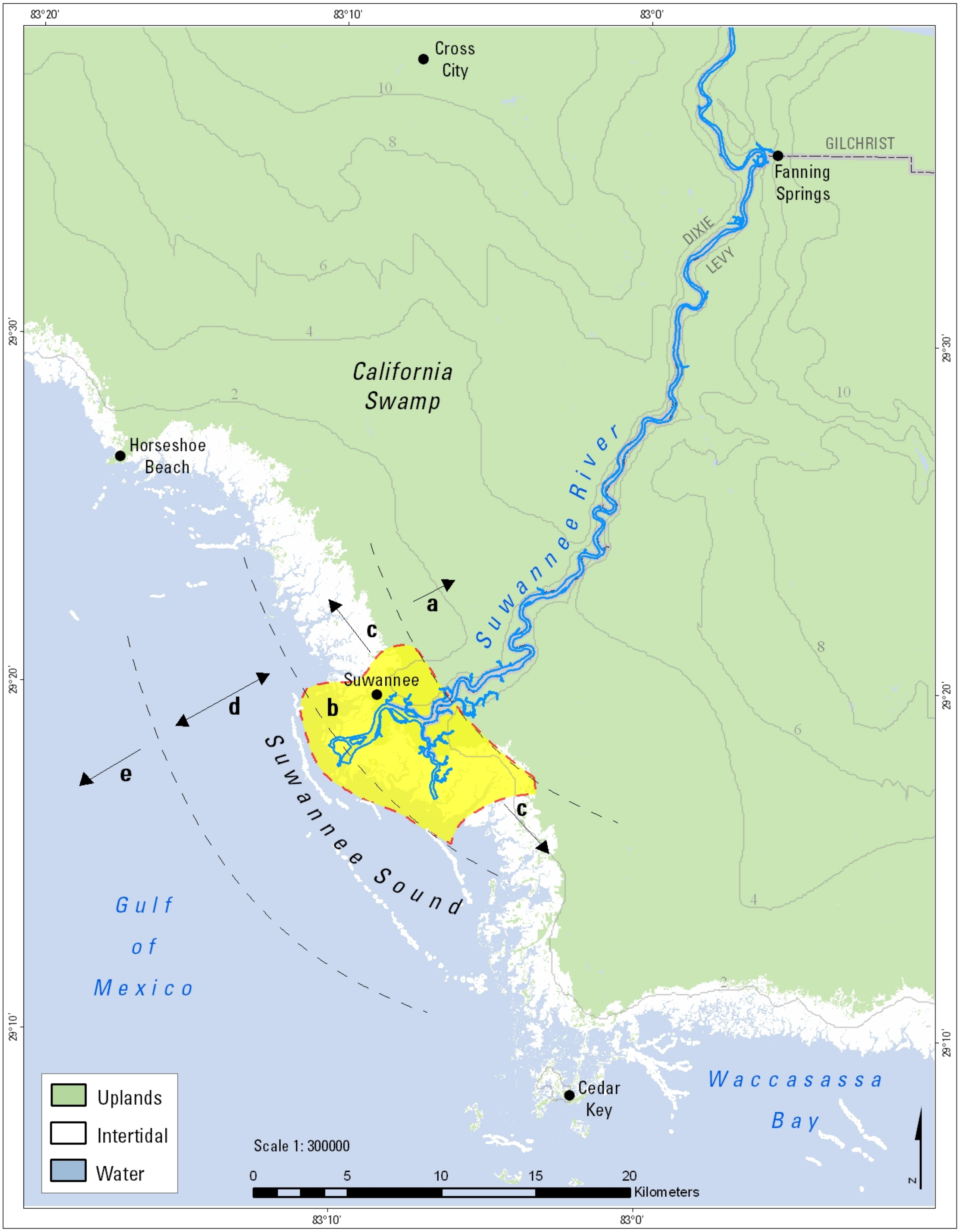


Figure 24. Revised Figure 2, Zones of Suwannee River Estuary: (a) tidal river, (b) delta marsh, (c) intertidal, (d) Suwannee Sound, (e) estuarine/marine. The delta marsh zone was delineated using the fresh marsh category shown in Fig. 6.

The delta-marsh zone starts at Salt Creek, just north of the river mouth, and extends to the west and northern banks of Barnett Creek, south of the Suwannee River. The delta marsh has greater species diversity and a higher representation and canopy cover of freshwater-tolerant plants than the intertidal zone and was clearly identifiable from the hyperspectral imagery. The zone of intertidal marsh, extending north of Salt Creek and south of Barnett Creek, is similar in composition to the tidal marshes of the Big Bend dominated by black needlerush and cordgrass (Kurz and Wagner, 1957; Montague and Weigert, 1990; Raabe and Stumpf, 1997). Freshwater flow from small spring-fed rivers, surface runoff, and seepage from the Floridan aquifer support smaller populations of brackish and freshwater species in the intertidal marsh (Montague and Odum, 1997).

Hydrologic monitoring identified four important characteristics of the tidal creeks. (1) Barnett Creek is substantially fresher than Bumblebee Creek. The extent to which freshwater influx is tied to stage and discharge from the Suwannee River or from groundwater flow is not known. (2) Bumblebee Creek displays greater range in water levels than Barnett Creek, and receives temporary freshwater influx from local precipitation events, possibly from the California Swamp. (3) Although both creeks show a net influx from groundwater, the inflow to Bumblebee is greater by an order of magnitude. The origin of this flow remains to be determined, whether it is from the Floridan aquifer or is a lagged release from marsh peat during falling tides. (4) Tides in the Big Bend region are substantially affected by winds. There can be a substantial lag, 1-2 hours later than predicted, for tides to reach lowest levels in the creeks. Groundwater flow into the river and the tidal creeks and overland flow into the intertidal zone remain to be assessed.

Tidal-creek hydrology and creek habitats are affected by tidal, surface, and groundwater flow. In fact, upwelling from subsurface to surface in the tidal creeks may constitute a substantial contribution to creek flow during low-tide conditions. Monitoring over a full annual cycle with a gridwork of sensors is needed to quantify the spatial distribution of the upwelling process. Although the locations of the sampling sites for hydraulic-head and temperature measurements were too disparate to make direct comparisons, the data indicate that the northern creeks may experience a greater upwelling from groundwater. Also, the interface of fresh and saline groundwater may be farther inland to the north of the Suwannee River than to the south.

Fish surveys were limited to one collection time period in spring 2003. Combined results of the three sampling techniques showed highest abundance of small fish and greatest species diversity in the southern creeks. Seine and rivulet nets showed greater number of species in the southern creeks, but higher species diversity and abundance were observed in throw-trap samples from the northern creeks. Overall, 45 species were collected, 41 in the southern creeks, and 30 in the northern creeks. Species preferring less-saline environments were collected more frequently in the southern creeks, but they were a small portion of the total effort. Rivulet nets captured the greatest abundance of organisms. This method sampled small organisms in mid- to high-elevation zones in the marsh during high-tide inundation. The seine nets and throw traps sampled organisms for a short period of time and only in the submerged creek zone. The trends found during this brief study demonstrate the need for further monitoring of biotic resources and hydrologic processes to establish correlations. Additional data in the form of tidal-creek recharge areas, aquifer levels, tidal-creek salinities, precipitation records, and other parameters are needed.

In some years, water levels remain high and salinities very low for many weeks, giving much more time and flexibility for fish-community sampling. In other years, water levels and resultant salinity regime may not result in extensive freshening of the system, and estuarine fish communities will be found throughout the tributaries. To assess effects of salinity transition on fish communities, future fish sampling should be designed to permit sampling after protracted periods of high-river stage and low salinity, before water levels and salinity return to previous conditions, and during prolonged low-river discharge with higher salinities. Sampling might also include efforts following high-precipitation events and storm surge. In order to observe the greatest effects of river outflow across the southern marshes, daily data from the recording station should be monitored, and field crews should be available to sample on about two days' notice. After river-stage water levels fall and remain low (below 1.2 m), sampling should be done again after about two weeks and subsequently on a biweekly basis to determine the temporal pattern of fish-community response to the higher-salinity regime. Similar sampling strategies for key invertebrate species could also be conducted.

Quantitative evaluations of habitat derived from imagery include creek width, length, area and sinuosity, substrate type, distance from the Gulf of Mexico, and vegetation characteristics. If such parameters can be effectively linked to fish assemblages, then hyperspectral imaging may be a useful tool for predicting relative "fisheries usage" in a ranked analysis of tidal creeks within a landscape. This approach warrants further development as a resource-management tool.

Recommendations for further studies

Suggestions based on results of the pilot study:

- Water level, during image acquisition, varied from beginning of falling tide to low tide with the higher water levels in the southern flight lines. This variation may have a bearing on the amount of exposed sand/shell identified in the southern creeks, the amount of low marsh identifiable in the southern creeks, and in general may create a slightly skewed comparison between southern and northern creeks. Recommend subsequent flights with adjustments in timing for tide level.
- The outgoing tide produces a 'dirtier' picture in the water column, especially in the tidal creeks and Suwannee Sound. Future flights would best be flown during an incoming- to high-tide time frame.
- Fish were collected at the beginning of high-river levels and freshened conditions in the tidal creeks in 2003. Future efforts could be focused on two time periods: (1) low-river level, high salinities in December-January, and (2) high-river level, low salinities in March-April. Since the timing of these events varies from year to year, the timing of the collection effort would be based on river-level phase, not precise dates. Collection efforts could also be timed to coincide with the movement of spawn or juveniles.
- Need velocity, water-surface slope, mean grain size, width/depth ratio, extended evaluation of drainage density to include all tributaries, and quantification of SAV beds for first-, second-, and third-order streams in each tidal-creek basin.
- Need evaluation of benthic fauna, bacteria, and algae, and relation to structural (median grain size, bed slope,…), and water-column environment.

Products

DVD release of USGS Open-File Report 2007-1382 includes:

1. Open-File Report in PDF format (OFR_2007-1382)
2. Categories derived from hyperspectral imagery as single-band GeoTIFF files. These maps are intended to be viewed at a scale of 1:25,000 or greater. Further enhancement or 'zoom' level beyond 4x is not recommended.
    a. Three basic categories: submerged, emergent, and upland
    b. Habitat categories
    c. Tidal flood zones
3. False Color and Natural Color mosaics as three-band GeoTIFF files
4. Complete 12-band hyperspectral image mosaic as a GeoTIFF
5. Metadata

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