DeBary Bayou Watershed Assessment Study

US Army Corps of Engineers®
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City of DeBary, Volusia County, Florida

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Padgett Creek (DeBary Bayou), looking east, 1969.
Photo courtesy of Saundra Hagood Gray, DeBary, Florida.

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Final Report

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1 STUDY AUTHORITY AND PURPOSE

DeBary Bayou Watershed Assessment Study was prompted by locally reported concerns that sedimentation rates have accelerated within DeBary Bayou channel, impeding water flow and navigation and potentially impacting ecological conditions in the DeBary Bayou system. The findings of this study will be important to determining the nature of reported problems within DeBary Bayou watershed and will assist refinement of roles and responsibilities of involved stakeholders in designing and implementing remediation solutions where warranted.

This study was undertaken to evaluate issues and potential remediation opportunities for the DeBary Bayou watershed within the City of DeBary, Volusia County, Florida. This study is sponsored by the Florida Department of Transportation (FDOT), in cooperation with the US Army Corps of Engineers, Jacksonville District (CESAJ), the Coastal and Hydraulics Laboratory (CHL) and the Environmental Laboratory (EL) of the US Army Engineer Research and Development Center (CEERD or ERDC). Significant technical support was provided by the St. Johns River Water Management District (SJRWMD).

2 ACRONYMS AND ABBREVIATIONS

Many terms and agency titles are abbreviated in this report and whereas the abbreviation or acronym is spelled out at first mention in the report text by convention, they are summarized here for reference.

BMP	best management practice
BOD	biochemical oxygen demand
CESAJ	US Army Corps of Engineers, Jacksonville District
cfs	cubic feet per second
CHL	Coastal and Hydraulics Laboratory
CIAT	2-chloro-4-isopropylamino-6-amino-s-triazine
CIR	color infrared
cms, cmm	cubic meters per second, cubic meters per minute
DEET	N,N'-diethylmethyl-toluamide (DEET)
DEM	digital elevation model
DO	dissolved oxygen
EB, WB	Eastbound, Westbound
EFMS (EEFMS, WEFMS)	Emergency Flood Management System (Eastside, Westside)
EL	Environmental Laboratory

ERDC (or CEERD)	US Army Engineer Research and Development Center
FAC	facultative
FACW	facultative wet
FAS	Floridan aquifer system
FAVA	Florida Aquifer Vulnerability Assessment
FDEP	Florida Department of Environmental Protection
FDOT	Florida Department of Transportation
FEMA	Federal Emergency Management Agency
FIRM	Flood Insurance Rate Maps
FIU	Florida International University
Floc	flocculant
fps	feet per second
FWDM	Florida Wetlands Delineation Manual
gpm	gallons per minute
GIS	Geographic Information System
Hwy	Highway
I-4	Interstate 4, or SR 400
lpm	liters per minute

MHW	mean high water
mps	meters per second
MSJRB	Middle St. Johns River Basin
ppm	parts per million
NGVD	National Geodetic Vertical Datum
NOAA	National Oceanographic and Atmospheric Administration
NRHP	National Register of Historic Places
OBL	obligate
^{210}Pb	lead-210
RGB	red-green-blue (color spectrum photography)
RSSF	Regional Stormwater Storage Facility
SAV	submerged aquatic vegetation
SCM	sands/clays/grey mud
SERC	Southeast Environmental Research Center
SF_6	sulfur hexafluoride
SJRWMD	St. Johns River Water Management District
SR	State Route
SWIM (Plan)	Surface Water Improvement and Management Plan

TMDL	Total Maximum Daily Load
TSI	Trophic State Index
^{238}U	uranium-238
UPL	upland
USACE	United States Army Corps of Engineers
USDA	United States Department of Agriculture
USF&W	United States Fish and Wildlife Service
USGS	United States Geological Survey
WEFMS	Westside Emergency Flood Management System (see also EEFMS or Eastside EFMS above)
XS	cross-section

3 UNIT CONVERSION FACTORS

Metric and US Standard units are used in this report to document numerical data from many different sources. Because the convention for using one or the other unit systems differs depending on the field or agency reporting the data, this study endeavors to note both for each measurement as it appears in the report for ease of communication. Certain values, such as recorded river or lake stage (water surface elevation) at a stream gaging station, are not converted from their original unit system because these numbers constitute a point of reference rather than a quantity. Estimates, generalized or average numbers (e.g., several feet, up to three miles) are typically not reported as a specific quantity so may not be converted. The numerical factors used to convert from the Standard unit system to the Metric system are summarized below for selected commonly used length, area, volume and mass measurements.

Multiply Standard Units		By	To Obtain Metric Units	
LENGTH				
inches	in	2.54	centimeters	cm
feet	ft	30.48	centimeters	cm
feet	ft	0.3048	meters	m
yards	yd	0.914	meters	m
miles (U.S. statute)	mi	1.609	kilometers	km
AREA				
square inches	in^2	6.452	square centimeters	cm^2
square feet	ft^2	0.093	square meters	m^2
square yards	yd^2	0.836	square meters	m^2
acres	ac	0.405	hectares	ha
square miles	mi^2	2.59	square kilometers	km^2
VOLUME				
fluid ounces	fl oz	29.57	milliliters	mL
gallons	gal	3.785	liters	L
gallons (U.S. liquid)	gal	3.785 E-03	cubic meters	m^3 or cu. m.
cubic feet	cu. ft. or ft^3	0.028	cubic meters	cu. m. or m^3
cubic yards	yd^3	0.765	cubic meters	m^3
MASS				

Multiply Standard Units		By	To Obtain Metric Units	
ounces (mass)	oz	28.34	grams	g
pounds (mass)	lb	0.4535	kilograms	kg
tons (2,000 pounds, mass)	T	907.1847	metric ton	t

4 EXECUTIVE SUMMARY

Determining the source, extent and direction of potential changes in ecology, hydrology, geomorphology and sediment processes requires detailed data from a variety of sources, a careful examination of anthropogenic (human-influenced) impacts and natural ambient processes, and analysis of rates of change at local, regional and perhaps larger scale. Results of this study are based primarily on existing information, supplemented by technical and professional judgment, wherein the role of various causal factors will be fairly evaluated. This study has sought to describe how the system works and parse out the role that each component plays in ecological integrity of the DeBary Bayou and its watershed. Comparison with past and future potential trajectory of ambient regional conditions is used to determine the value inherent in potential restoration alternatives or strategies, and to identify any information gaps for additional recommended analysis.

This study has included review and consideration of a wide variety of existing data sources and documents available that cover the study area from the 1800's to the present, including aerial imagery, topographic and bathymetric surveys, detailed weather records, water quality and quantity monitoring, sediment sampling and analysis, and urban/infrastructure development activity records. In addition, through careful analysis of previous meeting minutes, correspondence, and anecdotal evidence paired with site visits and additional face to face meetings, the technical team was able to identify a suite of stakeholder issues and concerns that form the basis for the research questions investigated in this study. Findings from this investigation in turn form the basis for recommended additional areas of further study or data gathering to answer unsolved questions or provide additional information that was not realized herein.

Of particular concern for the present study are questions of sedimentation rates within DeBary Bayou. In addition to description and interpretation of a variety of watershed characteristics, this study looked into specific data and documentation of sediment accumulation in Mullet Lake, DeBary Bayou channel, and Lake Monroe to determine the quantity and character of deposits, and determine the age and rate of deposition where possible. The primary questions to be answered are whether sediment or organic matter accumulation has been excessive, whether rates have increased, and how rates compare regionally. Sediment core evidence collected within the DeBary Bayou mainstem (primary stream channel) commissioned to support this study suggests long-term sediment accumulation rates of roughly 0.3 cm/yr (0.01 ft/yr or 0.12 in/yr) over the last 100 years (approximately 30 cm or 1.0 ft total), consistent with measurements in many regional Florida lake and wetland sites (Brenner et al. 2010). Recent deposits show an increase in rate to 0.4 cm/yr (0.013 ft/yr or 0.16 in/yr) (Brenner et al. 2010).

By contrast, sediment accumulation rates in Lake Monroe were shown to be generally low, the last 100 years were represented by approximately the upper 15 cm (0.5 ft or 6 in). Though sedimentation rates have increased most likely due to increases in nutrient loading (which causes excessive vegetation growth and decay), the rates remain fairly low - roughly half the rate of accumulation as for DeBary Bayou. Sediment cores collected for Mullet Lake showed much thicker layers of unconsolidated organic sediments largely attributable to prior agricultural practices (livestock, fertilizer use), invasive vegetation treatment and development in the basin. Highly organic unconsolidated and flocculated sediments ranged from 0.4 to 1.5 m (1.3 to 4.9 ft) depth at 31 sampling locations within Mullet Lake, with five intact cores containing 0.4 to 0.5 m (1.3 to 1.6 ft) of unconsolidated sediments (SJRWMD 2002a). This suggests rates of accumulation in Mullet Lake may have been much faster than for either Lake Monroe or DeBary Bayou. Sediment loading to the Bayou may have been increased for some period of time – these are legacy sediments having been deposited in the Lake at a much faster rate than in the Bayou or Lake Monroe, suggesting ranching activity, spring water quality and stormwater inputs may have been influential.

While the evidence does show an increase in sedimentation rate in DeBary Bayou in the last 50 years (total accumulation of 25 cm (0.8 ft or 9.6 in), this does not explain anecdotal reports of several feet of navigable depth lost over the last 50 years, nor does it support the contention that there is any such impact due specifically to I-4 having cut off Lake Monroe from DeBary Bayou. This remains an unresolved discrepancy, as none of the data or documented evidence found in the course of this study suggests that DeBary Bayou was more than a few feet deep during low flow conditions at any time during the last 100 years (even the *Fannie Dugan*, a famous side-wheeler steamboat which was able to navigate into the DeBary Bayou in the 1880's, required less than three feet of draft to operate), nor that the channel has filled in appreciably during the last 50 years. There are measureable declines in water quality and ecological condition within DeBary Bayou, though the DeBary Bayou shares many of these in character and magnitude with other similar systems in this region of Florida. There is very close hydrologic connection between DeBary Bayou and Lake Monroe, demonstrated by very similar water quality and stage, indicating a significant degree of influence from Lake Monroe and the St Johns River on water-impacted ecological conditions within DeBary Bayou, particularly during rising or high Lake Monroe stage.

Nonetheless, there are worthwhile gains to be made in addressing clear declines in water quality and ecological health in this system through a series of restoration measures. This report therefore ends with a series of restoration actions that may be taken to address the suite of locally-driven restoration objectives where the study team judged improvements might practicably be made. In particular, there are a number of meaningful and valuable ecosystem restoration opportunities within DeBary Bayou and within the Middle St Johns River Basin. Whereas all stakeholder concerns were considered, objectives that are unfeasible, impractical or clearly beyond the scope of the problem (i.e., the source of the problem is outside the control of any feasible project or restoration action), this study does not provide a recommended solution.

5 BACKGROUND

DeBary Bayou Watershed Assessment Project Underpinnings

During the last century, many developments and changes have occurred within the middle St. Johns River, its tributaries and watershed areas. At least since 1940, ecological quality and character in the Middle St. Johns River region are reported to have changed, prompting many local and regional stakeholders to focus attention and resources on the trajectory of these changes and expected impacts. Increasing development pressure and anthropogenic alterations in hydrology throughout the region and the state have resulted in increased sediment and stormwater loading and decreased water quality with concomitant habitat degradation and shifts in ecological communities state-wide. These shifts have been marked by declines in native plant and animal populations, increases in nuisance species and damaging invasive and exotic species, and a loss of the quality and character of many valuable, often interconnected habitats and unique natural resources.

For regional scientists and resource managers, these trends comprise strong impetus to determine the sources or causes of environmental problems and to identify and evaluate potential solutions that can be applied broadly. For the City of Debary and proponents of a healthy DeBary Bayou, the unique combination of specific development pressures and infrastructure combined with reported increase in sedimentation and sediment accumulation rates prompted concerned citizens to coordinate with FDOT to determine causes, effects and potential solutions to these problems.

In particular, the location and configuration of Interstate 4 (I-4) has been the focus of local attention because the road embankment bisects the Lake Monroe and DeBary Bayou interface at the shoreline of Lake Monroe, with one bridge opening at the stream channel outlet. The concern centers around the extent to which I-4 and its embankment influence hydrologic, hydraulic and sediment transport processes, and any impacts this might have on the resources in the Bayou. There are many other elements at play in this system – intensive development alongside the DeBary Bayou itself including River Oaks Estates, Riverside Condominiums, the City of DeBary and its stormwater infrastructure, highly influential hydrologic and nutrient/sediment cycling from Lake Monroe and the St. Johns River, invasive and exotic plants and animals throughout the region, and generally declining conditions of Florida Springs and groundwater resources. For example, Walsh (2009) analyzed 30-year land use changes for springs and springsheds including Gemini Springs, using data from 1973 to 2004 to determine and analyze general land use characteristics and concomitant changes in spring water quality and biological communities. According to Walsh (2009), between 1973 and 2004, urban area in Gemini Springs springshed increased dramatically, from 10% to 40%, and open water areas increased from 25% to 55%, while at the same time forested area decreased from 60% to<5%. The complexity of these interactions therefore requires a broader and more deliberate analysis to ensure a comprehensive and accurate representation of reported problems and issues, and to outline a set of workable solutions.

Though a relatively small watershed, DeBary Bayou represents and includes many of the resource issues that continue to generate concerns among stakeholders as environmental conditions change throughout the middle St. Johns River region. Lessons learned in a detailed study of DeBary Bayou, a direct tributary to St. Johns River via the inline Lake Monroe, might provide useful insight to other regional watersheds with similar ecological issues.

The FDOT has sponsored this study and created a capable core Technical Team consisting of representatives from FDOT, CESAJ, CEERD (ERDC), and SJRWMD. Many additional agencies, organizations and groups were included in this effort, described below in Section 5.1, Outreach and Coordination.

Community Reported Watershed Condition

Variously recorded as Padgett Creek, Padgett's Creek, DeBary Creek, or DeBary Bayou Creek, the DeBary Bayou and surrounding City of DeBary have enjoyed a rich and storied history due in large part to the comparatively unique collection of natural resources this area contains and its proximity to and accessibility by Lake Monroe on the St. Johns River. The true impetus for this study derives from the community of the City of DeBary, whose focus on and dedication to the natural resources of this area has brought a range of ecological issues and potential needs for environmental restoration to light. Invaluable local accounts and rich historical details have been provided by citizens and interested parties, from which a series of hypotheses have been developed for investigation. Most notably, long time residents and local historians Saundra H. Gray and J. Charles Gray, who have witnessed first-hand many changes in DeBary Bayou and its associated features, have painted a vivid picture of the ecological history of this area. They have provided many points of reference for past conditions and changes that with the combined accounts of other local residents and regional stakeholders have prompted the present comprehensive watershed assessment.

The following characterization is summarized exclusively from meeting minutes, correspondence and transcripts representing local stakeholder accounts and observations, including City Council Workshops held November 20, 2007 and January 30, 2008; DeBary Bayou Public Workshop held at the Town Hall in DeBary on December 16, 2008; and a series of meetings held in DeBary and DeLand on October 6 and 7, 2009 (see Section 5.1, Outreach and Coordination, for additional documentation of location and attendees). These anecdotal characterizations of past and present conditions in the DeBary Bayou form the basis of study hypotheses to which the remainder of this report applies published data, scientific studies and other reports in attempt to explain these observations.

By most accounts, the DeBary Bayou and associated natural hydrologic features – Mullet Lake and Gemini Springs – have historically been a popular destination for hunting, fishing and sightseeing, in addition to serving a role in commerce via both the St. Johns River to the south and the CSX Transportation's Railroad to the west (Figure 1). The Grays note that when they purchased Gemini Springs in 1969, they enjoyed a pristine setting they say included crystal clear water, excellent water quality at Gemini Springs, great bass fishing (with spawning populations) in DeBary Bayou, ample duck hunting at Mullet Lake and a deep and navigable channel with a sand and shell bottom that all provided a unique outdoor experience. Mr. Gray tells of catching 18 bass between 3.5 and 8.5 lbs (1.6 to 3.9 kg) each from his dock in 1970. Others have also reported great fishing and duck hunting, navigable waters, white sand bottom and a wide open marsh or grass prairie area that formed the southern portion of the bayou on the shore of Lake Monroe. Personal accounts of phenomenal bass fishing, sighting of river otters and manatee were noted into the late 1990's. The Grays impounded Gemini Springs and added other infrastructure around the springs shortly after they arrived in 1969. They owned and managed the Gemini Springs property until 1994 when they turned it over to become a public park managed by Volusia County. Sections of land in the watershed were maintained as pastureland for cattle ranching until 2003, at which time all ranching ceased as shown in (Figure 1).

Figure 1. Location map showing DeBary Bayou (Padgett Creek), associated hydrologic features and selected infrastructure. Map images produced using ArcGIS Explorer.

Within the last 40-50 years, residents have reported witnessing declines in environmental quality and accessibility within DeBary Bayou. Most notably, residents report that accumulation of fine sediment and organic material has affected boating access and general recreation opportunities, as well as declines in bass spawning, duck feeding, and access or use by other wildlife. By 2004 the creek has been described by some as all but impassable excepting air boats, alligators and small fish, particularly following tropical storm Fay in 2008, which brought in additional fine sediment and organic debris and resulted in persistent widespread turbid conditions throughout the Middle Basin (Figure 2). This storm produced the highest water levels in the St. Johns River and Lake Monroe in the period of time the Grays have lived in DeBary Bayou (for a point of reference, United States Geological Survey (USGS) gaging station on the St. Johns River at Lake Monroe reached a maximum stage of 7.9 ft during that storm, compared to 7.5 ft maximum stage in 2004 during hurricane Ivan, which was the first peak stage over 7.0 ft since 1964). These very extreme events may produce unusual amounts of sediment or organic debris.

Figure 2. Fine Sediment and Organic Debris at Gray's dock, 2008 after the water receded from Tropical Storm Fay (content and characteristics of the material are unknown, though this was a widespread and persistent condition throughout the Middle Basin of the St. Johns River). Photo courtesy of Saundra Gray.

Residents also report that invasive aquatic vegetation has increased especially within the last 20 years and includes *Phragmites*, water hyacinth (*Eichornia crassipes*) and water lettuce (*Pistia stratiotes*). The typical "spray and lay" method of treatment adds more organic material to the muck bottom. In addition, invasive blue tilapia is thought to have largely displaced the native bass, especially apparent since the 1980's.

Along with these issues, general water quality has declined both within DeBary Bayou and regionally, despite reductions in fertilizer use in the City of DeBary and elimination of ranching activities (all cattle were removed with no further leases by 2003). There are numerous coliform bacteria violations in Gemini Springs that limit recreation opportunities, and algal blooms in Mullet Lake, DeBary Bayou channel, Lake Monroe and St. Johns River are more commonly witnessed. Increasing stormwater inputs from the City of DeBary plus the use of reclaimed wastewater for groundwater recharge are thought to contribute excessive nutrients and sediments to the system. Most of the stormwater inputs attributable to FDOT are routed through stormwater ponds or interchange ponds that allow some settling of sediments and FDOT no longer fertilizes within their right of way, so inputs from these areas are thought to be minor by comparison.

A shift in the marsh community to more terrestrial species has also been observed, though there are no reports on when this is said to have occurred, or whether any shift is in response to recent droughts or much longer term processes. One theory regarding hydrologic changes in DeBary Bayou is that the lack of direct surface water connection between DeBary Bayou and Lake Monroe along the length of the I-4 corridor (despite access under the bridge designed to pass at least the 50 year flood) may prevent a seasonal "flushing" action. Reduced access by Lake Monroe limited to one location at the bridge is theorized by local residents to have prevented washing through DeBary Bayou. The theory is that this action would otherwise maintain channel depth with a shell or sand bottom, hydrate the area to preserve marsh lands, and keep the water cleaner by removing organic matter. Understanding of the nature of these interactions and possible causes of perceived shifts in wetland communities and sediment fluxes has been incomplete. One opinion is that part of the reduced water flow to the Creek was possibly attributed to the large pond where material was excavated for use in I-4 construction in the late 1950's (the "borrow pit"), thought to cause deposition of organic sediment up to three feet in depth in some areas, though the mechanism for this effect was not described in detail.

Placing local events and associated data sources on a rough timeline can help to visualize the potential for cause and effect (Figure 3). Simply looking at events in time may not entirely explain ecological changes, particularly if there are elements of import that are not included in the timeline (such as weather patterns), if there are regional influences at play (such as St. Johns River discharge) or there is a lag in impacts from certain events or activities (such as groundwater residence time). For example, construction of I-4 and introduction of invasive tilapia both predate reports of excellent bass fishing on DeBary Bayou by approximately 10 years, though at the same time the City of DeBary was over half forested and only 10% urbanized.

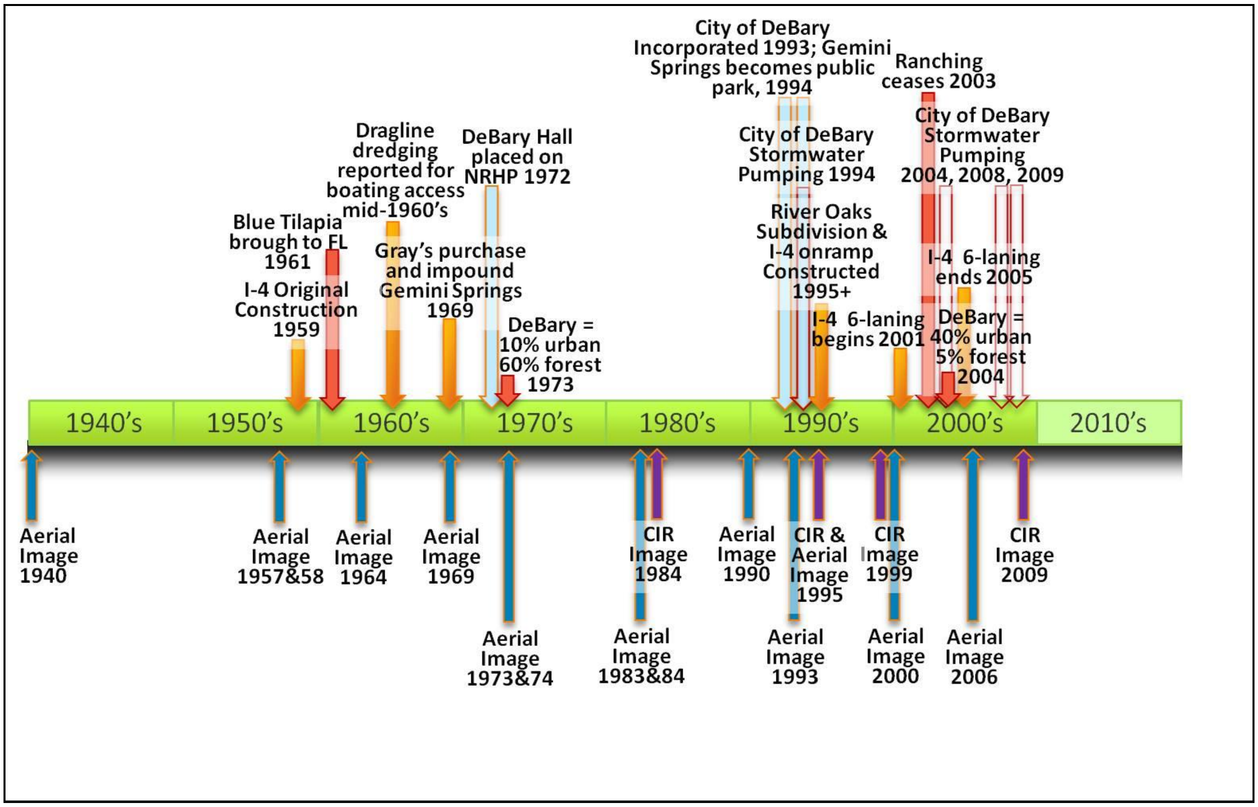

Figure 3. DeBary Bayou timeline of selected construction or development events in light orange, historic dates in light blue, landuse- or resource-related dates in dark orange, stormwater pumping dates outlined in red, and remotely sensed data available in dark blue and purple depending on type of imagery.

Research Study Questions

From the above accounts and observations, primary areas of concern are summarized below, in no particular order. Information and analyses conducted for this study will comprise investigation of the nature of issues expressed in each study question and will be used in support of possible restoration recommendations. Chapter 8, Documented Watershed Description, presents published or otherwise documented research, reports, data collection and analysis in an effort to present information to answer these research questions. Some questions can be readily addressed in a single discussion, having relatively narrow focus, though others are more open-ended and will draw on information from multiple sections for a more complete answer. Hydraulic and hydrologic connection questions

(1 and 2) are addressed primarily in Section 8.2.4, Inundation Dynamics Between Lake Monroe and DeBary Bayou. Sediment related questions (3 through 7) are addressed individually in Section 8.3, Sediment Quantity and Quality. Water quality questions (8 and 9) in Section 8.4, Water Quality, and ecosystem changes questions (10 through 12) are addressed in Section 8.5, Biological Communities.

1. Have sediment or organic matter inputs increased or decreased as a result of I-4 embankment limiting Lake Monroe access to DeBary Bayou (i.e., “flushing”)?
2. What is different about the hydrologic and hydraulic connection between Lake Monroe and DeBary Bayou through the I-4 bridge vs. along the former shore of Lake Monroe prior to I-4?
3. Have fine sediment and organic matter deposition or accumulation rates increased in DeBary Bayou over historical rates?
4. Are fine sediment or organic material accumulation rates in DeBary Bayou consistent with regional rates, or rates within St. Johns River or Lake Monroe?
5. How do historical bed conditions in DeBary Bayou – sediment quantity, quality and channel depth – compare with current conditions?
6. What are the likely sources of sediment, nutrients and organic matter in the DeBary Bayou system?
7. What are the mechanisms for sediment supply, sediment removal and general sediment cycling in this system?
8. What are the possible causes for water quality declines in the DeBary Bayou system?
9. To what extent do water quality declines compare between Gemini Springs, Mullet Lake, DeBary Bayou, Lake Monroe and St. Johns River?
10. Has fine sediment accumulation limited native vegetation growth or establishment or resulted in other ecological or water quality issues?
11. What are possible causes of shifts in marsh communities in DeBary Bayou?
12. What are possible causes of wildlife changes or declines in DeBary Bayou?

6 STUDY LOCATION AND MANAGEMENT JURISDICTIONS

The Study is focused primarily on the DeBary Bayou stream channel and watershed area and includes Gemini Springs and its springshed. Due to inevitable and important hydrologic and ecological interactions, the study will also consider Lake Monroe and the St. Johns River, designated Planning Unit 4D of the Middle St. Johns River Planning Basin (MSJRB) by St. Johns River Water Management District (Figure 4). The highlighted area for 4D is the 139 square mile (mi^2) floodplain watershed draining to Lake Monroe. The total drainage area at the outlet of Lake Monroe is 2,582 mi^2 as documented by the USGS at its gaging stations for Lake Monroe and the St. Johns River at the Lake outlet location where the river crosses US Highway (Hwy) 17-92.

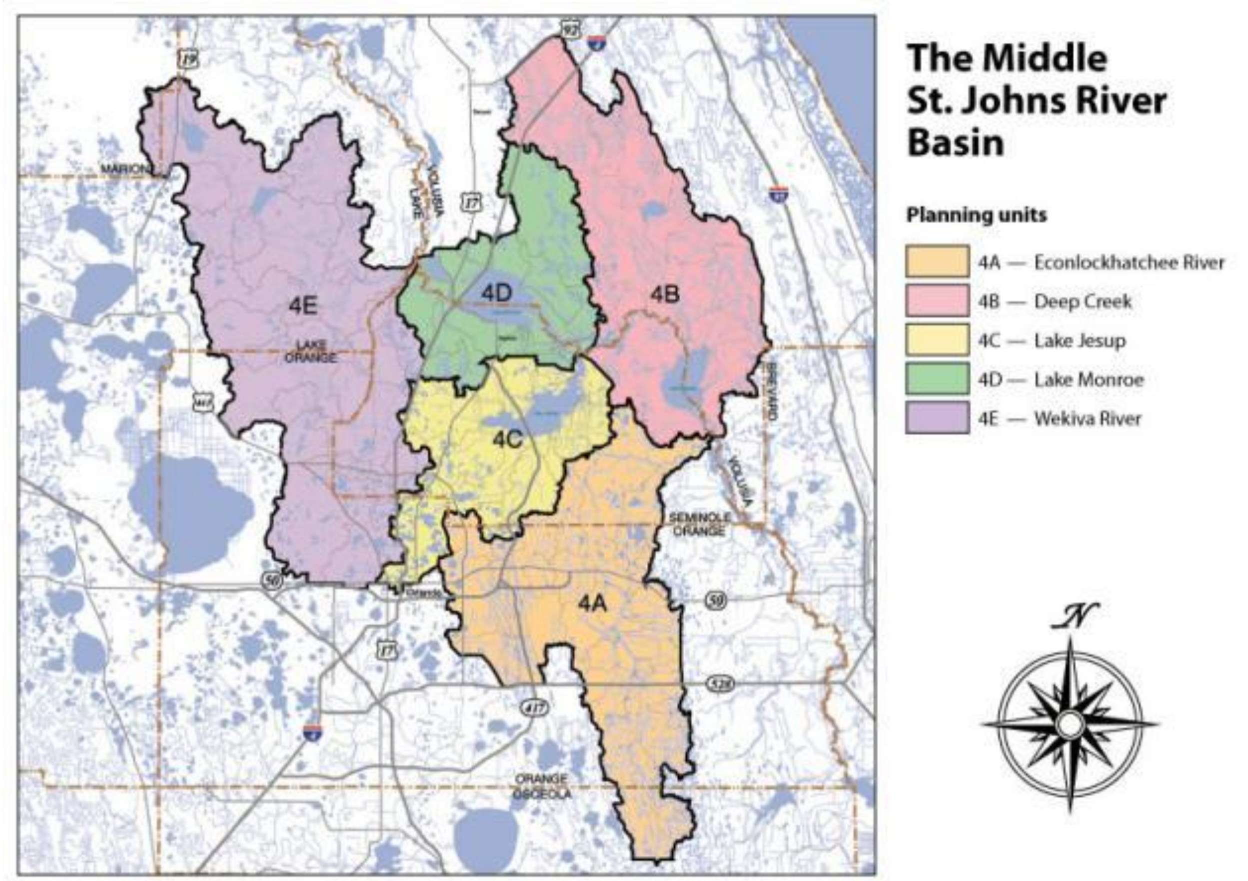

Figure 4. Location map showing St. Johns River Water Management District designated Middle St. Johns River Planning Basin; Lake Monroe Planning Unit #4D includes DeBary Bayou study area. Map image from SJRWMD website http://www.sjrwmd.com/middlestjohnsriver/

The study area for the present investigation lies within the political jurisdiction of two Congressional Districts (Figure 5). Florida's 7th Congressional District, representative Honorable John Mica, includes most of the City of DeBary, the northern portion of the DeBary Bayou watershed and most of Gemini Springs springshed. Florida's 3rd Congressional District, representative Honorable Corrine Brown, includes DeBary Bayou itself, Mullet Lake, Gemini Springs and Lake Monroe

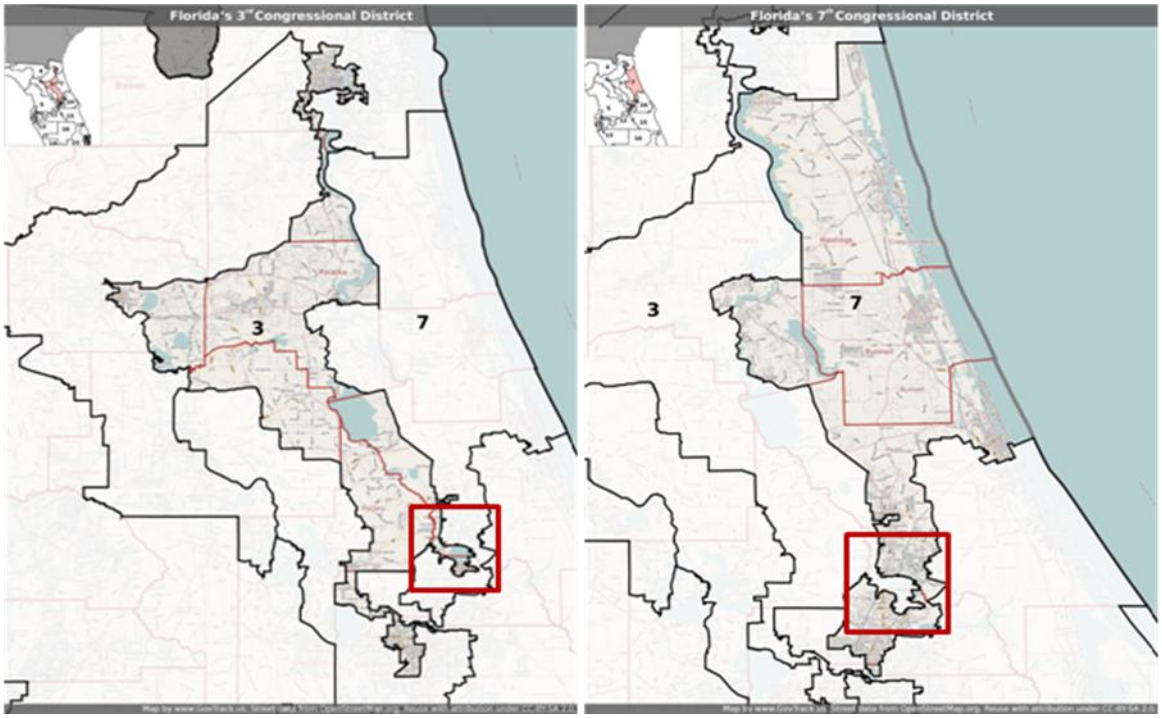

Figure 5. Florida Congressional Districts #3 and #7, encompassing the DeBary Bayou study area (study area included within red squares; maps are of differing scale though red squares encompass approximately the same area). Map images from GovTrack.us.

The entirety of the DeBary Bayou watershed (topographic drainage area) is contained within the City of DeBary municipal boundaries. The exact extent of the hydrologic drainage area is unknown due to the periodic and variable influence of stormwater inputs (gravity and pumped stormwater) from areas of the City of DeBary that would otherwise be outside the topographic drainage. Additional discussion of these boundaries and considerations is included in Section 6, Documented Watershed Description.

7 METHODS

Determining the source, extent and direction of potential changes in ecology, hydrology, geomorphology and sediment processes requires detailed data from a variety of sources, a careful examination of anthropogenic activities and natural ambient processes, and analysis of rates of change at local, regional and perhaps larger scale. This study has included review and consideration of a wide variety of existing data sources and documents available that cover the study area from the 1800's to the present, including aerial imagery, topographic and bathymetric surveys, detailed weather records, water quality and quantity monitoring, sediment sampling and analysis, and urban/infrastructure development activity records (Appendix A). In addition, through careful analysis of previous meeting minutes, correspondence, and anecdotal evidence paired with site visits and additional face to face meetings, the technical team was able to identify a suite of stakeholder issues and concerns.

Outreach and Coordination

To ensure a detailed characterization of historic and current conditions and a thorough understanding of the study area and concerns of all involved parties, multiple agencies, organizations and citizens groups have been broadly solicited for input to this study (Table 1). The technical team has reviewed numerous contact letters, meeting minutes, meeting transcripts and official memoranda, have convened and been invited to attend additional public workshops, technical team meetings and telephone conferences, and have collected additional anecdotal information through field site visits and interview notes from many sub-group meetings (Table 2). Each individual and organization was important for the pertinent data, reports, photos, imagery and a wealth of personal and professional knowledge these many people brought to the table. Agencies or groups authoring or cooperating on reports referred to in this study, such as the United States Geological Survey, University of Florida or the Florida Fish and Wildlife Conservation Commission, are not included in the table because a specific representative was not contacted directly, but nonetheless are represented in the analysis and conclusions in this study through additional information from web materials or published reports (Table 1 and Table 2).

Table 1. Agencies and stakeholder groups from which representatives have provided information for the DeBary Bayou Watershed Assessment Study.

Jurisdiction	Name	Abbreviation
Federal	United States Army Corps of Engineers, Jacksonville District	CESAJ (USACE)
	United States Army Engineer Research and Development Center	CEERD (ERDC)
	United States Congress, Florida Congressional District 7	
	United States Fish and Wildlife Service	USF&W
State	Florida Department of Transportation, District 5	FDOT
	Florida Department of Environmental Protection	FDEP
Regional	St. Johns River Water Management District, various Departments	SJRWMD
County	County of Volusia, various Departments	Volusia Co.
Municipal	City of DeBary, various Departments	DeBary
Stakeholder Associations	DeBary Waterway Restoration Committee	
	River Oaks Homeowners Association	
	Riverside Condominium Association	
Academia	Southeast Environmental Research Center, Florida International University	SERC, FIU
	University of Florida, Department of Geological Sciences	

Table 2. Selected important meetings with attendees, DeBary, FL.

Meeting Date	Location	Attendees
11/20/2007	City Council Workshop: Florence K. Little Town Hall, DeBary, FL	(partial list) Mayor George Coleman, Congressman John Mica, Pete Milam, Charles Gray, Stephen Bacon
1/30/2008	City Council Workshop: Florence K. Little Town Hall, DeBary, FL	(partial list) Mayor George Coleman, Congressman John Mica, Pete Milam, Alan Hyman (FDOT), David Fisk (SJRWMD), Noranne Downs (FDOT), Herky Huffman (SJRWMD)
12/16/2008	DeBary Bayou Public Workshop: Florence K. Little Town Hall, DeBary, FL	Mayor George Coleman, City Council Members (Lenny Marks, Jack Lenzen, Chris Carson, Norman), Dick Harkey (congressman Mica's office), Tom Carey (Volusia Co Environmental Mngt), Bobbi Bryant (Parks, Rec and Culture), Jonas Stewart (Mosquito Ctrl), Pete Milam (CESAJ), Meg Jonas (CEERD), Angie Huebner (CESAJ), Stephen Bacon (DeBary Waterway Restoration Committee), Charles and Saundra Gray, Joe Alemany, Gary Meadows (River Oaks), Sherry Brandt-Williams (SJRWMD), Mary Brabham (SJRWMD), Ferrell Hickson (FDOT), Alan Hyman (FDOT), Bob Garcia (Mayor-Elect, DeBary), Maryann Courson (DeBary City Manager), David Hamstra (DeBary), Pat Northey (Volusia Co Council), Andy Kelly, Adam Cairo (Riverside Condo Assoc.), by phone – Congressman Mica
10/6-7/2009	General Public Meetings 1 and 2 – DeBary and DeLand	1 [Sherry Brandt-Williams, Ferrell Hickson, Alan Hyman, Nelson Colon, Pete Milam, Judy Sloan, David Hamstra, Meg Jonas, Sarah Miller]; 2 [Anne Bennedetti, Dick Harkey, Charles and Saundra Gray, Herky Huffman, Alan Hyman, Pete Milam, Ferrell Hickson, Meg Jonas, Sherry Brandt-Williams, Nelson Colon, Sarah Miller]

Literature Review

A wealth of documented data and records including several completed local and regional plans and studies provided useful information (Table 3).

Reports, analyses and plans documenting I-4 causeway and bridge assessment, design, construction and widening activities, including design documentation, specifications and plan drawings from 1959 (original plans), 1996, 1997, 2004 and 2008, as well as the following reports, were included in this study as provided by FDOT:

- Scour Evaluation Report – State Bridge No. 790099 (EB) & 790941 (WB). Padgett Creek Bridges over S.R. 400 (Interstate 4), Volusia County, Florida. Prepared for: Florida Department of Transportation District Five, Submitted by: Parsons Brinckerhoff Quade & Douglas, Inc. May, 1996, Revised July, 1996, 162 pp.
- Design Documentation (Roadway & Drainage) 90% Submittal – I-4 from Seminole County Line to 0.5 Km West of Saxon Boulevard, Volusia County, Florida. Prepared Florida Department of Transportation District Five by Parsons Brinckerhoff. January 1997, 159 pp.
- Final Report – Preliminary Engineering Report for the I-4 Six Laning and St. Johns River Bridge Project Segment I – from US 17-92 to SR 472, Seminole and Volusia Counties, Florida. Prepared by URS Greiner Woodward Clyde and CH2MHill for Florida Department of Transportation District Five. May 2000. 146 pp.
- Final Location Hydraulics Report I-4 Project Development and Environment Study – Section 2 from Beeline Expressway to SR 472. August 2000. 31 pp.
- Drainage Calculations for I-4 (SR 400) St. Johns River Bridge Replacement and Six-Laning, Volumes I and II. Prepared by URS, Inc. for Florida Department of Transportation. May 2001. 36 pp and 257 pp, respectively.
- Preliminary Engineering Report for the Interstate 4 (SR 400) Project Development and Environmental Study Section 2, Orange County, Seminole County and Volusia County, FL. Prepared by URS & CH2MHill for Florida Department of Transportation District Five. August 2002. 358 pp.

Table 3. Completed studies and reports referred to in DeBary Bayou Watershed Assessment Study.

Date	Title	Preparing Organization	Subject	Conclusion or Recommendation
1996	Scour Evaluation Report, Padgett Creek Bridges over S.R 400 (Interstate 4), Volusia County, Florida	Parsons Brinckerhoff Quade & Douglas, Inc. for Florida Department of Transportation District 5	Scour analysis to determine scour depth for bridge reconstruction project due to widening of I-4 and provide information for design depth of bridge foundations.	Determined that very little change has occurred in XS under the bridge between 1959 and 1996, low risk and low priority, no evidence of aggradation or degradation, a total of 2.6 ft scour and 2.9 ft scour in a 100 yr and 500 yr storm, respectively.
2002	Mullet Lake Enhancement Project – Baseline Water and Sediment Quality and Sediment Depth Profiles Report	DB Environmental, Inc., for St. Johns River Water Management District	Water and sediment quality study to determine most appropriate sediment restoration actions.	Due to high nutrient content and sediment resuspension rates, sediment should be removed and reduced, vs. chemically stabilized.
2002	Middle St. Johns River Basin Surface Water Improvement and Management Plan	St. Johns River Water Management District	Description of SWIM plan for 5th priority-ranked MSJRB to set a course of action for remediation.	Sets a plan that identifies causes and effects of surface water quality declines in the Middle Basin and defines additional studies, projects, estimated costs and timeline to implement.
2003	Mullet Lake Enhancement Project – Effects of Desiccation and Reflood on Inorganic Nitrogen Phosphorus Release Under Oxic and Anoxic Conditions (2nd Interim Report)	DB Environmental, Inc., for St. Johns River Water Management District	Assessment of treatment options to reduce sediment thickness with least impact on water quality.	Drawdown has least nutrient release but limited sediment reduction. Excavation can lead to significant releases if lower horizons dry; dredging limits lake releases but increases impact in spoils area.
2004	Lake Monroe Sediment Accumulation and Past Water Quality Final Report	Southeast Environmental Research Center, Florida International University for St. Johns River Water Management District	Determine nutrients associated with sediments in Lake Monroe to evaluate water quality restoration.	Lake Monroe has 15cm floc over 3-20cm sediment (gyttja, peat, sands/clays/grey mud). Phosphorous, productivity and sediment accumulation rates increased in the last 100 yrs coincident w/development, similar to nearby lakes.
2006	Gemini Springs Addition Land Management Plan, Middle St. Johns River Basin, Volusia County	St. Johns River Water Management District	Plan for 948-acre acquisition focused on key resource issues: water, fire, pasture restoration, invasive/exotic species, wildlife, cultural resources and recreation.	Detailed management tasks and implementation strategy with lead agencies and cooperators for all resource issues.

Date	Title	Preparing Organization	Subject	Conclusion or Recommendation
2006	The Drought of 1998-2002: Impacts on Florida's Hydrology and Landscape – Circular 1295	U.S. Geological Survey, with Florida Department of Transportation and Florida Department of Environmental Protection	Document lower than normal precipitation and statewide drought impacts on landscape and hydrology, with historic comparison.	This drought was as severe as the worst drought of the 20th century ('49-'57), setting low flow records at 14 of 32 stream gages studied, with similar records for low well flows. Sinkholes and fires result.
2007	Surveyor's Report for Middle St. Johns River Basin–Topographic and Hydrographic Survey, Volusia and Seminole Counties, Florida	Degrove Surveyors, Inc., for St. Johns River Water Management District. September	Soundings transects completed along or near waterways, except Gemini Creek (too narrow, shallow).	Coordinate files, shape files and drawing file (map of location of control points, transects and hydrographic surveys).

In addition to reports described above, this study refers to a number of additional studies that cover hydrology, water quality, aquatic communities and other information on regional springs, and a useful website maintained by SJRWMD with information on springs within the St. Johns River basin. A complete list of documents referenced in this report with full citations appears in Reference Section, though the following selected reports provided particularly useful information on regional springs and Gemini Springs in particular.

1. Rutledge (1985) described groundwater hydrogeology of Volusia County as a whole.
2. Katz (2004) included 12 first magnitude springs, all west of St. Johns River.
3. Scott et al. (2004) cover the most territory, describing 462 springs in an updated document from the 1977 *Springs of Florida* by Rosenau, covering 300 springs. Though neither document includes specific monitoring of Gemini Springs, Scott et al. (2004) visited, photographed and described the springs in their report.
4. Phelps (2006) focused on four springs, three of which flow from the De Land Ridge and including Gemini Springs.
5. Brown et al. (2008) canvassed the literature on effects of nutrients on spring systems in Florida in general.
6. Walsh et al. (2009) studied nine springs including Gemini Springs.
7. Harrington et al. (2009) included 49 springs, nine of which are located in the Middle St. Johns River Basin, though Gemini Springs was not included.

In addition to existing reports and plan documents, FDOT initiated a sediment accumulation study within the context of this DeBary Bayou watershed assessment. The sediment investigation and report titled Recent Sediment Accumulation in Padgett Creek; Middle St. Johns River Basin was done by the Land Use and Environmental Change Institute, Department of Geological Sciences, University of Florida (Brenner 2010). The purpose of the sediment study and report is to provide additional information on sediment accumulation rates within DeBary Bayou (Padgett Creek) using radionuclide dating methods to corroborate anecdotal evidence of increased rate of accumulation. This and other sediment sampling and analysis data, with a series of recent transects surveyed by the SJRWMD in 2009, were carefully compared to determine amounts and rates of sediment accumulation and any departure from the norm.

Field Investigation and Imagery Comparison

Site visits and analysis of aerial and on the ground photography were instrumental in assessing watershed and stream conditions and issues. FDOT guided a driving tour of stormwater outfalls was especially useful in that these areas reveal the relative activity of stormwater infrastructure, as well as give some qualitative indication of the relatively amount and size distribution of sediment inputs from this source.

Qualitative (i.e., size distribution was not specifically analyzed) sediment and substrate conditions were assessed observed both by airboat tour and through subsequent walking tour within DeBary Bayou main channel, Mullet Lake, Gemini Springs, and some limited areas of Lake Monroe. In all, several types of field visits were made to a number of different locations by ERDC personnel accompanied by representatives of several cooperating agencies and groups to get differing perspective for comparison with outreach and documented information sources.

Aerial imagery from 1940 to the present comprised a critical set of information on the evolution of conditions in DeBary Bayou. These images were compared with USGS-measured daily average water level (stage) at Lake Monroe outlet on those dates to determine the appearance and impact of Lake Monroe water level on the Bayou and compare impact or changes apparent over time including construction of I-4 and ongoing development in the watershed.

To analyze hydrologic connection between Lake Monroe and DeBary Bayou, a combination of data were assessed, including bridge flow conveyance capacity, stage (water surface elevation) data for Lake Monroe, soil types and long-term inundation patterns, aerial imagery interpretation for selected dates, and topographic elevation combined with selected important Lake Monroe elevations. Stage data at USGS surface water gaging stations for Lake Monroe and St. Johns River at the outlet of Lake Monroe were closely analyzed to determine long term and seasonal patterns of Lake Monroe stage, compared with the known capacity of the I-4 bridge to pass water in and out of DeBary Bayou and the concomitant rise and fall of stage within the Bayou in tandem with Lake Monroe.

8 DOCUMENTED WATERSHED DESCRIPTION

A unique combination of natural and human-made components comprises the DeBary Bayou system (see Figure 1). These elements together create the complex ecological condition in DeBary Bayou. This section includes summary descriptions of physical, chemical, biological and anthropogenic attributes of DeBary Bayou and its regional context as documented in published literature, scientific studies, agency reports, and online resources. This characterization centers on those attributes of most interest to answering previously identified research study questions targeted at determining current and former ecological state, defining the magnitude and direction of any alterations or changes in functions or processes, and explaining causal factors where discernible. In particular, this study is focused on hydrology and sediment processes and any factors that influence reported increases in sedimentation rates and concomitant ecological impacts within DeBary Bayou.

Physical Watershed Features

Physical features of the DeBary Bayou watershed include the topographic watershed, underlying bedrock and soils, interactions that produce geomorphic character and condition of the channel and its valley, and climate characteristics including surrounding areas that are responsible for the current morphology and landscape configuration.

Watershed Boundaries and Hydrologic Features

The study area and all hydrologic features are located within the Lake Monroe Planning Unit, one of five in the Middle St. Johns River Basin of the St. Johns River Water Management District (SJRWMD 2002b). Hydrologic features of interest in this study include the St. Johns River, Lake Monroe, DeBary Bayou, Gemini Springs, Mullet Lake and the FDOT Borrow Pit/Pond and possibly the FDOT Stormwater Retention Pond (see Figure 1). These elements will be described in more detail in subsequent sections, including various characteristics of potential impact to the study where information is available. Mullet Lake, Gemini Springs, DeBary Bayou, Lake Monroe and St. Johns River are all classified Class III waters by the Florida Department of Environmental Protection. Class III designation includes recreational uses with propagation and maintenance of healthy, well-balanced fish and wildlife populations.

Additional nearby aquatic features such as Konomac Lake to the West and numerous small stormwater or other ponds and depressions in the City of DeBary were not explicitly described or considered as influential elements in the study, though may play a role in future remediation activities. Note that Konomac Lake is a Florida Power and Light (FPL) constructed cooling pond reservoir, and functions as a closed system assumed to have no influence on the DeBary Bayou system.

Lake Monroe on St. Johns River is an inline or "river run" lake roughly 6 mi long, 4 mi wide and seven feet deep on average (SJRWMD 2002a). The Middle Basin Planning Unit 4D consists of a floodplain watershed area of 139 mi^2 (360 km^2); the study area is on the north-west shore of Lake Monroe, immediately to the north of St. Johns River (see Figure 1).

DeBary Bayou is a small tributary flowing west to east to Lake Monroe, approximately 1.5 mi (24.1 km) in length and draining a topographic watershed of approximately 3.1 mi^2 (8 km^2). The City of DeBary estimate was measured from City-derived data using Volusia County GIS from 2004; this estimate differs from the 1957 USGS Quadrangle map used to delineate 3.52 mi^2 (9.1 km^2) watershed (FDOT1996). All drainage sub-basins feeding DeBary Bayou are within City of DeBary limits, though the extent of functional drainage area remains unclear due to periodic discharge additions from extensive stormwater infrastructure as noted above.

Gemini Springs is one of more than a dozen natural springs located within the Middle St. Johns River Basin. The Gemini Springs springshed or recharge basin is a 3.59 mi^2 (9.3 km^2) area north and west of the springs, within the City of DeBary. The Gemini Springs springshed overlaps roughly half of the DeBary Bayou topographic watershed. The Springs consist of two primary vents, Gemini North and Gemini South, plus additional seepage.

Mullet Lake is a relatively shallow (less than 6 ft or 1.8 m) 60-ac (24.3 ha) natural water body at the western end of DeBary Bayou, draining into the Bayou at its north-eastern side (SJRWMD 2002a). Mullet Lake has been found to be eutrophic to hypereutrophic, though has attracted and supported numerous species of waterfowl and fish (SJRWMD 2002a). There is no defined inlet to Mullet Lake.

Borrow Pit (Pond) is a 55-acre (22.3 ha) pond sits to the south of DeBary Bayou, between the main channel and Lake Monroe. This pond resulted from an FDOT borrow pit from which material was used in construction of the I-4 corridor through this area in 1959. This pond is hydrologically connected to DeBary Bayou being within the floodplain, though actual flow direction or magnitude is not clear, partially due to a one- to three-foot berm surrounding this pond, with one apparent opening.

FDOT Stormwater Retention Pond is a 30-acre (12.2 ha) retention pond draining to Mullet Lake adjacent to US Hwy 17-92 in the southern portion of the DeBary Bayou watershed area, created by FDOT during the construction of the I-4 causeway. There are numerous stormwater retention and detention ponds throughout the study area, though this is the largest of the constructed stormwater ponds in the study area.

Climate

The climate of this region is subtropical maritime with average temperatures around 80 degrees Fahrenheit in summer and 60 degrees Fahrenheit in winter. Long term (1930 – 2007) average annual rainfall on the De Land Ridge to the north and inclusive of the study area is 56 in (142 cm) (Walsh 2009). Though De Land ridge has the highest local rainfall, it has historically had the lowest runoff due to the dominant downward drainage and subsurface aquifer recharge (Knochenmus 1968).

Total rainfall amounts are influenced heavily by catastrophic events caused by tropical storms, hurricanes and tornadoes. Since the I-4 embankment and bridge crossing was completed in 1959 to the present, there have been at least 11 F2+ tornadoes interspersed or overlapping with five prolonged periods of drought lasting three to 11 years (Verdi et al. 2006, National Oceanographic and Atmospheric Administration (NOAA) online). NOAA records for the study area since 1993 show at least six hurricanes or tropical storms causing damages and five F2+ tornadoes in the same period regionally (NOAA online). This timeline also included a 5 year period of drought (Verdi et al. 2006) and at least one forest fire (NOAA online). Clearly this is a meteorologically dynamic region, with landscapes, streams and rivers required to handle extremes of storm magnitude, timing and duration.

Bedrock and Hydrogeology

The landscape in the study area is characterized by limestone karst topography, with hills and depressions to the north comprising the De Land Ridge and the flat floodplain river valley of the St. Johns River to the south (Phelps 2006, Scott et al. 2004). Numerous sinkholes, springs, lakes and downward drainage created by dissolution, erosion and collapse of underlying limestone typically characterize this topography. The City of DeBary itself contains approximately 43 small water table lakes and wet depressions (Stewart et al. 1999). Much of the valley bottom of the Middle St. Johns River surficial geology is of Holocene or Pleistocene age, the De Land Ridge is Pliocene or Pleistocene age (Scott et al. 2004). The surficial aquifer consists of quartz sand, sandy clay and locally small shell beds of Pleistocene and Holocene age, generally 20 to 50 ft (6 to 15 m) thick (Rutledge 1985).

According to the Florida Springs Classification System, springs are classified according to average discharge over a period of record with a total of eight defined magnitudes as follows (Scott et al. 2004):

1. first magnitude = 100 cfs (2.8 cms) or greater
2. second magnitude = 10 to 100 cfs (0.28 to 2.8 cms)
3. third magnitude = 1 to 10 cfs (0.028 to 0.28 cms or 1.68 to 16.8 cmm)
4. fourth magnitude = 100 gpm to 1 cfs (0.379 cmm or 379 liters per minute (lpm) to 1.68 cmm)
5. fifth magnitude = 10 to 100 gpm (37.9 to 379 lpm)
6. sixth magnitude = 1 to 10 gpm (3.79 to 379 lpm)
7. seventh magnitude = 1 pint/min to 1 gpm (0.47 to 3.79 lpm)
8. eighth magnitude = less than 1 pint/min (less than 0.47 lpm)

Current Florida Geological Survey documents 33 first, 191 second, and 151 third magnitude springs in the central region of Florida. The majority of these springs are fed by the Upper Floridan aquifer of the Floridan aquifer system (FAS) consisting of limestone and dolostone of late Eocene to mid-Oligocene age, underneath an intermediate aquifer (depending on location) of fine sand, silt and calcareous silty clays and carbonate (Rutledge 1985, Scott et al. 2004). The vast majority of the 720 Florida

Geological Survey documented springs in FL are karst springs, including all 33 first magnitude springs (Scott et al. 2004). Surficial aquifer as described above consists of quartz sand, sandy clay and locally small shell beds. Depth to water table is typically less than 10 ft (3 m), though may be up to 20 ft (6 m) in De Land Ridge. Groundwater throughout this region is heavily used for water supply – various sources report the Floridan aquifer is estimated to provide 95% of the water supply regionally, extending throughout most of the state's peninsula (Phelps 2006).

Gemini Springs emerges from its De Land Ridge springshed onto the karst plain in the St. Johns River valley, a typical geologic location for springs in this type of landscape, where the limestone of the Upper FAS is at or near the land surface (Scott et al. 2004, Phelps 2006). Gemini Springs consists of a North vent and a South vent, at each of which USGS maintains a gaging site. Both springs join into a spring run with approximate long term average discharge of 10 cfs (0.28 cms). Though Gemini Springs is variously reported as second magnitude or third magnitude, it is most often referred to as a third magnitude spring (Walsh 2009, Scott et al. 2004, SJRWMD online). Spring flow is impounded by a low-head dam, constructed in 1969 (Walsh 2009). Substrate of spring pools and spring run is primarily sand and small gravel, though much of the spring run and impoundment are covered by algal mats. Effects of the dam remain poorly understood at this time.

Ecological character of Gemini Springs is difficult to assess compared to other springs as each is different in length of channel, size of adjacent wetlands, effects of backwater from streams (or impoundments), water chemistry, land use in the springshed and possibly other factors.

Source of water within the Floridan aquifer and emerging from karstic artesian springs is primarily rainwater-derived recharge through the surficial aquifers (Walsh 2009, Phelps 2006). Residence time within each aquifer, response time to changes in recharge rates and water quality, and amount of mixing of water of various ages have all been aspects of study in determining what governs age, quantity and quality of spring water in these systems. A number of studies and reports have been written on Florida springs, including hundreds of locations (Katz et al 2001, Scott et al. 2004, Phelps 2006, Brown et al. 2008, Walsh 2009, and others). Though few of these have explicitly included data for Gemini springs primarily due to its small size, there have been data collection efforts that are important to compare with regional spring dynamics, and there are characteristics of FL springs in this geology that apply equally to Gemini Springs.

De Leon, Gemini and Green Springs all flow from the De Land Ridge in Volusia County and spring water here results primarily from water that has infiltrated the ridge (Phelps 2006, United States Department of Agriculture (USDA) 1977). Age of water emerging from Gemini Springs has been estimated using various methods in several different studies, with estimates ranging from five to 43 years, and shows evidence of some mixing of Upper and Lower Floridan aquifers (Phelps 2006, Katz et al 2001, Katz 2004, Walsh 2009). As noted above, the karst landscape on the De Land Ridge has previously had little external surface drainage, with large amounts of rainfall diverted to subsurface flow (Knochenmus,1968). However, development and impervious surface increases in the Gemini Springs springshed may have changed this distribution, though reclaimed wastewater used for groundwater recharge may offset some of this shift.

Though a smaller system, neighboring Green Springs provides a point of comparison with Gemini Springs (Table 4). Green Spring is a third magnitude spring emerging from the south end of DeLand Ridge, though with lower average discharge of 1.1 cfs (0.031 cms) and a springshed of 1.79 mi^2 (4.64 km^2). This spring discharges to a small creek running 0.25 mi (0.4 km) unimpeded into Lake Monroe – there are no structural or hydrologic controls on this spring system, so surface connection between Lake Monroe and the springshed and watershed and outfall creek of Green Spring is not interrupted by either a dam or a road embankment. The springshed of Green Spring has also seen an increase in developed areas and a decrease in forested areas, with urbanized and forested areas in 2004 estimated at 68.4% and 1.7% respectively, compared with Gemini Springs springshed at 40.9% and 3.0% respectively. Both springs show significant influence of wastewater in the number of contaminants recorded at each spring.

Table 4. Selected Published Attributes of Gemini Springs and Green Spring, tributary to Lake Monroe, St. Johns River, FL (Walsh 2009, Scott et al., 2004, SJRWMD online).

Attribute	Gemini Springs	Green Spring
Magnitude	Third	Third
Average Discharge	10 cfs (0.28 cms)	1.4 cfs (0.039 cms)
Outfall stream length	1.5 mi (2.4 km)	0.3 mi (0.48 km)
Springshed area	3.59 mi^2 (9.3 km^2)	1.79 mi^2 (4.6 km^2)
Reclaimed waste-water recharge area mi^2, %	1.2 mi^2 (3.1 km^2), 33%	0.39 mi^2 (0.8 km^2), 22%
Forested area % 1973 - 2004	59.7 – 3.0%	17.7 – 1.7%
Wetland/open water % 1973 - 2004	26.4 – 54.7%	24.0 – 29.9%
Developed area % 1973 – 2004	9.4 – 40.9%	58.1 – 68.4%
Barren % 1973 - 2004	2.4 – 0.8%	0.2 - <0.1%
Agriculture % 1973 - 2004	2.1 – 0.6%	<0.1%
Water age	<43 years	20 years
Pollutants from wastewater	phenol, benzophenone, DEET, triphenyl phosphate, methylnaphthalene, methyl salicylate, naphthatlene, triphenyl phosphate	phenol, benzophenone, DEET, methylnaphthalene, bisphenol A, methyl salicylate, naphthatlene, para-Cresol, para-nonylphenol
Pesticides	atrazine, atrazine degradate (CIAT)	None detected
2004 visitation numbers (Bohn, 2004)	57,755	14,439

Debary Bayou Soils

Wetland soils can provide a general idea about the duration of inundation throughout the year and the potential for groundwater interaction or connection. Generally, depositional sandy alluvial soils allow groundwater connection, particularly if the soil unit is contiguous. Soil types present in the DeBary Bayou watershed are largely wetland soils, with general periods of inundation required to create and sustain each soil type (Baldwin et al.1980, SJRWMD (2006). Specific soil types in the floodplain of DeBary Bayou indicate this area is inundated frequently, often for extended periods of time (Figure 6). Though not shown in Figure 6, soil types in DeBary Bayou floodplain continue into the shores of Lake Monroe, consisting primarily of Bluff series soils (SJRWMD 2006).

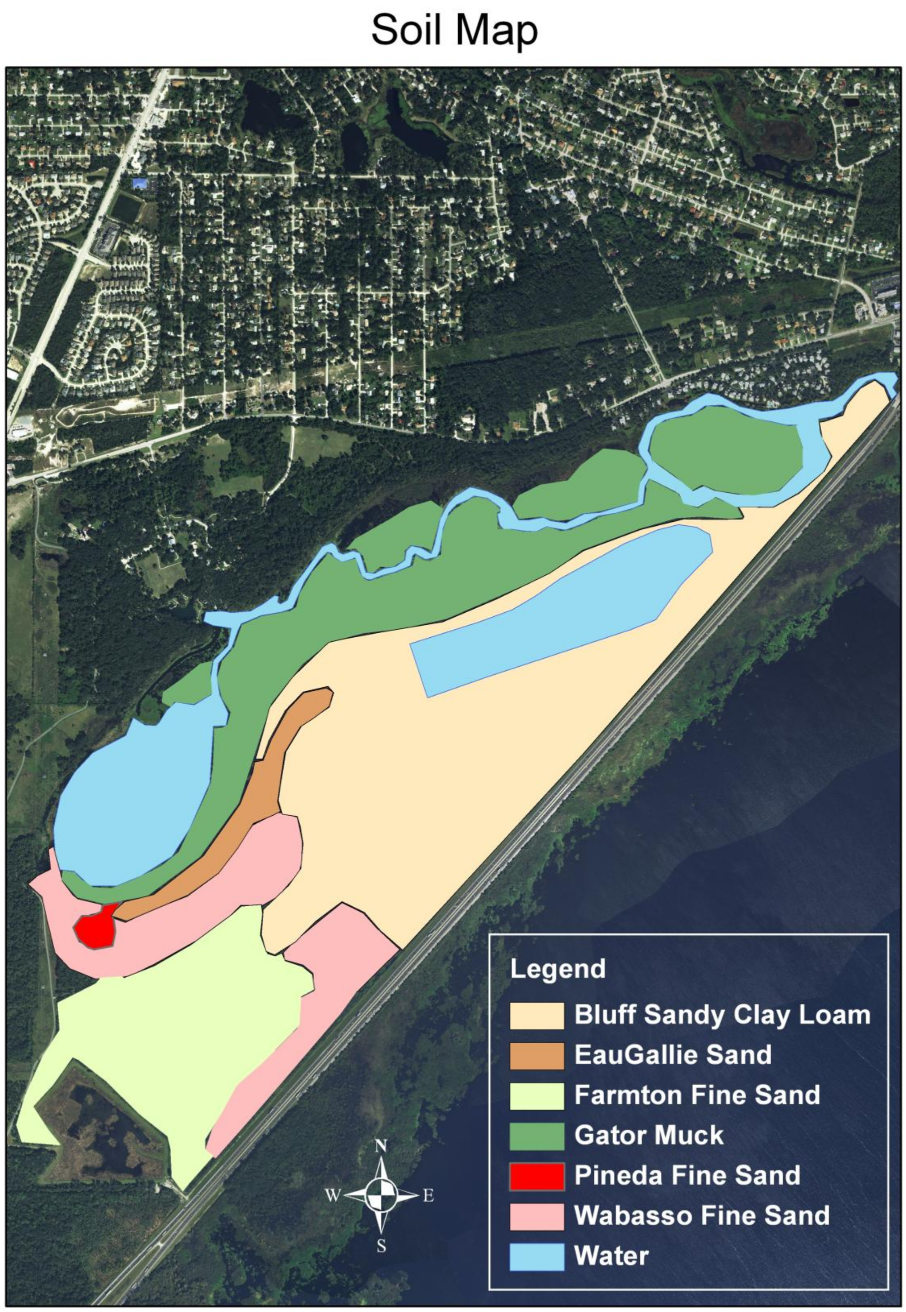

Figure 6. Soil types in DeBary Bayou, source information SJRWMD 2006. Image not to scale.

Soil Types in DeBary Bayou Floodplain

Bluff Sandy Clay Loam: Bluff series soils consist of nearly level, poorly drained soils of sandy clay and clay loam alluvial sediment associated with the St. Johns River drainage system and alkaline marine sediments.

Typical depth to water table: < 10 in (< ~25 cm) for 6 or more months and seldom recedes to depths greater than 20 in (~51 cm). This soil is saturated for long periods of the year. These soils are commonly flooded in the summer rainy season.

Euagallie Series: These soils are found in level broad flatwood areas and are poorly drained. The water table in Eaugallie Sand can fluctuate within 10 in (~25 cm) of the surface for 1-4 months out of the year. Most years the water table is found within 40 in (~102 cm) of the surface for over 6 months.

Farmton Series: These soils can be found in flat broad flatwood areas. Under normal conditions these soils stay saturated within 10 in (~25 cm) late in the summer and early fall. For a majority of the time (6 months) the water table is within 40 in (~102 cm) of the surface in Farmton Fine Sand, and for short durations (1-3 months) can be found within 10 in (~25 cm) of surface.

Gator Muck: Gator series soils consist of nearly level, very poorly drained organic soils that formed reasonably thick beds of hydrophytic non-woody plant remains, which is underlain by loamy and sandy material. These soils are found in freshwater swamps and marshes and can be found on flood plains of rivers and lakes. Slopes are less than 1 percent. Typical depth to water table: at the surface except during extended droughts. This soil generally has the water table at or above the surface for the entire year. Some winters the water surface may drop to within 10 in (~25 cm) of the surface.

Pineda Series: These soils can be found in low flat areas bordering lakes and swamps. They are poorly drained, with the water table at or near the surface during the rainy season. The water table can be within 10 in (~25 cm) of the surface of Pineda Fine Sand for around 6 months a year. Some areas can have standing water from 7 days to 6 months.

Wabasso Series: These soils can be found in flat broad areas of the flatwood and depressions. They are poorly drained and under normal conditions are saturated to within 10 in (~25 cm) of the surface during the summer and fall. The depressions will form seasonal ponds. The water table is within 40 in (~102 cm) of the surface in Wabasso Fine Sand for a majority of the year. During extreme droughts the water table may fall below 40 in (~102 cm) from the surface.

Additional Soil Types in DeBary Bayou Watershed

Chobee Series: These soils are composed of well drained sandy soils mainly associated with low ridges.

Daytona Series: These soils are moderately drained and found in nearly level to gently sloping settings. These soils are saturated below depths of 40 (~102 cm) in late in summer and in fall.

Electra Series: These soils can typically be found on low ridges in flatwoods. They are somewhat poorly drained and so a decrease in permeability with depth.

St. Johns Series: These soils are commonly found in flat low area adjacent to swamps and depressions. These soils tend to have moderate permeability.

Hydraulic and Hydrologic Watershed Processes

General Surface Hydrology

The St. Johns River is the third largest drainage basin in FL, with drainage area at the downstream end of Lake Monroe equal to 2,582 mi^2 (6,687.4 km^2) (USGS online). The USGS maintains two surface water gages in cooperation with SJRWMD at the US Hwy 17-92 bridge at the outlet of Lake Monroe. The first was established in 1941 to monitor St. Johns River stage (water level) and discharge with some selected water quality parameters. Published records for this gage include the following periods: 1941-1956, 1964-1968, 1987-1989 and 1995-present. The second gage was established in 1941 to monitor Lake Monroe elevation specifically for the period of record from 1941 to 2005, with selected water quality parameters monitored 1941 to 1982 (Figure 7, USGS online). These two gages demonstrate very close agreement in stage elevations, typically differing by no more than 0.1 ft (3 cm) from one another for any given date.

As a large and relatively flat river in a region with high annual precipitation, response time is correspondingly slow, that is, stage rises and falls very slowly, with elevated stage associated with a flood event persisting for months. Though during very rare storms stage can rise up to one ft per day, stage typically rises and falls at the Lake Monroe gages no faster than 0.5 ft (15.2 cm) per day, and more often around 0.2 ft (6.1 cm) per day, though stage can remain high for many weeks or months. For example, a hurricane-related high flow event in the fall of 2004 caused stage at both gages to rise above 5 ft on 6 September, peak at approximately 7.4 ft on 4 October, and drop back to 5 ft again on 23 November, a total of 11 weeks above 5 ft (USGS online). Five feet in stage is an arbitrary elevation for this discussion, though this contour line is a good landmark as it is easily seen on a USGS topographic contour map of the area. A stage of 5 ft elevation inundates all of DeBary Bayou except a small higher area adjoining I-4 south of the borrow pit including Mullet Lake, and possibly some of Gemini Springs. For points of reference, the 100-year flood elevation for Lake Monroe at DeBary Bayou is 9.3 ft, the mean high water (MHW) or average annual high water level at DeBary Bayou is 1.8 ft, and the I-4 bridges over DeBary Bayou were designed and rated to pass the 50-year flood (FDOT 1996). The long term average summer base flow stage (the lowest it gets) at Lake Monroe is approximately 0.1 ft, long term average spring/summer stage is approximately 1.1 ft from April - June, long term average fall/winter stage is approximately 3.5 ft from September – November (USGS online) (Figure 7).

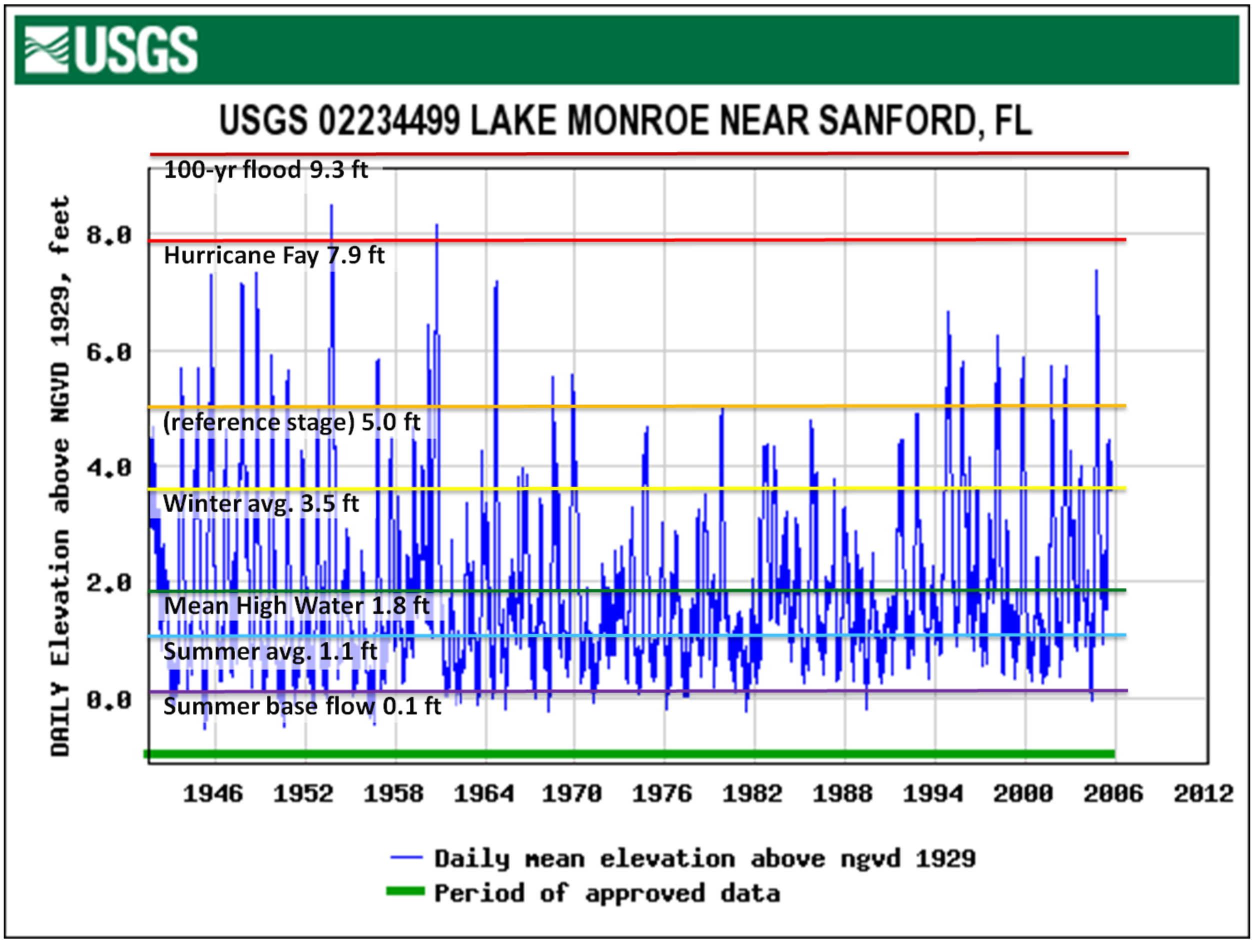

Figure 7. Water surface elevation (stage) for the period of record (1941 – 2005) for Lake Monroe gage near Sanford, FL, with seven stages of interest to DeBary Bayou. Summer base flow, summer average, winter average, reference stage and Hurricane Fay stages pertain to St. Johns River; Mean High Water and 100-yr flood stages were noted for DeBary Bayou explicitly. Reference stage is for discussion and mapping analysis purposes only, and does not have any specific hydrologic significance.

Flooding and Stormwater

As noted above, flooding in the St. Johns River translates to elevated stage within the DeBary Bayou, with regular inundation of the Bayou especially during the fall and winter months. According to the Federal Emergency Management Agency (FEMA) Flood Insurance Rate Maps (FIRM) maps, the 100 year flood elevation at Lake Monroe is approximately 9 ft (reported in FDOT documents at 9.3 ft). Though the data are intermittent in time and parameters collected, the flood record for the St. Johns River USGS stream gaging station shows that in 1953 the river reached about 17,500 cfs (490 cms), corresponding to a gage height of 8.59 ft, 0.7 ft from the 100 year event. While this magnitude event is highly unusual, the example event discussed above that exceeded 5.0 ft elevation happens much more frequently than the 100 year event. The flood record for the period between 1995 and 2010 shows St. Johns River stage at Lake Monroe exceeded 5.0 ft at some time during eight out of those 16 years. As discussed above, elevated stage associated with this type of event can persist for months, resulting in prolonged inundation of low lying areas, including DeBary Bayou, every other year on average.

However, not only is the St. Johns River and Lake Monroe influential in the flow characteristics of DeBary Bayou – the channel itself does maintain a positive flow much of the time, partially due to perennial flow from Gemini Springs, but also due to both topographic runoff and stormwater inputs. In addition to basic overland flow from direct rainfall and runoff and collected and channeled stormwater runoff through six primary outfalls, the City of DeBary pumps additional stormwater into DeBary Bayou during extreme flood events from six additional sub-basins in areas of the City to the north. During pumping events, the effective drainage area of DeBary Bayou is more than doubled, from 3.1 to 6.4 mi^2 (8 to 16.6 km^2) with the additional stormwater drainage basins. Some of this stormwater is partially treated through marshes or settling basins, but some amount of sediment and other contaminants (amounts unknown) enter the channel carried by the additional stormwater.

The locally high De Land Ridge relief, numerous landlocked lakes and the amount of development and impervious surfaces, and the relatively poorly draining soils of the surrounding landscapes in the St. Johns River valley all have implications for runoff and stormwater management for the City of DeBary. The City of DeBary has seen rapid development and expansion in recent decades, with concomitant increases in stormwater runoff in an area that historically would have had much precipitation directed into aquifer recharge. Attempts to direct more of the surface runoff through and under existing lakes and in other areas to increase the amount of groundwater recharge may have its own set of difficulties considering poorer quality alongside increased quantity. Stormwater can contain high concentrations of nutrients, pathogens, pesticides, heavy metals and other contaminants, as well as considerable amounts of fine sediments.

The City of DeBary stormwater system is managed primarily by the City of DeBary, has involved cooperative agreements with Volusia County, and includes a combination of City, County, FDOT and privately owned property and infrastructure. As DeBary has increased in population and size, with concurrent increases in impervious surfaces (estimated currently at 30%), stormwater runoff and infrastructure requirements have increased. Stormwater is currently managed by a combination of gravity and pumping in both above ground and below ground open channels, pipes and force mains and includes a series of ponds, lakes and storage basins. Gravity drainage systems that feed DeBary Bayou watershed directly account for the entire topographic drainage area of approximately 1985 ac (804 ha). There are an additional 2131 ac (863 ha) outside the natural DeBary Bayou watershed, divided into six basins that comprise the current City of DeBary Eastside Emergency Flood Management System (EEFMS).

During 1994 – 1996, Volusia County set up permitted temporary above-ground pipelines to pump landlocked lake floodwaters from within the City Limits to DeBary Bayou for a total of 18 months (4-127-23152-1 1997). The DeBary Emergency Flood Management System was initially designed and permitted by the SJRWMD in 1997 (with three modifications over the following several years, see 4-127-23152-2, 4-127-23152-3, 4-127-23152-4) to address persistent flooding problems in eight landlocked lakes within the City limits. Initial gravity watersheds to these lakes equaled 2544 acres (1030 ha). The main trunkline discharges to an existing stormwater channel on the west side of I-4 at Bill Keller Park, where it joins the natural topographic drainage to DeBary Bayou. The receiving stormwater channel runs along I-4, around the on/off ramps, crosses Dirksen Drive through a 36 in (91.4 cm) diameter culvert, and runs through a small stormwater pond in the Riverside Condominiums development prior to discharge to DeBary Bayou just upstream from the I-4 bridge.

Though no specific requirements for modifications were made to existing infrastructure, a site visit in 2009 to several locations at the stormwater ditch along I-4 shows evidence of erosion and headcutting, indicating this channel may be undersized or inadequately stabilized to accommodate stormwater flows (at least pumped flows) and may be producing additional sediment load to the stormwater system at this location. Filters are used to protect pumps from sediment, so stormwater entering the I-4 channel contains little sediment initially, though increased flow rates will inevitably pick up additional sediment within the natural ditch network.

Sediment stored in the stormwater pond at Riverside Condominiums appears to be from topographic stormwater drainage during regular runoff events as well as from the storm drainage ditch alongside I-4, picked up by increased discharge from pumped stormwater from the EEFMS. The stormwater pond was at its sediment storage capacity at the site visit in 2009 and is likely undersized for the effective watershed area during pumping events, though may be appropriately sized for the topographic drainage and treatment of Riverside Condominiums only.

The original 1.5 mi (2.4 km) underground stormwater pipe trunkline was designed to carry a maximum pumped discharge of 4.5 cfs (0.13 cms) and only to be used during emergency flood situations, with a number of special conditions to limit water quality and quantity impacts. Among these were set minimum and maximum elevations of lakes to be pumped, typically a maximum “pump-on” elevation and minimum “pump-off” elevation to preserve lake hydroperiods and protect infrastructure. Typically, this pumping schedule was based on initiating pumping when lake levels were within one foot of the lowest pavement grade or within three feet of the lowest finished floor elevation of a dwelling. Permit(s) specified that DeBary Bayou water surface elevation could be no more than 9 ft (2.74 m) National Geodetic Vertical Datum (NGVD) to prevent additional flooding by pumped stormwater discharge and that Lake Monroe could be no less than 6 ft (1.83 m) NGVD to preserve water quality. This provides the basis for the assumption that there are no adverse impacts from flow or water quality to surrounding waters, though there were objections on both counts on file prior to the permit being awarded.

This cross-basin transfer (pumping from areas not normally included in DeBary Bayou drainage basin) occurs during extreme events only, with original anticipated usage to be on the order of a few months every 10 to 20 years. Stormwater pumping is known to have occurred during three years out of the last 10: 2004, 2008 and 2009, for up to six months at a time. USGS gaging station data for Lake Monroe and St. Johns River show that the St. Johns River has exceeded 6 ft in recorded stage 11 times during the combined period of record from 1941 through 2011, or roughly one out of every 7 years (Figure 8 and Figure 9). This is an average number only, meaning there is a lot of variation in how high flows and high stage are distributed. For example, during the 25 year period from 1970 through

1994, stage never exceeded 5 ft, whereas during the 20 year period from 1941 through 1970, stage exceeded 6 ft six times, and even peaked at 8.14 ft in 1960. The frequency of the need for pumping stormwater is highly variable and may be greater than once every 10 years, though most likely won't be a common occurrence over the long term. Additionally, while pumping is constant over periods of up to several months, the maximum flow rate from permanent infrastructure of 4.5 cfs (0.13 cms) is still less than half the long term average flow of Gemini Springs that occurs year round, so is too low to raise flood levels at the mouth of DeBary Bayou.

August and September of 2004 were particularly storm-intense, with hurricanes Frances and Jeanne reaching Category 2 and 3 respectively over Florida, causing major damages. Hurricane season 2004 caused $11M of damages and flooded 170 homes and 30 roadways, requiring $1M to be spent pumping water to the DeBary Bayou and St. Johns River (Stormwater Overview and Funding Page, City of DeBary online). Total 2005 costs were near that, and funding has been an issue both to construct and maintain adequate stormwater infrastructure. Tropical Storm Fay in 2008 rivaled flooding and damages from Hurricane season 2004. These years also required pumping of excess stormwater, including deploying additional temporary pipes and portable pumps, bringing the total peak pumped rate to an estimated 12.6 cfs (0.35 cms) during the 2004 Hurricane season. The Westside Emergency Flood Management System (WEFMS) was proposed to address this increased need, also proposing a dedicated outfall facility (the Regional Stormwater Storage Facility, or RSSF) rather than discharge this system to existing ditches or streams. Kings Lake (draining 518 ac or 210 ha) was added to the Westside System, while subsequent permits also provided for outfall from Lake Susan (subsequently to include Lakes Anna Marie, Maud and Olivia) for ultimate outfall to the proposed RSSF (4-127-23152-5, 4-127-23152-6). Total maximum flow rate from the WEFMS to the RSSF is calculated in permit documents at 24.7 cfs (0.7 cms).

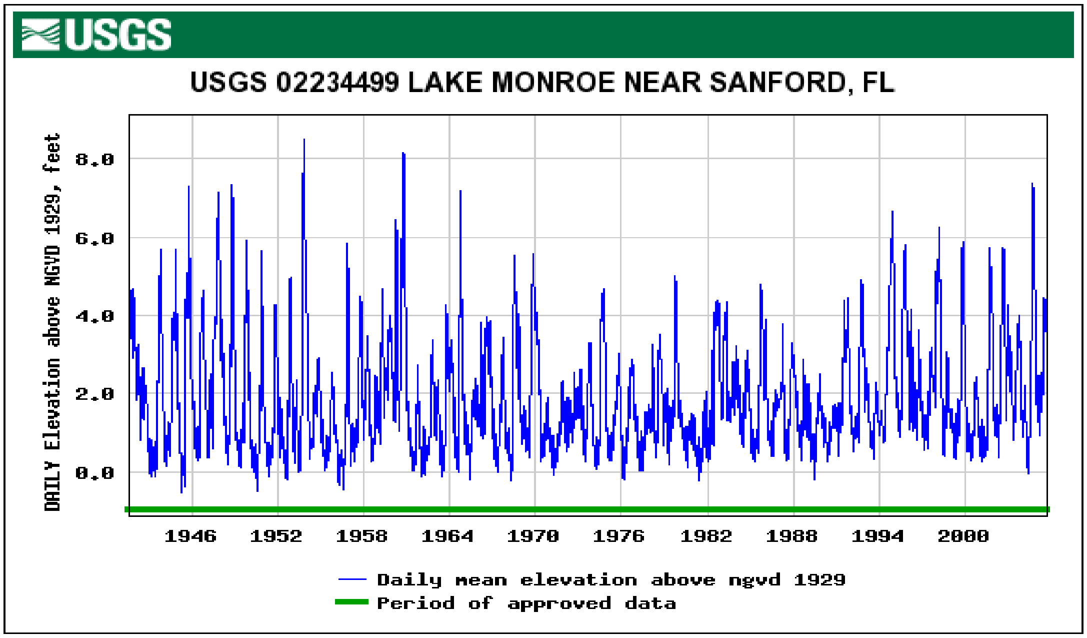

Figure 8. Gage Height for the period of record 1941 through 30 September 2005. Stage exceeded 6.0 ft 10 times during 9 storm events during the period shown.

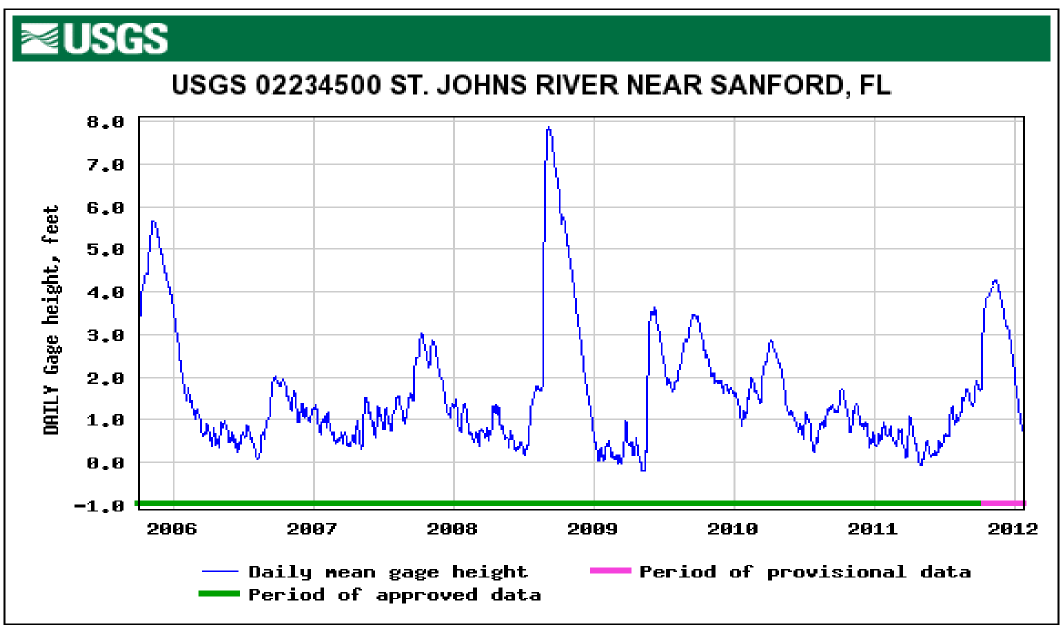

Figure 9. Gage Height for the period shown 1 October 2005 through 26 January 2012 (entire period of record for the gage from 1987). Stage exceeded 6.0 once during the period shown.

Per permit requirements, pumped stormwater must be regularly monitored for various water quality parameters to ensure receiving waters are not adversely impacted. At a minimum, this ensures that water quality in receiving waters is at least worse than stormwater being pumped in. Finally, the majority of pumped stormwater appears to enter DeBary

Bayou at the mouth at Lake Monroe, so may benefit from additional dilution from Lake Monroe. Stormwater from the remaining gravity system occurs much more regularly with every storm, and may not have as much opportunity for settling or filtering as does pumped stormwater – runoff gathers first in a pond or basin, and is filtered prior to pumping, in addition to being routed primarily through pipelines.

In contrast, gravity fed stormwater may not enter a settling basin and may run through a series of open ditches prior to discharge into receiving waters. Quality of such water is typically unknown, and may vary widely from storm to storm, depending on length of time from previous event and amount and timing of rainfall, all of which determine how much pollutants are available and picked up by runoff in addition to how much these pollutants are diluted. Field site visits to gravity stormwater outfalls along Dirksen Drive in 2009 indicated the potential for large amounts of sediment input to DeBary Bayou, particularly from the older stormwater areas without treatment, with outfalls relatively near the main channel or with infrequent maintenance activities. Specific flow rates, frequency, timing and concentrations of sediment, nutrients, pathogens, heavy metals or other pollutants of concern is unknown.

Fluvial Geomorphology

DeBary Bayou flows roughly west to east along the southern edge of the De Land Ridge, characterized by greater relief and higher average elevations than the broad, flat and lower elevation terraces and karst plains elsewhere in the region (Rutledge 1985). DeBary Bayou drainage basin total relief is approximately 85 ft (26 m), typical of the localized relatively high land area of the De Land Ridge. The De Land Ridge contains the county-wide maximum elevation of 120 ft (36.6 m), just to the north of the City of DeBary (Rutledge 1985). Topographically, all of DeBary Bayou south of its mainstem is within the St. Johns River valley, within the 100-yr Flood Zone as defined by FEMA as shown in the FIRM Maps. Average baseflow water surface slope from Mullet Lake and Gemini Springs outlet to the mouth at Lake Monroe at the I-4 bridge is very low, approximately 0.00013, or approximately 0.7 ft (0.2 m) of drop per mile. St. Johns River has even lower slope, approximately one inch per mile.

Dramatic weather patterns are often expressed in the landscape, particularly in the morphology of streams and floodplains and in sediment transport processes that help create stream morphology. Streams in the karstic plains and flat, poorly drained terraces in this region are characterized by low gradients, large channel storage capacity in swampy areas and undefined or poorly defined or shifting channels. Due to the dominance of subsurface flow, streams typically react slowly – this is the type of topography that characterizes DeBary Bayou. However, increased surface drainage from development-derived impervious surfaces and stormwater runoff can reduce this effect. Relatively fine-grained soils rich in organic matter, limestone bedrock and karst topography, and high rainfall amounts can result in a shifting stream profile, rapid cycles of sediment erosion, transport and deposition, and measurable aggradation and degradation in stream systems. Influence from Lake Monroe water levels can override response time and characteristics seen in DeBary Bayou channel, depending on timing and duration of high flows in St. Johns River. As noted above, long term average seasonal water level (stage) fluctuates from approximately 1.1 ft in spring/summer to 3.5 ft in fall/winter during hurricane and tropical storm season.

Analysis of the aerial imagery available for this area has shown that from 1940 to at least 1990 there appeared to be two distinct channels visible (a north channel and a south channel) in the eastern portion of DeBary Bayou upstream from the I-4 bridge location, at the approximate current location of River Oaks Estates (Table 5). The original images on file are at differing scale and quality, though a selection is included in the discussion here for reference, not to scale (Figure 10 through Figure 15). To what extent the switching of dominance between north and south channels is real or a result of vegetation, or to what extent the dominance could switch back to the south channel, is unknown. Interpreting channel locations through imagery can be complicated by seasonal differences in vegetation growth and flood stage, variations in both of which can either create or mask the appearance of a separate channel area. For example, very low stage may reveal the dominant channel if a secondary channel is filled with vegetation, or may allow the dominant channel to become filled with vegetation that requires lower stage. Alternatively, high stage can obscure multiple channels through widespread inundation, or can show multiple channels as open water where dominance can't be determined. From the present imagery series, the dominant channel appears to have shifted from the southern channel to the northern channel sometime between the 60's and the 80's. All available imagery on file following 1990 shows a single north channel regardless of stage or season. Overall, many of the smaller and more sinuous (longer and more meandering) channels appear less clear over time even as the main channel appears more clear, indicating a possible shift in the ecological community from open water to more wetland-dominated. A shifting channel pattern is not inconsistent with streams in this setting. DeBary Bayou appears to have settled into a single channel at the River Oaks Estate location for at least the past 20 years, though two channels existed in this vicinity for the previous 50 years of record. The likelihood whether this shift is natural or due to previous dredging activity that has occurred in this system is unknown, however, due to the timing of the apparent shift and known use and activity of this channel suggests it is more likely the shift was anthropogenic, at least initially.

The full extent to which the north channel may have been actively maintained by dredging is unknown, though was reportedly dragline dredged through the 60's for recreational boat traffic and significantly dredged in association with construction of the River Oaks development in the mid 1990's. Permits on record show one permitted dredging action within the Bayou issued 1985 and one permitted dredging action in Gemini Springs issued 1996 (Andrew Phillips, personal communication). There are no permits on record for FDOT that include channel dredging during this period, though minor fill within the right of way was permitted associated with I-4 onramp repair to repair bridge bulkheads, with a total of 0.022 ac (0.009 ha) permitted to be filled, and minor fill was placed in the borrow pond associated with the 6-laning of I-4 (Andrew Phillips, personal communication) (Table 5 and Figure 10 through Figure 15).

Table 5. Aerial Imagery on file for DeBary Bayou Watershed Assessment Study, with Associated North/South Channel Interpretation and Lake Monroe Stage in feet for Corresponding Imagery Date.

Image Year	Calendar date	Channels at River Oaks Estates	Estimated Lake Monroe Stage, ft
1940	unknown	Both channels clear	unknown
1957	3-11	South channel main, north channel unclear	0.84
1958	3-10	Both channels clear, south appears main	3.14
1964	10-23	Both channels clear, south appears main	4.55
1969	11-10	Both channels clear	5.50
1973	unknown	Both channels clear	unknown
1974	11-22	Both channels unclear (photo not good quality)	1.88
1983	3-12	Both channels apparent, image not clear	3.37
1984(CIR)	3-28	Both channels clear	2.07
1984	3-21	Both channels clear, north appears main	1.48
1990	unknown	Both channels clear	unknown
1993	2-13	North channel main, south channel unclear	2.52
1995(CIR)	4-4	North channel main, south channel unclear	1.79
2000(CIR)	1-26	North channel main, south channel unclear	1.26
2004	unknown	North channel main, south channel unclear	unknown
2006	unknown	North channel main, south channel unclear	unknown
2009(CIR)	10-27	North channel main, south channel unclear	4.9

Figure 10. Aerial photograph, 1940, DeBary Bayou and Lake Monroe. Image prior to I-4 construction. Image not to scale in this reproduction.

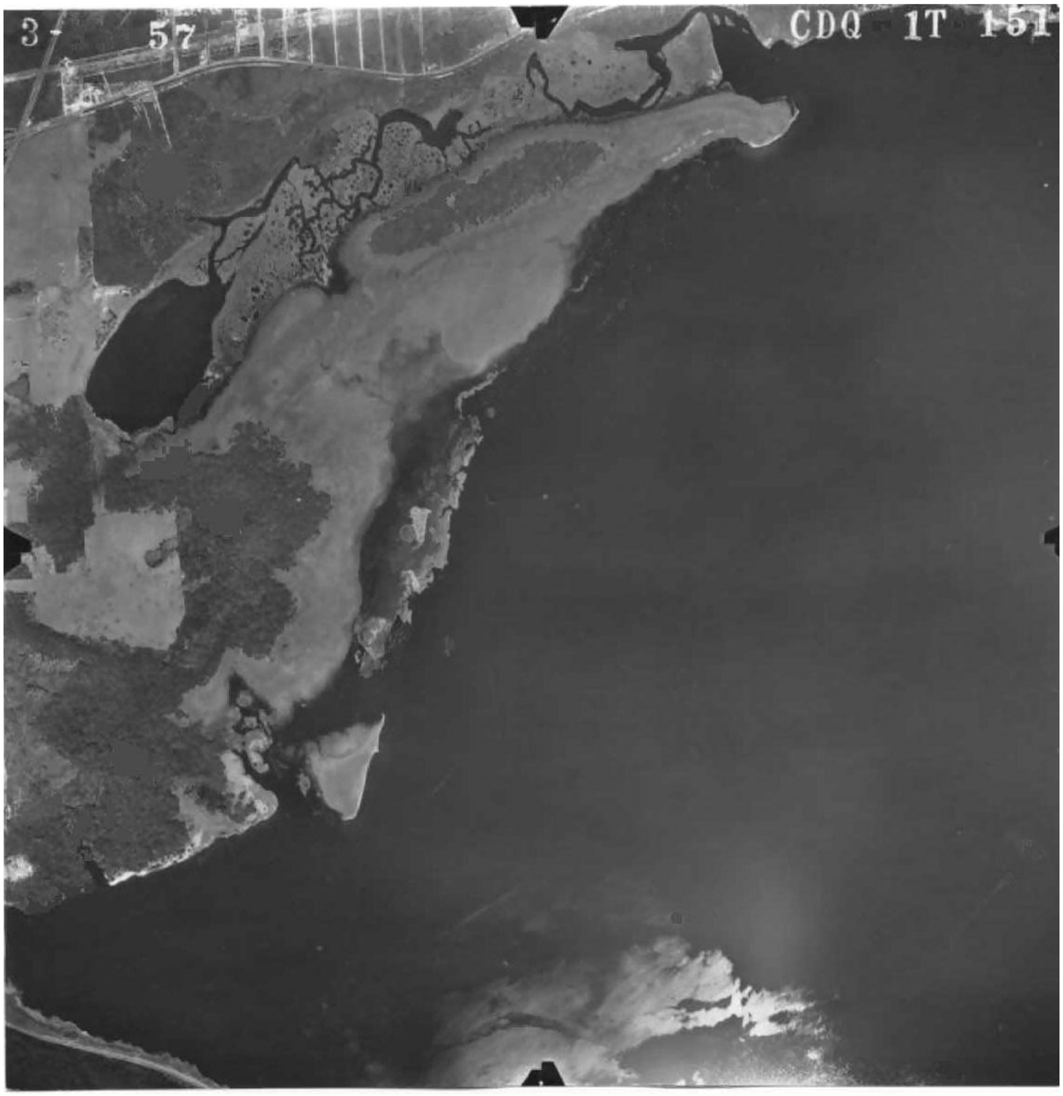

Figure 11. Aerial photograph,1957, DeBary Bayou and Lake Monroe, stage 0.84 ft. Image prior to I-4 construction. Image not to scale in this reproduction.

Figure 12. Aerial photograph, 1969, DeBary Bayou and Lake Monroe, stage 5.5 ft. Image following I-4 construction, prior to development of River Oaks Estates. Image not to scale in this reproduction.

Figure 13. Aerial photograph, 1984, DeBary Bayou and Lake Monroe, stage 2.07 ft. Image following I-4 construction, prior to development of River Oaks Estates, prior to six laning of I-4. Image not to scale in this reproduction.

Figure 14. Aerial photograph, 1995, DeBary Bayou and Lake Monroe, stage 1.79 ft. Image following I-4 construction, during development of River Oaks Estates, prior to six laning of I-4. Image not to scale in this reproduction.

Figure 15. Aerial photograph, 2006, DeBary Bayou and Lake Monroe. Image following I-4 construction, development of River Oaks Estates, and six laning of I-4. Image not to scale in this reproduction.

Inundation Dynamics Between Lake Monroe and DeBary Bayou

One concern for the potential for impact of limiting Lake Monroe access to DeBary Bayou to just under the I-4 bridge is that water is kept out of DeBary Bayou, resulting in drying of the wetland communities and prevention of flushing of sediments or nutrients. The topography of these two areas shows that the water surface elevation in DeBary Bayou is heavily controlled by Lake Monroe at all stages above zero ft, with Lake Monroe and DeBary Bayou water surfaces reaching some equilibrium through the I-4 bridge opening. The only limit to this connection is potential lag time depending on the rate of rise and fall of Lake Monroe during precipitation and flood events (and potentially of DeBary Bayou itself) and the capacity of the I-4 bridge to pass these increases. During extreme flood events, DeBary Bayou can experience a reverse flow condition as increases in Lake Monroe stage result in flow under the bridge into the Bayou as flow that would have passed into the Bayou by way of the shore of Lake Monroe proceeds instead through the bridge opening. As long as the elevation of Lake Monroe rises and falls at a slow enough rate for the bridge to accommodate the increases in flow rates, equilibration should happen quickly enough to keep the Bayou hydrated and not result in sediment movement and scour at the bridge.

The only way in which limiting flow to just under the I-4 bridge could result in drying of the DeBary Bayou is if the I-4 bridge could not pass increases in flow during rising stage and if the water levels did not equilibrate. The flood records from USGS gages show that the typical rate of rise and fall during a flood event is on the order of 0.2 to 0.5 ft (0.06 to 0.15 m) per day. The maximum rate of 1.77 ft (0.52 m) of stage increase measured during Tropical Storm Fay occurred between 21 and 22 August 2008 measured at the St Johns River Near Sanford, FL, gage. Recorded stage increased from 3.07 ft on 21 August to 4.84 ft on 22 August, corresponding to flow rates of 3,460 to 5,100 cfs (96.9 to 142.8 cms) at the gage, an increase of 2,594 cfs (72.6 cms). The bridge would therefore need to accommodate not only the starting flow but the increase in flow to ensure equilibration of stage within the DeBary Bayou. As long as the bridge can accommodate the changes in rates, stage between Lake Monroe and DeBary bayou will maintain equilibrium throughout a flood event, and through the longer term to ensure sufficient hydration of wetland communities.

The bridge under I-4 is designed for the 50-year flood, though the FDOT-reported maximum event of record at 4.048 m (13.3 ft) in 1880 is contained under the I-4 bridge, which prior to six-laning had a vertical navigation clearance of 5.908 m (19.38 ft) above high water 1.067 m (3.5 ft) which leaves a total of 6.975 m (22.88 ft) to the estimated low flow condition (FDOT 1996). At 15.85 m (52 ft) bottom width under the main bulkhead walls, the total area under the bridge above the low flow elevation at zero ft is 110.55 m^2 (1189.76 ft^2), not including the concrete overbank slope areas. The velocity of the 100-year event for DeBary Bayou is approximately 1.036 mps (3.4 fps) which considering the relatively low slopes in this system is a reasonable velocity even for a flood event through this bridge. Approximately 114.52 cms (4,045 cfs) would fill the main bridge opening at this velocity. Including the overbank areas would roughly double the flow capacity at that velocity. The capacity of I-4 is therefore sufficient to accommodate rates of stage change at extreme events between Lake Monroe and DeBary Bayou, ensuring hydrologic balance between these systems. Balance of sediment flux is addressed in Section 6.2, Sediment Quantity and Quality.

The following topographic analysis is a simplified method for showing areas of DeBary Bayou that are inundated at various stages of Lake Monroe, assuming equilibration of water surface elevation between these two water bodies as determined above, that is, Lake Monroe water surface elevation will match the water surface within DeBary Bayou. A 2009 aerial photograph of DeBary Bayou is shown with differing Lake Monroe water surface elevations filled in to show the area that would be inundated. To simplify the analysis, these maps show water level (stage) at 1.0, 2.0, 3.0, 4.0, 5.0, 6.0, and 7.0 ft (Figure 16 through Figure 22 below). As described above, the long term summer base flow stage at Lake Monroe is approximately 0.1 ft, long term average spring/summer stage is approximately 1.1 ft, long term average fall/winter stage is approximately 3.5 ft. Tropical Storm Fay resulted in a peak stage of approximately 7.9 ft, and the 100 year flood stage on DeBary Bayou is 9.3 ft.

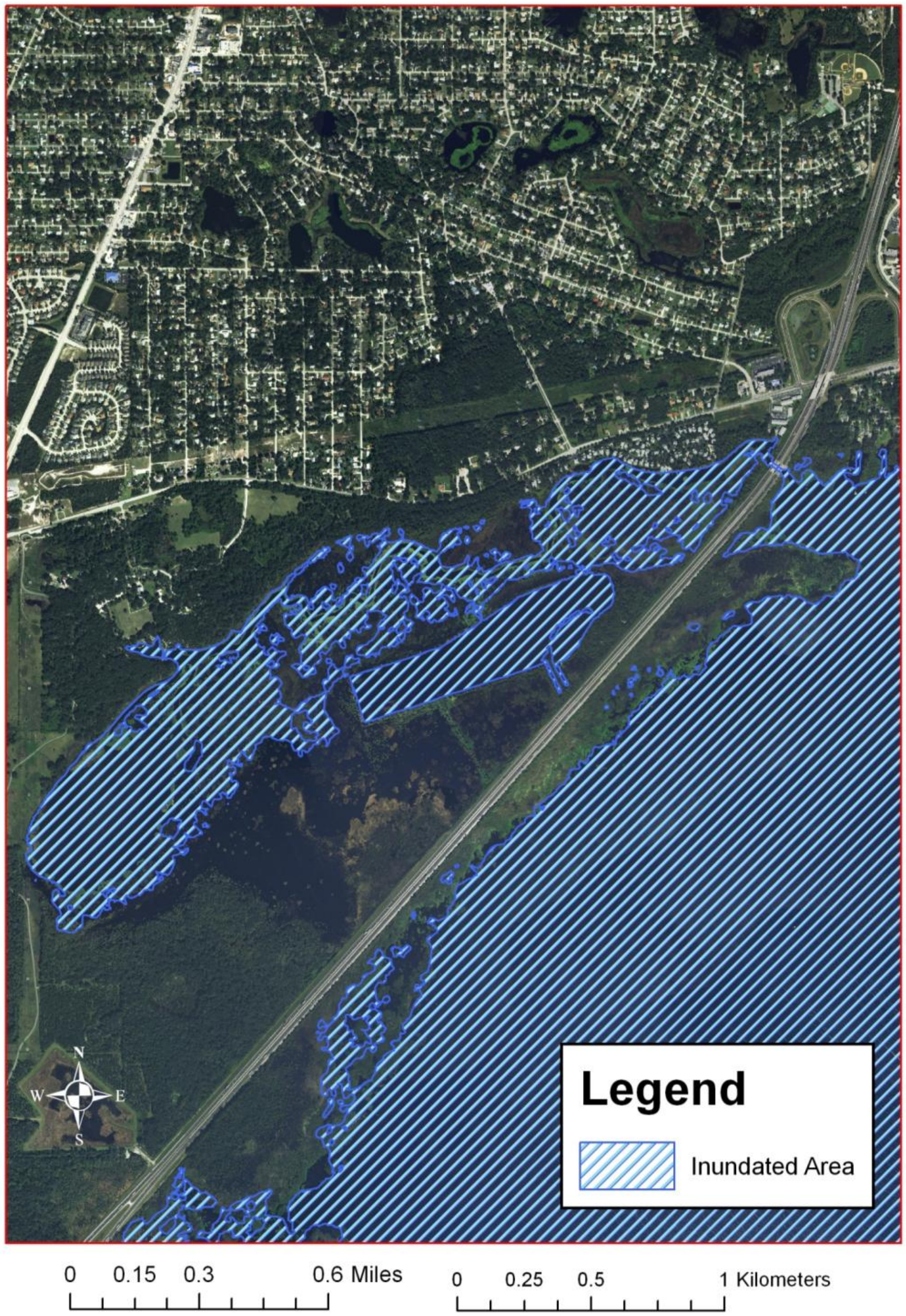

Figure 16. Land area inundated when water surface elevation is 1.0 ft, Lake Monroe and DeBary Bayou.

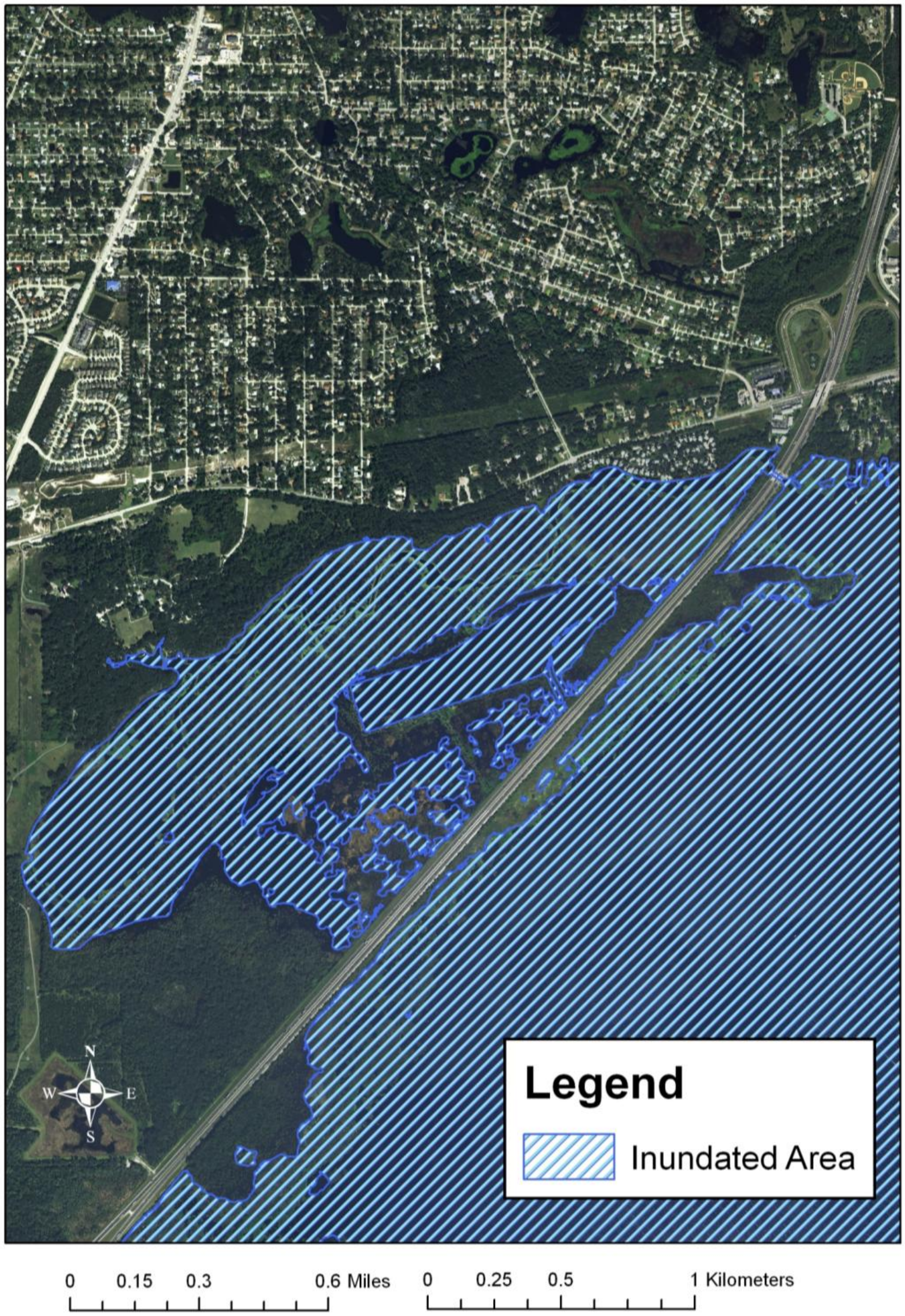

Figure 17. Land area inundated when water surface elevation is 2.0 ft, Lake Monroe and DeBary Bayou.

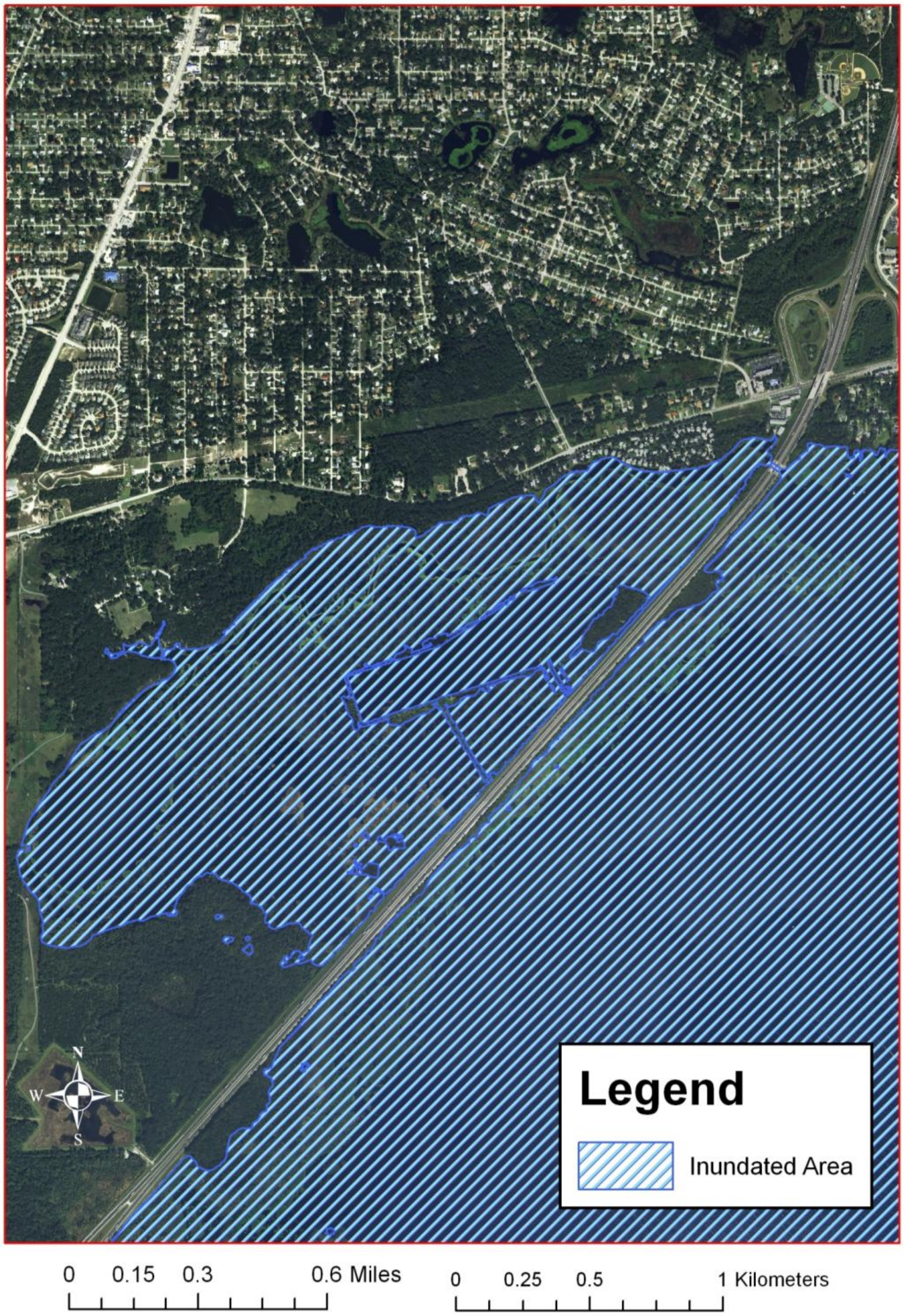

Figure 18. Land area inundated when water surface elevation is 3.0 ft, Lake Monroe and DeBary Bayou.

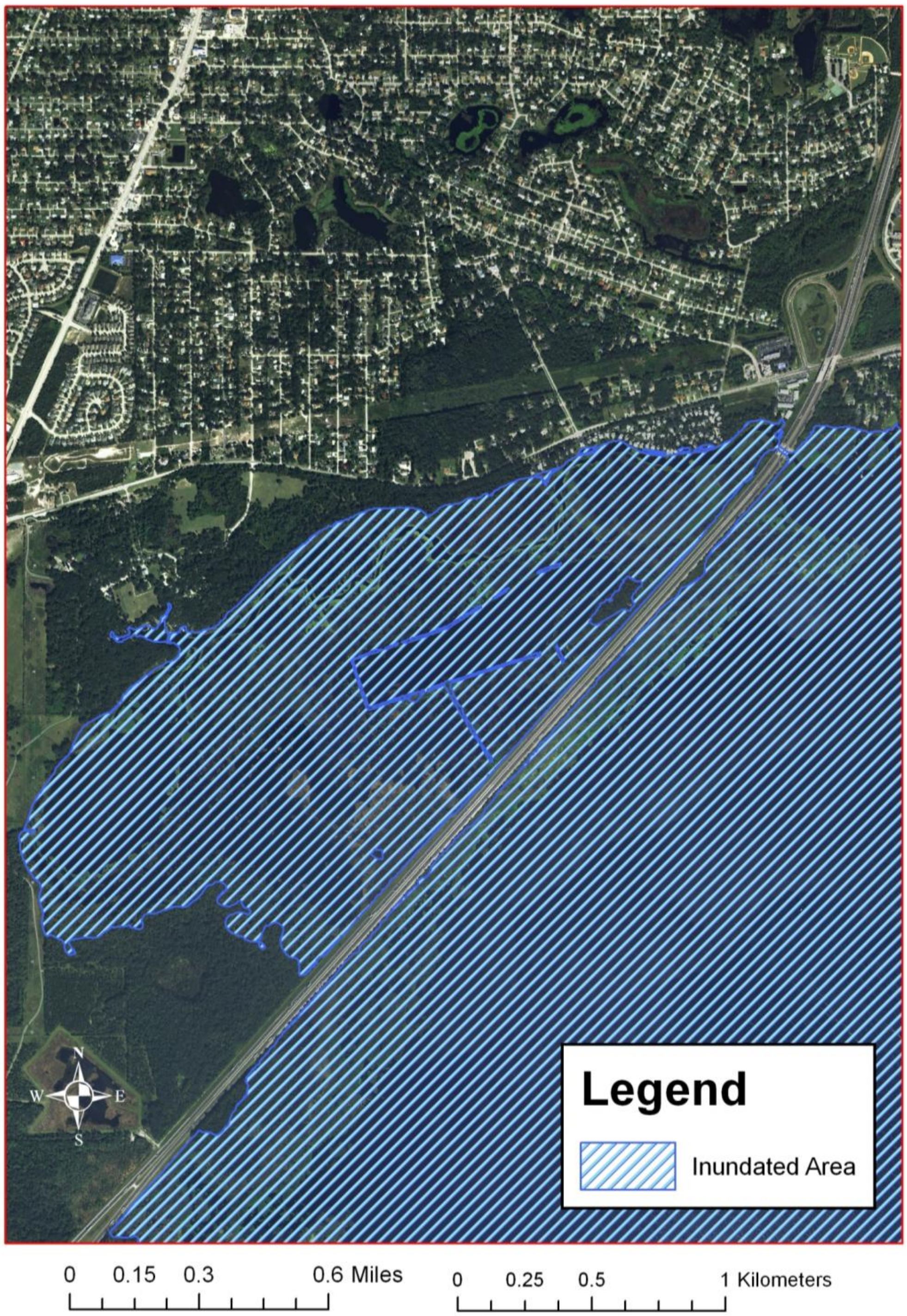

Figure 19. Land area inundated when water surface elevation is 4.0 ft, Lake Monroe and DeBary Bayou.

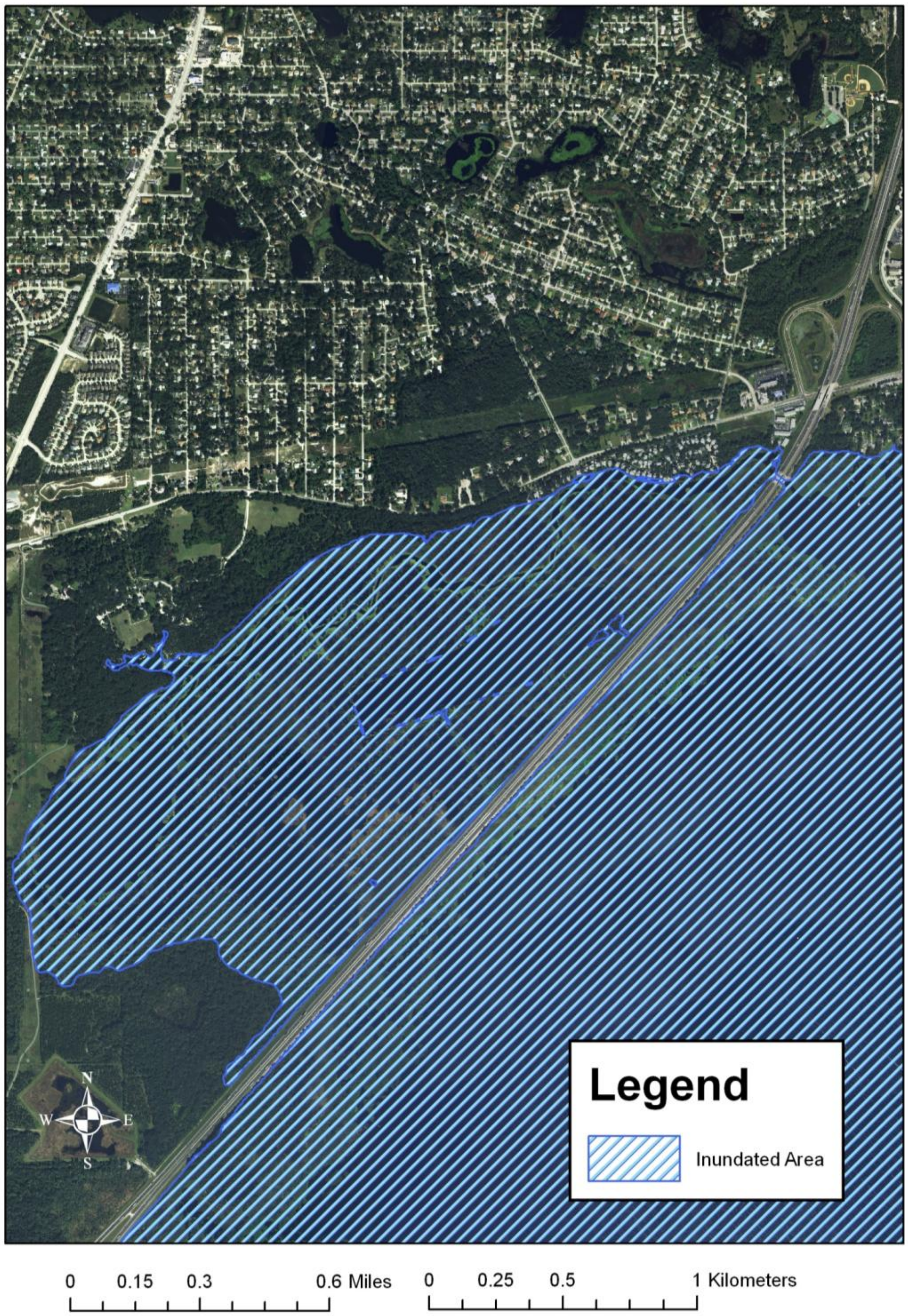

Figure 20. Land area inundated when water surface elevation is 5.0 ft, Lake Monroe and DeBary Bayou.

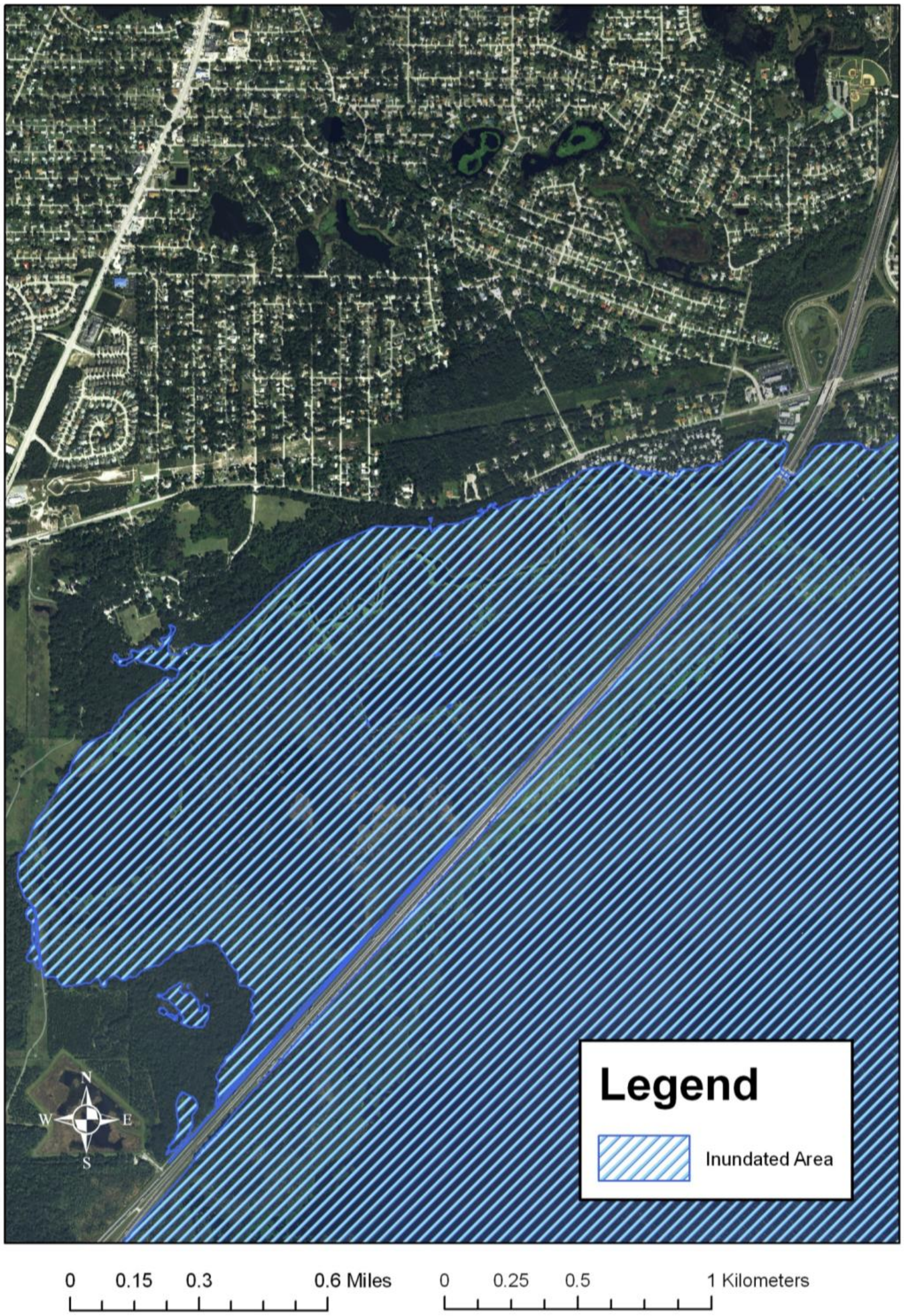

Figure 21. Land area inundated when water surface elevation is 6.0 ft, Lake Monroe and DeBary Bayou.

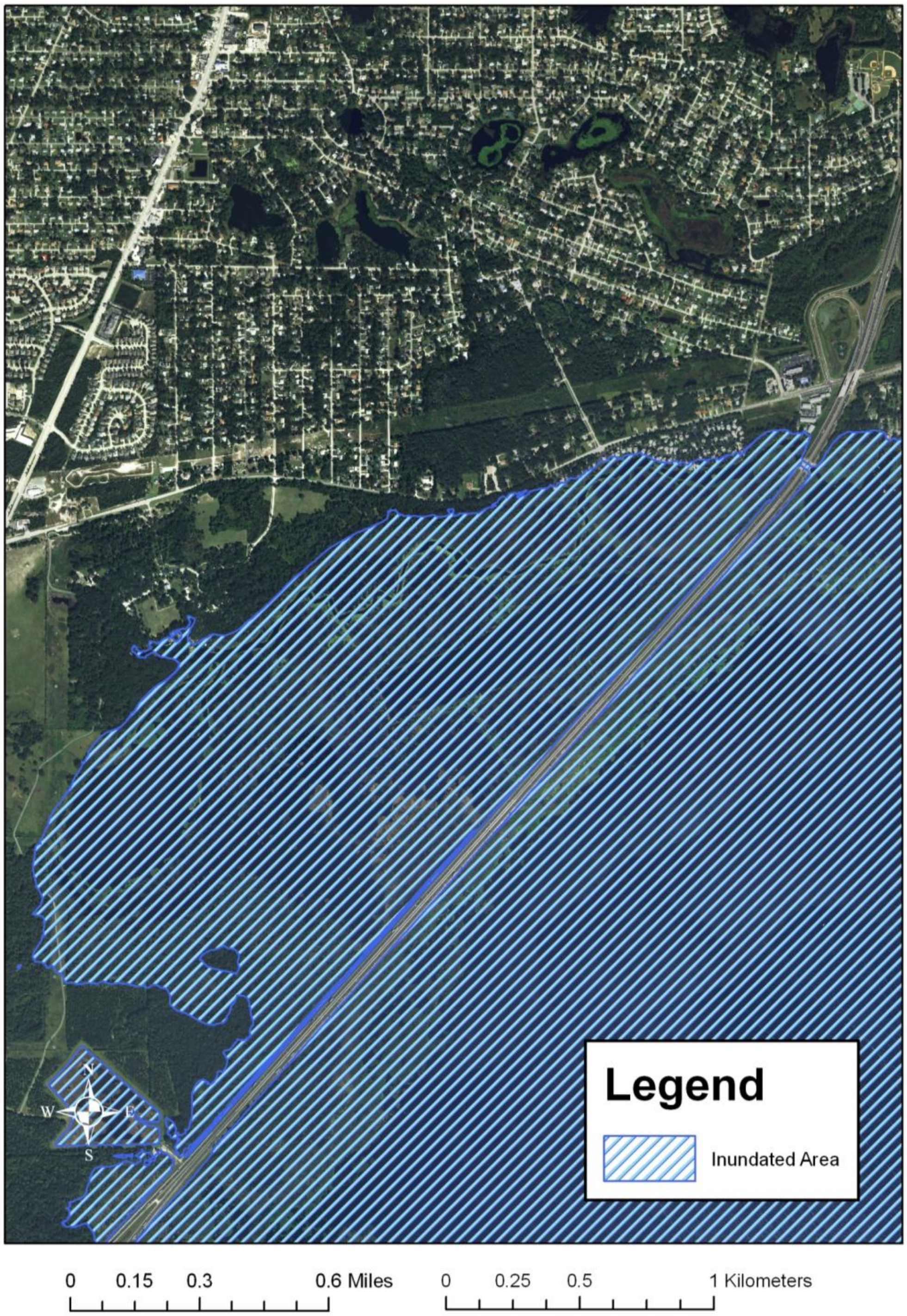

Figure 22. Land area inundated when water surface elevation is 7.0 ft, Lake Monroe and DeBary Bayou.

Sediment Quantity and Quality

Typical of streams in this valley setting, DeBary Bayou is very flat, highly meandering with a somewhat shifting channel and with much fine sediment and organic material available in both bed and banks. The combination of frequent backwater effects from Lake Monroe, densely vegetated marsh habitats in the floodplain and generally low velocity in the channel makes this system susceptible to widespread deposition of fine sediments and formation of deep layers of unconsolidated organic material. This material is highly susceptible to resuspension, and doubtless becomes entrained and deposited many times throughout DeBary Bayou, particularly during periods of quiescent or reverse flow conditions during high stage in St. Johns River and Lake Monroe. These sediments have high nutrient load (high nitrogen, phosphorus and high oxygen demand) and encourage growth of phytoplankton within the water column leading to an increased rate of eutrophication (SJRWMD 2002a). One result is increasing amounts of aquatic vegetation, most often overgrowth of nuisance and invasive or exotic vegetation. Spray and lay treatment and seasonal natural death of this material adds additional organic matter. The water in Mullet Lake and DeBary Bayou channel is frequently turbid, limiting light penetration to bottom sediments which is critical for survival of some important native species of submerged aquatic vegetation on which various animal populations depend. The depth of unconsolidated “muck” with limited light penetration to the bottom of Mullet Lake, for example, limits the capability of this water body to support a healthy ecological community.

In recent decades anecdotal reports suggest accelerated sediment accumulation throughout DeBary Bayou channel, particularly in the lower reaches. Study hypotheses relating to sedimentation rates, causes and impacts are analyzed in context of data sources and reports cited above. In particular, available sediment sampling studies were analyzed that include DeBary Bayou (Brenner 2010), Mullet Lake (SJRWMD 2002a), Lake Monroe (SJRWMD 2004) and DeBary Bayou under the I-4 bridge (FLDOT 1996).

The sediment core study for DeBary Bayou was conducted as part of this watershed assessment study (Brenner 2010). Three locations were chosen by FDOT, SJRWMD and ERDC from which sediment cores were sampled (Figure 23). Amounts of unsupported ^{210}Pb were analyzed to provide age/depth and a chronology of sediment layers. The study suggests long term sedimentation rates are consistent with many mid-lake and wetland sites in FL, though with some important local differences. Additional details and discussion of the findings of this report in comparison to other sediment studies appears in subsequent sections.

All but the FDOT study document the presence of an unconsolidated material layer, variously referred to as muck, floc, soft sediment or gyttja, a fine-grained nutrient-rich organic mud deposited in lakes and ponds (Olila et al. 1995, Olila and Reddy 1997). Various studies in Florida lakes have characterized this material as highly organic and loosely consolidated, consisting of recent algal deposits, allochthonous particulate matter and sometimes fragments of shell material that have settled out of the water column and/or have resulted from resuspension of underlying sediments (Ollila and Reddy 1997, Schelske and Kenney 2001, Hoyer et al. 2005, Schelske 2006). This material is not typically composed of silt or clay sediments, which may remain in suspension in lake or river waters indefinitely, but is primarily composed of decaying organic matter and water and is a common feature in shallow eutrophic and hypereutrophic lakes in this setting (Olila et al. 1995).

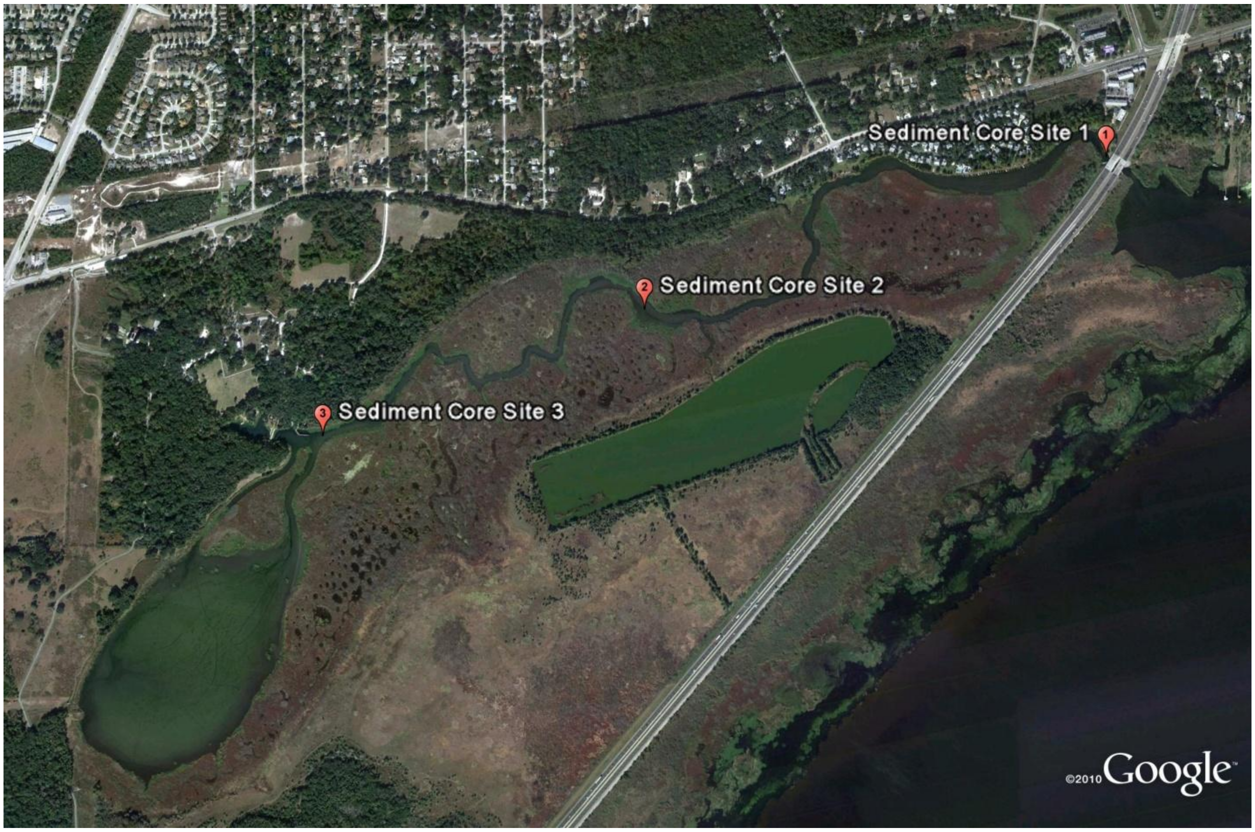

Figure 23. Sediment core sampling locations for Recent Sediment Accumulations in Padgett Creek, Middle St. Johns River Basin, 2010. Imagery from Google Earth, 12/6/2010, Lake Monroe stage shown = 0.81 ft.

Transects surveyed within the DeBary Bayou by SJRWMD in 2009 documented depths of fine sediments overlying consolidated sandy sediments (Figure 24). These studies provide information on the relative depths of very fine organic “floc” material, soft or unconsolidated sediments below this material and the top depth of consolidated sediments, in addition to selected sediment characteristics, age and accumulation rates in some studies.

Discussion below centers on whether DeBary Bayou sedimentation rates have increased, how sedimentation rates compare with local and regional rates, what are potential or likely sources of fine sediment and organic material, and how this material cycles through this system. Treatment and restoration strategies are covered in Section 8.

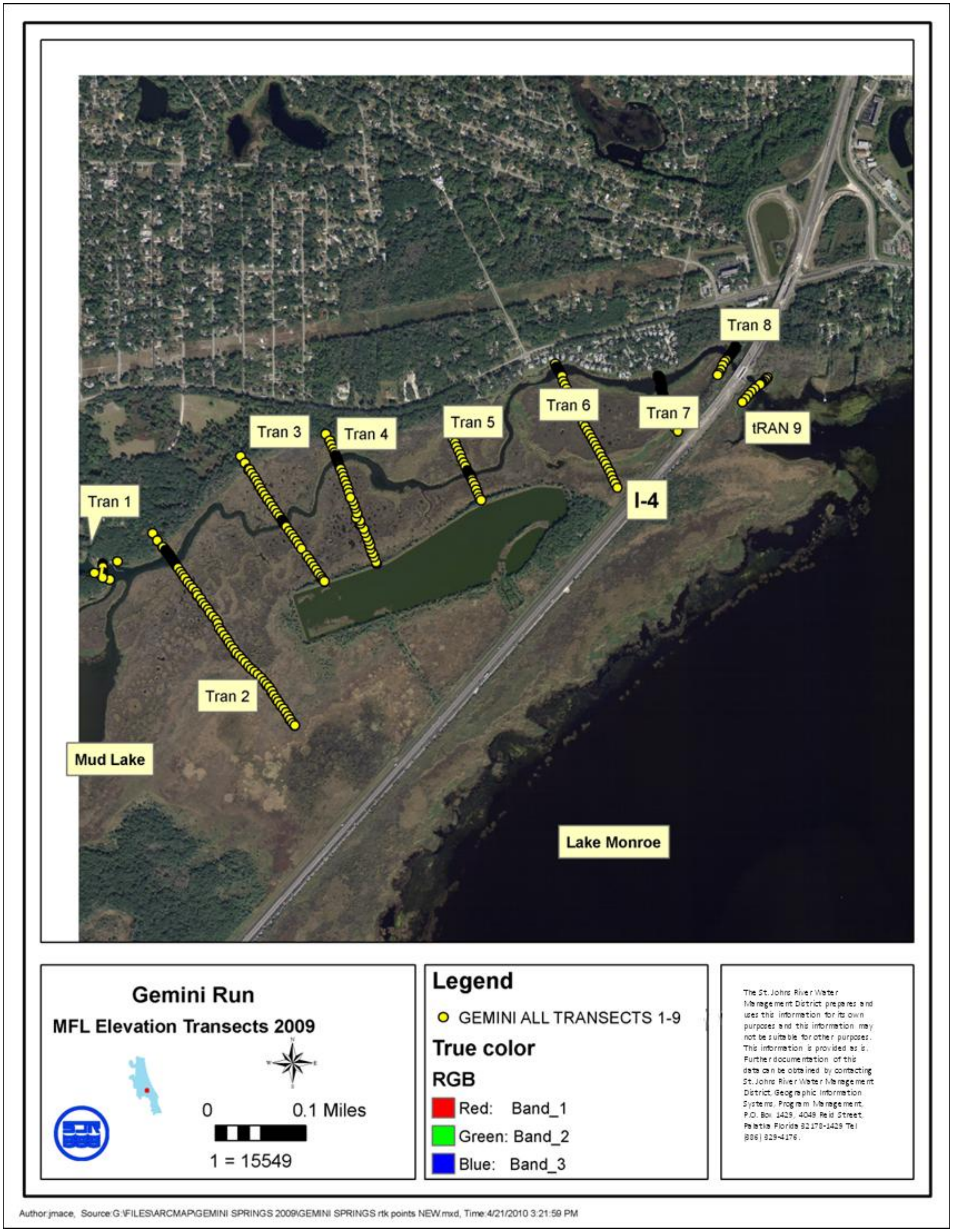

Figure 24. Transect locations surveyed within the DeBary Bayou by SJRWMD in 2009.

Have fine sediment and organic matter deposition or accumulation rates increased in DeBary Bayou over historical rates?

Sediment core evidence collected within the DeBary Bayou Mainstem suggests long-term sediment accumulation rates of roughly 0.3 cm/yr (0.01 ft/yr) over the last 100 years (approximately 1.0 ft or 30.5 cm total), consistent with measurements in many regional Florida lake and wetland sites (Brenner et al. 2010). Recent deposits, however, show 0.4 cm/yr (0.013 ft/yr or 0.16 in/yr). This may either represent an actual increase in rate or may be due to a lack of compaction of the top sediment layers, also consistent with similar waterbodies (Brenner et al. 2010).

Are fine sediment or organic material accumulation rates in DeBary Bayou consistent with regional rates, or rates within St. Johns River or Lake Monroe?

Lake Monroe sediment cores were collected to investigate nutrient dynamics associated with lake sediments to facilitate water quality restoration to address increasing organic matter accumulation caused by anthropogenically influenced eutrophication, and to determine sedimentation rates in the St. Johns River as evidenced by Lake Monroe sediment characteristics using radiometric dating (Anderson et al. 2004). Recent work in the Upper St. Johns River Basin had suggested up to threefold increase in sedimentation rates between the 1880's and 1990's.

Twenty cores from 15 to 72 cm in depth were collected from Lake Monroe and analyzed (six of these were dated), as well as additional sediment and floc thickness measured at 60 sites showing a mean floc thickness of 15 cm or 0.5 ft (ranging from 0 to 20 or 0.7 ft) and total mean sediment thickness of 132 cm or 4.3 ft (ranging from 23 to 250 cm or 0.8 to 8.2 ft, Anderson et al. 2004). Sediment in Lake Monroe cores consists of gyttja, peat and sands/clays/grey mud (SCM), with peat and gyttja having the greatest organic content, and generally organic gyttja overlying peat and or SCM (Anderson et al. 2004).

Sediment accumulation rates were shown to be generally low; the last 100 years were represented by approximately the upper 15 cm or 0.5 ft of organic rich gyttja with intermittent mollusk shells, though the past 100 years accumulation rate is faster than for previous time periods. Basically, though sedimentation rates have increased, this is most likely due to increases in nutrient loading and the rates remain fairly low - roughly half the rate of accumulation as for DeBary Bayou. DeBary Bayou appears to be experiencing a modest though detectable increased sediment accumulation rate.

The fine, organic-rich sediments and high nutrient and planktonic productivity has implications for the hydrologically connected DeBary Bayou and Mullet Lake, which appear to show similar responses and trends. Because the surface sediments consist of loose gyttja rather than peat, resuspension is easier, and may result in entrainment and adding additional nutrients to the water column increasing planktonic productivity for both Lake Monroe and DeBary Bayou.

Sediment cores collected for Mullet Lake provided information on nutrient loading and water quality to inform restoration activities to address much thicker layers of unconsolidated organic sediments largely attributable to prior agricultural practices (livestock, fertilizer use), invasive vegetation treatment and development in the basin. Highly organic unconsolidated and flocculated sediments ranged from 0.4 to 1.5 m (1.3 to 4.9 ft) depth at 31 sampling locations within Mullet Lake, with five intact cores containing 0.4 to 0.5 m (1.3 to 1.6 ft) of unconsolidated sediments (SJRWMD 2002a). This suggests rates of accumulation in Mullet Lake may have been much faster than for Lake Monroe or DeBary Bayou. Sediment loading to the Bayou may be increased for some period of time as a result – these are legacy sediments having been deposited in Mullet Lake at a much faster rate than in the Bayou or Lake Monroe, suggesting ranching activity, spring water quality and stormwater inputs may have been influential. Ranching has stopped and spring water quality is declining very slowly, though development pressure in the City of DeBary and increasing stormwater inputs will continue.

How do historical bed conditions in DeBary Bayou – sediment quantity, quality and channel depth – compare with current conditions?

Bathymetry (distance in feet from water surface to channel bed) of DeBary Bayou was measured in 2007 by SJRWMD including Mullet Lake, Gemini Springs below the dam, DeBary Bayou through the I-4 bridge, and the embayment of Lake Monroe at the outlet of DeBary Bayou (Figure 25). DeBary Bayou is a shallow system overall consistent with the setting, though currently its most shallow locations are in the vicinity of River Oaks Estates and several smaller intermittent sections up the main channel into Mullet Lake. Deepest sections include shore sections just downstream of the dam at Gemini Springs and sections upstream and through the I-4 bridge. Transects completed in 2009 (above) show a similar pattern. Transects 1-8 through DeBary Bayou itself show average depths of fine or soft sediments from approximately 0.7 ft to 2.3 ft (0.2 to 0.7 m), with no discernible pattern from Gemini Springs to Transect 8 just upstream from the I-4 bridge. No soft sediment was measured in Transect 9, which was also the deepest section at the time of the survey, at the I-4 bridge. It is not entirely clear whether the soft sediment measured in DeBary Bayou is the same type of sediment represented by the unconsolidated floc material in Lake Monroe, though total thickness of this material measures up to 0.7 ft (0.2 m) in Lake Monroe, averaging 0.5 ft (0.15 m), considerably less than that in DeBary Bayou.

Figure 25. DeBary Bayou bathymetry from Mullet Lake to the Southwest through I-4 crossing into Lake Monroe to the east.

The 1996 FDOT Scour Evaluation Report for the vicinity of I-4 bridges over DeBary Bayou showed no change in cross section at the bridge location from prior to completion in 1957 (estimated final construction completed 1959) to 1993. Sediment cores collected for this report in conjunction with widening activities for I-4 were strictly for construction purposes – no constituent analysis was performed. However, core layers were characterized in some detail and provide important information about the types of sediment underlying DeBary Bayou in that area (FDOT 1996). The three sediment cores collected as part of this scour report in DeBary Bayou mainstem in the vicinity of the I-4 bridge were driven to 27.43, 27.86 and 32.50 m (90, 91.4 and 106.6 ft) below 0.0 NGVD 1929, respectively (FDOT 1996). These cores showed fine sand depth to approximately to 10 to 13 m (32.8 to 42.7 ft) before reaching the first shell fragments, with most of the topmost layers of material noted as brown or dark brown fine sand, silty sand or containing a trace of clay or sometimes muck (FDOT 1966). The first weathered limestone was reached at approximately 20 to 22 m (65.6 to 72.2 ft). All layers with any shell material were described as some kind of brown sand, usually with silt, with “shell fragments” or more commonly “some shell fragments” listed (FDOT 1996).

St. Johns River and Lake Monroe access to DeBary Bayou is now limited to a single entry point at the I-4 bridge (SJRWMD 2002a). Aerial imagery from 1940 shows that prior to I-4 construction, the opening at the mouth of DeBary Bayou appears much wider than the current bridge opening of approximately 52 ft (15.8 m), though the actual width is not clearly discernible from the image. Reports of the wreck of the *Fannie Dugan* indicate steamboat access was once possible into DeBary Bayou, which has been thought to indicate the channel was considerably deeper and wider than the present-day DeBary Bayou. Research into steamboat access, however, revealed the *Fannie Dugan* and similar sidewheeler steamboats required less than three feet of draft to operate (32 in (81.3 cm) for the *Fannie Dugan*), and were typically less than 30 ft (9.1 m) wide (Cowart 2005). This suggests she did not require a much deeper channel than the current DeBary Bayou, especially if Lake Monroe is elevated at higher stages in St. Johns River. While the sediment core evidence collected and analyzed by Brenner et al. (2010) does show an increase in sedimentation rate in the last 50 years, accumulation of a total of 25 cm or approximately 0.8 ft (9.8 in) in the last 50 years does not explain anecdotal reports of several feet of depth lost over the last 50 years. This remains an unresolved discrepancy, as none of the data or documented evidence found in the course of this study suggests that DeBary Bayou was several feet deep during low flow conditions during the last 100 years, nor that the channel has filled in appreciably during the last 50 years.

What are the likely sources of fine sediment, nutrients and organic matter in the DeBary Bayou system?

Sediment quantity and quality has been an area of concern with specific regard to Mullet Lake, where accumulations of fine sediment and organic materials have coincided with shifts in vegetation and waterfowl communities (SJRWMD 2002a). Sediment and organic matter accumulations in Mullet Lake are greater than in DeBary Bayou or Lake Monroe, potentially due to ranching operations or increases in stormwater runoff within the drainage to Mullet Lake. As noted above, highly organic unconsolidated and flocculated sediments ranged from 0.4 to 1.5 m (1.3 to 4.9 ft) depth at 31 sampling locations within Mullet Lake, with five intact cores containing 0.4 to 0.5 m (1.3 to 1.6 ft) of unconsolidated sediments (SJRWMD 2002a). Elevated nitrogen levels and frequent resuspension of these materials adds significant nutrients to the water column that also support phytoplankton (algae) productivity – this is known to compete with rooted macrophytic vegetation that can otherwise stabilize bed sediments and decrease nutrient loading. Sediment data indicate a large, potentially mobile nutrient reservoir in Mullet Lake, with sediment resuspension and recycling contributing to the advanced trophic state of Mullet Lake and likely of DeBary Bayou as well. Sediment removal strategies appear likely to increase oxygen demand and soluble nutrient release, causing further declines in water quality, though these may be temporary (SJRWMD 2003).

Based on the SJRWMD sediment studies described above, the amount and condition of sediments in Mullet Lake may be influencing the quantity and quality of sediment in DeBary Bayou, though the relative contribution compared to other sources is unknown. Sediment and water quality in Mullet Lake may be linked to the type and quality of sediments that form and accumulate in DeBary Bayou not only because it contributes sediments directly, but also because it affects conditions under which sediment becomes resuspended or consolidated due to the influence of which type of vegetation is encountered (planktonic vs. macrophytic).

The generally eutrophic condition of Mullet Lake will likely continue. Studies initiated by SJRWMD of sediment accumulation and condition suggest this condition is self-perpetuating, and may be resulting in positive feedback loops with regards to vegetation and fish species impacts.

What are the mechanisms for sediment supply, sediment removal and general sediment cycling in this system?

Due to the relatively low relief of DeBary Bayou, this setting may be particularly sensitive to fluxes in sediment loading. The combination of extreme weather events, increases in invasive vegetation, declining region-wide water quality, removal of coarser sand and shell supply from Gemini Springs or other bed or bank sources and increased stormwater inputs carrying large amounts of fine sediments and nutrients, may have resulted in additional amounts of organic materials and perhaps additional very fine mineral sediment accumulation within DeBary Bayou.

No evidence suggests that any changes in sediment accumulation rates or channel morphology coincided in time with the damming of Gemini Springs, though the 2007 bathymetry shows the deepest portion of DeBary Bayou mainstem immediately downstream of the dam. The reason for this is unclear, though if there is finer sediment and organic material that had accumulated in this area that is subsequently resuspended here, this may be appearing downstream as additional surface deposits.

While narrowing the DeBary Bayou channel opening at the I-4 bridge has restricted water inflow to this area from what was a much broader surface along the shore of Lake Monroe, the probable impact of this should be to reduce sedimentation rates within the main channel and within the DeBary Bayou floodplain. Concentration of flow into a single channel and opening increases flow velocities which would tend to more easily suspend finer gyttja sediments from within the channel, and potentially move coarser sediments (silts and sands) through the system. However, flow of sediments out of the system would occur at times when there is higher flow in DeBary Bayou than from Lake Monroe, which likely occurs at the beginning of flood events before Lake Monroe elevation rises. The reverse is true once Lake Monroe exceeds DeBary Bayou stage and results in reverse flow conditions, though flow velocities would remain higher in the main channel and less so in the floodplain. As high stage persists for weeks to months in Lake Monroe, any additional settling of sediments would occur within DeBary Bayou and its floodplain regardless of the size of opening or area of access by Lake Monroe – stage between these two water bodies equilibrates relatively quickly, so any suspended sediment will drop out or remain suspended regardless of the area of Lake Monroe access to DeBary Bayou. Flow velocity across floodplain areas, considering the slow rate of rise and fall of Lake Monroe and very low relief, strongly suggest little to no sediment transport would have occurred over these floodplain areas even with direct access to Lake Monroe, but would be naturally concentrated within the channel of DeBary Bayou. What is not clear is the rate at which sediment contained in Lake Monroe water would drop out within DeBary Bayou floodplain.

Water Quality

Since the 1970s, scientists have observed degrading water quality in many Florida springs, the greatest threat demonstrated by dramatic and steady increases in nutrient concentrations in the form of nitrate-nitrogen (Harrington et al. 2009, Scott et al. 2004). Historically, nitrate levels in FL springs was quite low, less than 0.2 mg/L (0.2 ppm or 0.000027 oz/gal), low enough in proportion to phosphorous to be growth limiting for algae (Harrington et al. 2009). Other studies have shown natural background groundwater nitrate levels at less than 0.05 mg/L (0.05 ppm or 0.0000067 oz/gal) (Scott et al. 2004). Numerous studies of springs and springsheds throughout FL have shown that the majority of FL springs exceed this value and that concentrations are becoming problematic (Harrington et al. 2009, Scott et al. 2004).

Drinking water standard for nitrate concentration in groundwater is 10 mg/L (10 ppm or 0.0013 oz/gal), but once it has emerged from the ground, spring water is considered surface water, for which there is no standard (Scott et al. 2004). Even if this standard were applied to surface waters, however, ecological impacts are seen well below this value. Based on theirs and others research, Florida Department of Environmental Protection (FDEP) has proposed a target threshold of nitrate in surface water of 0.35 mg/L (0.35 ppm or 0.000047 oz/gal), considering this a level at which nitrate concentration in spring water becomes environmentally problematic, resulting in abnormal, often profuse growth of algae or other non-native plants such as the invasive exotic hydrilla, with decreases in other water quality parameters and ecological impacts (Harrington et al. 2009). Based on monitoring data 2001 – 2006 compared with the proposed standard, nearly three quarters of FDEP monitored springs have median nitrate+nitrite concentrations high enough to result in problematic algal growth (Harrington et al. 2009). In other studies of regional springs that included Gemini Springs, increases in nitrate concentrations were also documented, highly correlated with land use or changes in land use.

Studies that included sampling and analysis of nitrate levels in Gemini Springs showed a statistically significant increase from 1995 to 2004 of 0.65 to 1.1 mg/L (0.65 to 1.1 ppm or 0.000087 to 0.00015 oz/gal) in 2004 respectively, with other springs also showing varying increases (Phelps 2006, Walsh 2009).

In addition to nitrate levels, dozens of organic compounds commonly found in or associated with wastewater sources were sampled at Gemini Springs and other area springs to determine possible influence of human activities on groundwater recharge and spring water quality (Phelps 2006, Walsh 2009). Phelps (2006) found organic compounds in all the springs sampled, indicating effects of human activities in the springsheds. Compounds found in Gemini Springs in one or both studies included N,N'-diethylmethyl-toluamide (DEET), phenol, benzophenone, triphenyl phosphate, the pesticide atrazine and its degradate 2-chloro-4-isopropylamino-6-amino-s-triazine (CIAT). Interestingly, though some of the same organic compounds were found, no pesticides were detected at neighboring Green Spring (Phelps 2006). Walsh (2009) found levels of sulfur hexafluoride (SF_6) much higher than atmospheric levels indicating probable wastewater sources. Otherwise, this compound is typically used as one of a number of techniques to age springwater – this method could therefore not be used for Gemini Springs.

A GIS-based model called Florida Aquifer Vulnerability Assessment (FAVA) uses a weights of evidence statistical method to assess the probability from Lowest to Highest vulnerability (seven gradations in all) that an aquifer is susceptible to contamination based on a number of factors including water table depth, thickness of confining units, soil properties and karst features (Scott et al. 2004). According to an early version of this model, the area north of Lake Monroe that comprises Gemini Springs springshed sits within Highest and second Highest vulnerability areas (Scott et al. 2004).

Pollutant Sources

Generally speaking, stormwater runoff, wastewater discharge and agricultural runoff comprise the largest water quality threat in the St. Johns River basin, including Lake Monroe and DeBary Bayou, with nutrient pollution topping the list of ecological threats.

In many cases water quality declines in spring-fed systems are related to surface activities that impact the quality of recharge water – agricultural and residential fertilizer applications, animal waste, urban stormwater runoff, municipal wastewater from septic systems and sewage system discharges, and atmospheric deposition from air emissions (Harrington et al. 2009, Katz 2004). Small to large openings in the water-bearing limestone of the FAS form a network of conduits that translate to relatively rapid and direct delivery of surface waters to the aquifer, on the order of a few decades (Katz 2004). Regional studies have indicated the dominant source of nitrate is derived from inorganic fertilizers (Katz 2004).

Reclaimed wastewater and stormwater can augment groundwater recharge as one of many uses for this growing commodity (SJRWMD website). However, because recharge and residence times are on the order of decades, the quality of surface water recharge water is expressed in spring discharge and can persist for decades (Katz 2004). Reclaimed wastewater is applied to 1.2 mi^2 (3.1 km^2) of the land surface in Gemini springshed (Walsh 2009). While nitrogen concentrations are reduced somewhat by wastewater treatment and land application processes, this domestic wastewater discharge has the potential to contribute significant loads of nitrate to the Gemini Springs springshed and DeBary Bayou itself (Harrington et al. 2009).

Urban stormwater inputs that are partially treated or not treated prior to discharge to surface drainage systems can include numerous elements that compromise water quality – these can include fine sediments, nutrients, pesticides and various petroleum-based chemicals from pavement and other fuel sources. The City of DeBary maintains a complex stormwater management system within the City limits, which includes numerous ponds and catch basins to control and partially treat stormwater primarily by settling. Algal blooms are often observed in stormwater detention ponds, indicating an abundance of nutrients, though the time stormwater spends in these ponds can decrease sediments and nutrient pollution

(SJRWMD website). The highest flow events tend to contribute the greatest amount of contaminants due both to the increased quantity of water, as well as the relative reduction in settling or other treatment efficiency as infrastructure is overwhelmed by sheer amount, velocity and pollutant load of stormwater runoff. Additionally, pumped stormwater may have higher bacteria and nutrient content due to faster transport time to receiving waters.

Lake Monroe exhibits characteristics of eutrophication and is listed as not meeting 303d water quality standards for their designated uses by FDEP as a potentially impaired water body (SJRWMD 2002b). Water quality parameters of concern in Lake Monroe are low DO, high nutrients, lead, un-ionized ammonia and selenium levels (SJRWMD 2002b). St. Johns River has documented nutrient pollution including nitrates and phosphorus, which trigger algal blooms, though these are not seen every year or in all locations (SJRWMD online). However, DeBary Bayou from Gemini Springs and Mullet Lake to Lake Monroe share similar water quality concerns as the St. Johns River. Additionally, of the sub-basins in the Middle St. Johns River, Lake Monroe initially received a Low Priority based on the Middle Basin 1998 303(d) list as defined by water quality indices by FDEP, though has subsequently been assigned a Total Maximum Daily Load (TMDL) based on results of the Impaired Surface Waters Rule methodology for nutrient (nitrogen and phosphorus) and dissolved oxygen (DO) impairment, with target Trophic State Index (TSI) value less than 60 (FDEP 2009). Lake Monroe watershed is heavily developed with 22.7% urbanized area in its watershed, and represents one of the highest growth potential areas of Seminole County, receives wastewater discharges from Deltona (SJRWMD 2000b). Still, over 77% of the total area draining to Lake Monroe is from the Upper Basin of the St. Johns River. The Upper Basin 2006 list shows nine water bodies or segments that are impaired, with primary pollutants of concern include coliforms, nutrients, DO, biochemical oxygen demand (BOD), and metals copper and mercury (SJRWMD 2007, FDEP 2006).

Most of upper basin 139 water bodies or segments Class III, nine are on the verified list of impaired waters, six attain some uses but with insufficient data to assess completely, 95 had insufficient or no data to determine status, 24 were potentially impaired and three that are impaired due to natural conditions or physical/hydrological alterations (FDEP

2006). Pollutants of concern included iron, mercury, lead, turbidity, chlorophyll *a* levels, silver, cadmium, and selenium. Also included were BOD, DO, fecal and total coliforms, unionized ammonia, nutrients and their indicators (nitrogen, phosphorus, and chlorophyll *a*), and total suspended solids (FDEP 2006).

The recent historical trend can be expected to continue, though ongoing conservation and restoration efforts in the Upper and Middle St. Johns River Basins should begin to reduce the nutrient loading that is correlated with the changes in sediment character and accumulation rates seen in the Lake and in DeBary Bayou.

Biological Communities

Assessments of the biological communities of Gemini Springs and DeBary Bayou have shown a mix of native and non-native species of both plants and animals. Additionally, there have been shifts in biological communities that are of concern here, though the cause of these shifts may not be determined in the context of this study. The extent to which region-wide shifts or declines in populations of various desirable or native species impacts DeBary Bayou is likely to be high considering proximity to and influence by Lake Monroe and the St. Johns River. To the extent local water quality from watershed runoff, stormwater inputs or spring water is influential to the biotic communities, these parameters are of interest to the conclusions and outcomes of this study as parameters that might be controllable in the context of management of the DeBary Bayou.

Aquatic and Terrestrial Animals

There are a number of sources of information on the aquatic and terrestrial communities of DeBary Bayou. Phelps (2006) and Walsh (2009) both documented the presence of non-native fish species in regional springs during their studies. Phelps (2006) concludes that the presence of non-indigenous fishes in Silver Springs, De Leon Spring, and Gemini Springs indicates the impact of rapid colonization by these species throughout the St. Johns River basin. Walsh (2009) notes that natives are generally in low abundance in Gemini Springs, and that of the 11 species documented, three were non-indigenous, including

- Common carp *(Cyprinus carpio)* (previously having been unknown to be established in the St. Johns River drainage)
- Blue tilapia or nile perch *(Oreochromis aureus)*
- Vermiculated sailfin catfish (Pterygoplichthys disjunctivus).

The blue tilapia, a native of Africa, has been of particular concern. Brought to the US in 1954 then later to Florida in 1961 by the Florida Game and Freshwater Fish Commission as a possible biological control agent for nuisance aquatic plants and potential sportfish (Sills 1970, cichlidworld.net). This species later proved to serve neither of those purposes and instead spread widely and began to outcompete native bass and bluegill (Stjohnsriverkeeper.org, cichlidworld.net).

Phelps (2006) noted the same three non-indigenous species, also noting the presence of the common carp to be of concern, not having been known to be established in the St. Johns River previously. Native species documented by Phelps (2006) included

- Seminole killifish (*Fundulus seminolis*)
- Bluefin killifish (*Lucania goodei*)
- Eastern mosquitofish (*Gambusia holbrooki*)
- Largemouth bass(Micropterus salmoides)
- Bluegill (Lepomis macrochirus)
- Redear sunfish (*L. microlophus*)
- Redbreastt sunfish (*L. auritus*)
- Gizzardd shad (Dorosoma cepedianum).

Animal species known or seen within the DeBary Bayou area include

- Red-shouldered Hawk (*Buteo lineatus*)
- Osprey (Pandion haliaetus)
- Great Blue Heron (*Ardea herodias*)
- Cattle Egret (*Bubulcus ibis*)
- Great Egret (*Ardea alba*)
- Vermillion Flycatcher (Pyrocephalus rubinus)
- Wild turkey (Meleagris gallopavo)
- White-tailed Deer (Odocoileus virginianus)
- American Alligator (Alligator mississipiensis)
- Raccoon (Procyon lotor)

Exotic wildlife species include

- feral hog (Sus scrofa domestica)
- Coyote (Canis latrans)
- Brown Anole (Anolis sagrei)
- Nine-banded Armadillo (Dasypus novemcinctus)
-

In addition to the above, a diverse number and numerous species of ducks and coots are known to inhabit and use Mullet Lake, DeBary Baryou and the Borrow Pit. Anecdotal evidence suggests that the ducks are being replaced by coots in number and diversity, though this has not been confirmed through avian population survey.

Though there are currently no reported or otherwise known occurrences or sitings of any threatened or endangered species, this assumption should not be interpreted as a Threatened and Endangered Species investigation or survey. No Bald Eagles (*Haliaeetus leucocephalus leucocephalus*) or nesting sites have been seen or documented within the study area. Florida black bear (*Ursus americanus floridanus*) tracks have been seen on the Gemini Springs Addition property, though no individuals have been seen. American alligator (*Alligator mississippiensis*) and West Indian manatee (*Trichechus manatus latirostris*) have been sighted in DeBary Bayou, though actual frequency of sighting or use of DeBary Bayou by these animals is unknown.

Native Vegetation and Marsh Communities

Concern regarding shifting marsh communities in DeBary Bayou, possibly due to additional sediment inputs causing additional terrestrial species to emerge and outcompete wetland species. More likely, any actual shift may have occurred in response to longer term hydrologic cycles in this area. The flood record shows a fairly prolonged period of relative drought from the 1970's through the 1990's that may account for some of this shift (see Figure 8, and SJRWMD 2007). This shifting pattern is common in this setting, and may not represent a problem but demonstrates a natural cycle. To change the topography enough to shift the vegetative community would require a much more rapid accumulation of sediment than has occurred, considering the relatively minor shift that has occurred in response to a few decades of reduced flows. This is especially evident in the lower elevation communities including wet prairie and shallow marsh communities, with high river and lake level cycles producing decreased wet prairie as shallow marsh shifts upslope, contrasting with reduced river and lake levels resulting in a corresponding increase in wet prairie as shallow marsh moves downslope (SJRWMD 2007). Higher elevation vegetative communities appear more stable. Currently, the hydrology has returned to a wetter cycle, with common native vegetation found in DeBary Bayou representing commonly found species in wet prairie, shallow and deep marsh, and hydric hammock communities (Table 6, SJRWMD).

Table 6. Common native vegetation found in DeBary Bayou Modified from SJRWMD, 2007 (Mace, 2007; Mace, 2009 unpublished).

Common Name	Scientific Name	Indicator Codes (FWDM)*
Bahiagrass	*Paspalum notatum*	UPL
Bald Cypress	*Taxodium distichum*	OBL
Beautyberry	*Callucarpa Americana*	FACU
Bluestem	*Sabal minor*	FACW
Buttonbush	*Cephalanthus occidentalis*	OBL
Carolina Willow	*Salix caroliniana*	OBL
Cattail	*Typha sp.*	OBL
Common reed	*Phragmites australis*	OBL
Dotted smartweed	*Polyponum punctatum*	OBL
Laurel Oak	*Quercus laurifolia*	FACW
Marsh pennywort	*Hydrocotyle umbellate*	OBL
Sand cordgrass	*Spartina bakeri*	FACW
Saw Palmetto	*Serenoa repens*	UPL
Swamp rosemallow	*Hibiscus grandiflorus*	OBL
Sweetgum	*Liquidambar styraciflua*	FACW
Water Oak	*Quercus nigra*	FACW

*Florida Wetlands Delineation Manual (FWDM) indicator categories (SJRWMD, 2007)
Upland (UPL) = Occurs almost always in uplands.
Facultative (FAC) = Can occur in both wetlands and uplands.

Facultative Wet (FACW) = Can be found sometime in uplands but mostly found in wetlands.
Obligate (OBL) = Occurs almost always in wetlands.

To lend another perspective, analysis and interpretation of color infrared (CIR) imagery was used to corroborate relative inundation patterns in DeBary Bayou with some correlation with Lake Monroe stage, and to determine if a trend in wetland communities by imagery interpretation is perceivable using this methodology (Appendix A).

Exotic Vegetation

Invasive aquatic plants are managed within the study area as noted above, currently by spraying without physical removal. Typically the Corps manages the channel and SJRWMD manages floodplain areas. Employees rake and manually remove invasive species within the Gemini Springs Park. Exotic vegetation treatment by the SJRWMD has included an aggressive spraying program for Chinese tallow (*Triadica sebifera,* formerly *Sapium sebiferum*) last noted in 2009 in the marsh and which may have been eliminated (Jane Mace, personal communication). Because most of the DeBary Bayou floodplain area is within the Gemini Springs Addition, owned by the SJRWMD, this area is routinely monitored for exotics and invasive species. The main channel is periodically treated by the Corps, with target species apparently Marsh pennywort (*Hydrocotyl umbellate*), Water lettuce (*Pistia stratiotes*) and the Cattail (*Typha sp.*), which periodically clog the main channel (Jane Mace, personal communication). Water hyacinth (*Eichornia crassipes*), *Phragmites* and excessive algae and phytoplankton can outcompete wild rice, millet, eel grass and other submerged aquatic vegetation (SAV) and macrophytes that historically grew on banks and bed.

Chinese Tallow

Chinese tallow (*Triadica sebifera*) is a deciduous tree that can grow up to 18 meters in height and resembles the cottonwood tree. This species is typically found in riparian areas as well as uplands (Miller, 2003). Recommended procedures for control are conducted based on growth stage of tree. For large trees it is recommended to make a stem injection with herbicide; for saplings it is advised to apply herbicide/petro mix to the base; for seedlings it is recommended to saturate all leaves with the appropriate herbicide (Miller, 2003). If this is done properly by a trained professional, herbicide application can be an ecologically sound approach for eradication of individual plants.

Water Lettuce

Water lettuce (*Pistia stratiotes*) is free-floating aquatic plant that can be commonly found in lakes and low energy streams (Emerine, et. al., 2010). Biological control has been used on aquatic plants like water lettuce, but can be unpredictable (Langeland and Stocker, 2001). Drawdowns and herbicides have also been used with success to control water lettuce (Mossler and Langeland, 2009).

Prior to roughly the 1970's, "excess" or nuisance vegetation was removed from Mullet Lake, Gemini Springs or elsewhere in DeBary Bayou primarily through raking or other physical removal (Figure 26). While labor intensive, this method enabled biomass removal, resulting in partial control of already accelerated nutrient loading, as well as limiting addition of potentially harmful chemicals that would otherwise have been added through herbicide treatment. Currently, overgrowth of invasive plants is treated in DeBary Bayou by spraying and leaving dead vegetation in place to decay (this method colloquially known as "spray and lay"). It appears much of the surface sediments within the system are overlain by a layer of flocculated (or "floc") material, primarily composed of decaying organic matter. Surface sediments below this unconsolidated material are also high in organic matter. Beyond the problems this causes for vegetation, sediment cycling and water quality, this material adds a volume of material to DeBary Bayou channel that will only continue to increase under this type of vegetation management. This type of treatment keeps nutrients in the system, encouraging the continued growth of water column plants and limiting vascular plants that might improve benthic sediment conditions and better sequester nutrients. Finally, this additional material is of a high volume by weight and can appear to be filling in the stream channel even with relatively low quantities of material.

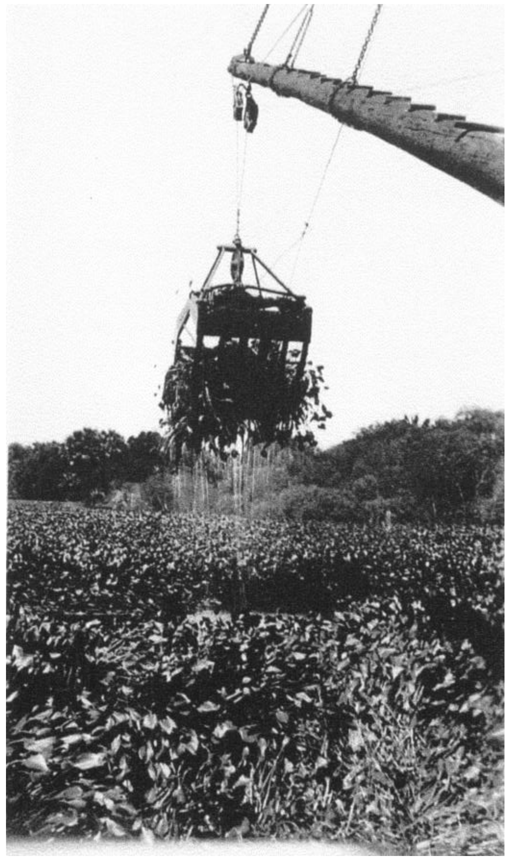

Figure 26. Clearing water hyacinth out of DeBary Bayou, 1970's. Photo courtesy of Saundra Gray.

Land Use and Infrastructure

The City of DeBary dominates this landscape as the primary settlement and source of development. DeBary has a population of approximately 20,000 and was incorporated in 1993. The City itself comprises approximately 25 sq mi, with City municipal boundaries extending from the I-4 bridge along St. Johns River and the Volusia and Seminole County lines to the west and north, roughly east south-east back to I-4, then south-west along I-4 back to the bridge. Constructed features of particular interest within DeBary Bayou watershed include the City of DeBary and associated roads, bridges, impervious surfaces and stormwater infrastructure, Florida SR 417, I-4 causeway and bridge, River Oaks Estates residential development, Gemini Springs County Park with impoundment, Gemini Springs Addition, Lake Monroe Park and DeBary Hall and other Historic Sites. Walsh (2009) studied 30-year landuse change trends within DeBary which show rapid urbanization and decreases in forested areas, with current impervious surface estimated at

30%. Agricultural and barren areas have remained roughly the same, below 3% total area. Springsheds with the most extensive land use change toward urbanization – Alexander, Apopka, De Leon, Gemini, Green and Wekiwa – show the greatest nutrient increases evidenced by abundant algal growth and high numbers of tolerant macroinvertebrate species (Walsh 2009).

Most of DeBary Bayou, Mullet Lake and Gemini Springs south of Dirksen Drive are zoned for Conservation, with the remainder of the DeBary Bayou corridor through the I-4 Bridge zoned for Resource Conservation (DeBary zoning map 2010, City of DeBary online). Sections along the north-east edge of the channel are zoned for Residential Planned Unit Development (a relatively large section including River Oaks Estates), Urban Multi-Family Residential (a small section containing River Oaks Condominiums) and a section of Highway Interchange Commercial between the two, roughly twice the area of the River Oaks development. To the west along US Highway 17-92, there is a patchwork of areas with zoning classifications including Industrial Planned Uses, Business Planned Uses and Mixed Planned Uses, and various Commercial and Agriculture Uses.

Heritage Sites

The City has a very rich and storied history, described in detail in a number of references and preserved and honored at selected historic locations within the City itself. First and foremost is DeBary Hall, placed on the National Register of Historic Places (NRHP) in 1972 as the restored 1871 winter home of Samuel Frederick de Bary, the first settler in this region (Stewart, et al., 1999). The DeBary Hall Historic Site is open to the public and features historic displays, docent-led tours, rotating local artists' work and multi-media programs.

A detailed archaeological survey done for the City of DeBary describes a total of 29 sites of interest with their NRHP status and recommendations, some sites dating from prehistoric times (Stewart, et al., 1999). One of the points of local historic interest is on the DeBary Bayou itself: the site of the *Fannie Duggan* Shipwreck south of the cul-de-sac on Hickory Street (Figure 27 and Figure 28). According to Stewart, et al (1999), this 165-foot wooden steamboat was abandoned on the north bank of DeBary Creek in 1885, and wood and ferrous fragments of the *Fannie Dugan* steamship can still be found along the shoreline. As noted above, the *Fannie Dugan* and similar sidewheeler steamboats required less than three feet of draft (32 in (81.3 cm) for the *Fannie Dugan*), and were typically less than 30 ft (9.1 m) wide (Cowart 2005).

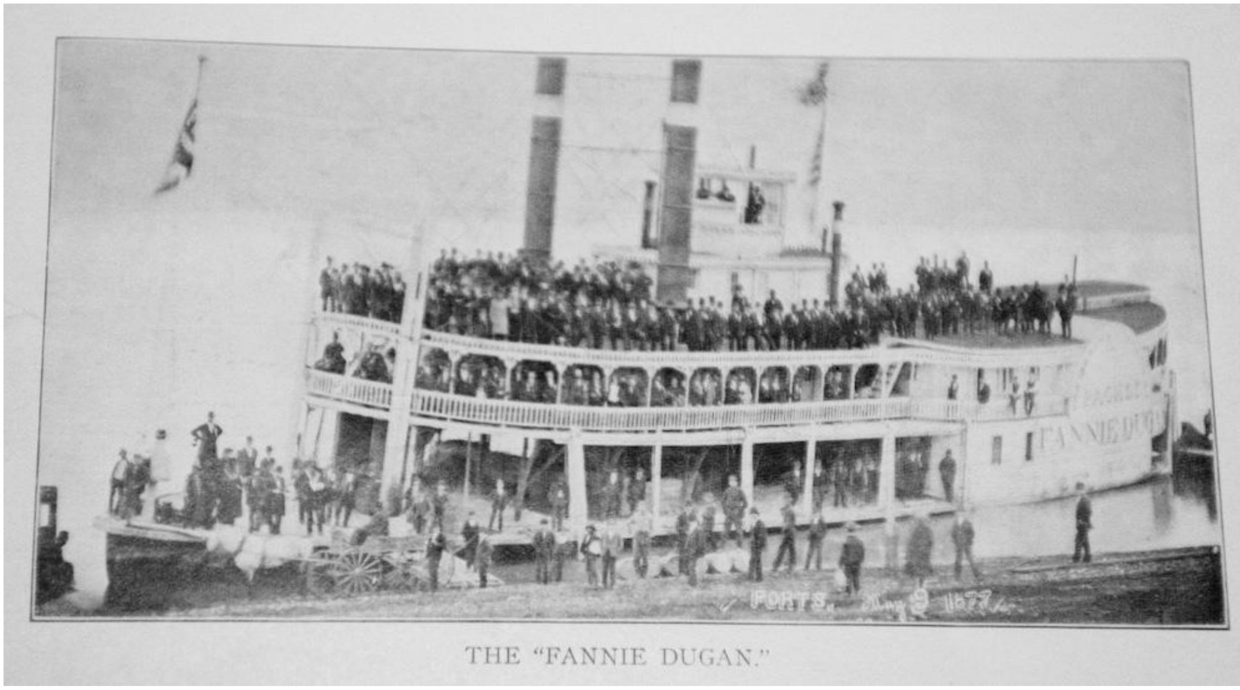

Figure 27. The *Fannie Dugan*, a 165-foot long sidewheeler steamboat, requiring 32 inches of draft (Image from Portsmouth Public Library).

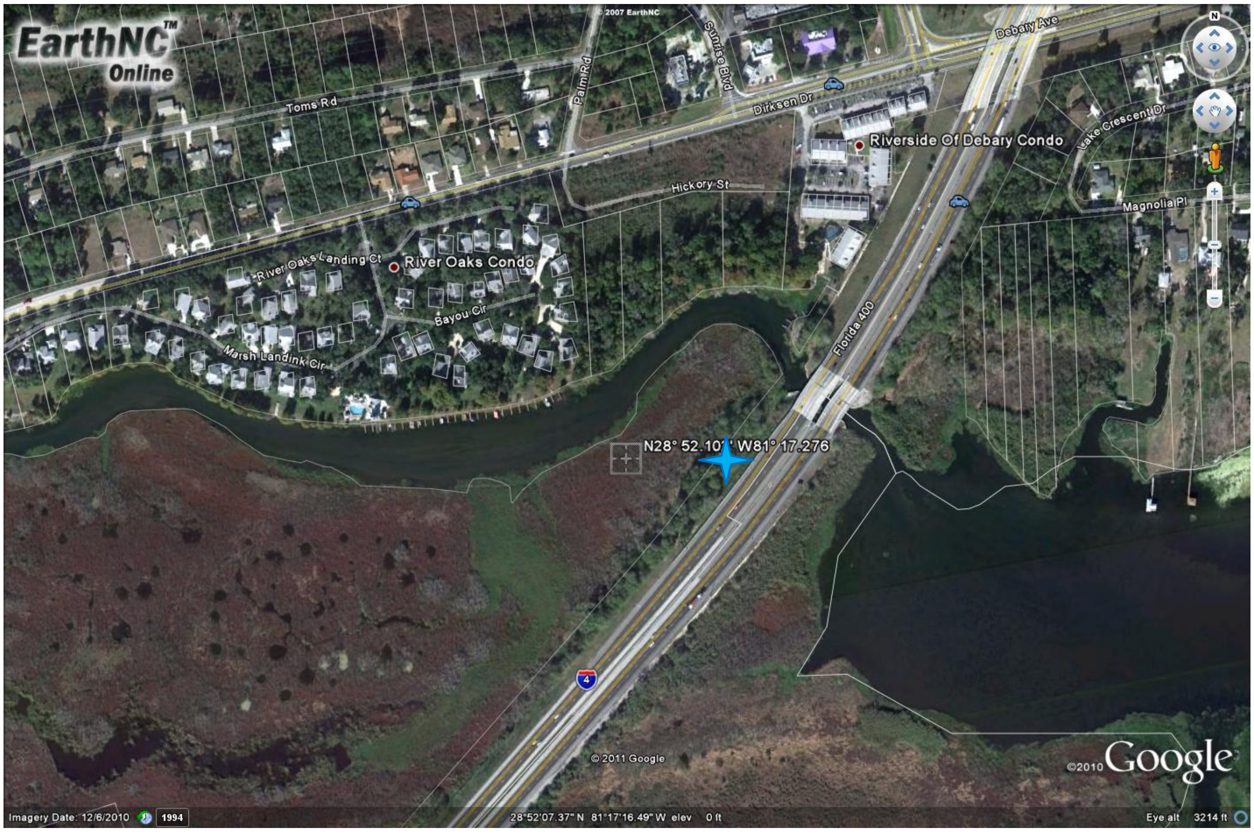

Figure 28. Published latitude and longitude location (blue cross) of the wreck of the *Fannie Dugan*.

Numerous additional historic sites such as Frederick DeBary Packing House, DeBary Creek Sugar Mill and Elijah Watson House are documented and described. Sites such as the Gemini Springs Midden site was recommended by Stewart et al (1999) as potentially eligible for the NRHP because it might provide important information about inland freshwater resource procurement strategies. Additional sites like the DuBarry Creek Midden located in River Oaks Estates south of the cul-de-sac on River Village Drive have been disturbed by development and shell-mining operations, though previous descriptions and artifacts discovered add to the rich history of the area.

9 SUMMARY OF WATERSHED CONDITION

From the data, reports and analyses considered above, there is no clear evidence that DeBary Bayou is experiencing significant anthropogenic degradation in aquatic communities, water quality or sediment accumulation that is different in pattern from similar settings within the Middle St. Johns River basin, all of which have undergone similar degradation patterns. While there are measureable declines in water quality and ecological condition, the DeBary Bayou shares most of these in character and magnitude with many other similar systems in this region of Florida. Like these systems, however, there are local as well as regional effects on ecological health.

Sediment accumulation and water quality studies, scour analysis and cross section comparisons, bathymetry and aerial images show no changes in DeBary Bayou configuration, morphology or depth that can be correlated in time with either initial construction of I-4 in the late 1950's or with widening activities in the 2000's. While the evidence does show a minor increase in sedimentation rate in DeBary Bayou in comparison with Lake Monroe, this appears to be due more to increases in supply rather than limited removal mechanisms. None of the data or documented evidence found in the course of this study suggests that DeBary Bayou was several feet deep during low flow conditions at any time during the last 100 years (even the famous side-wheeler steamboat, the *Fannie Dugan*, which was able to navigate into the DeBary Bayou in the 1880's, required less than three feet of draft to operate), nor that the channel has filled in appreciably during the last 50 years. Sedimentation may not be what is impacting boating access or wildlife condition as much as organic material and nutrient loading adding to organic sediments and nuisance vegetation growth, as actual depths in the DeBary Bayou presently reflect recent historic conditions (the last 100 years or so). Sediments deposited on the bed appear to be primarily of organic origin, likely the result of primary productivity by aquatic vegetation within the Bayou, Mullet Lake and the floodplain area, though additional nutrient pollution from development within the watershed as well as increased stormwater inputs that contain excess nutrients, pollutants and additional fine sediment material, is highly likely to have accelerated this process resulting in evidence suggesting accelerated rates of floc accumulation (especially evident in Mullet Lake showing up to 5 ft (1.5 m) of floc material) as well as fine sediment accumulation in DeBary Bayou (evident in sediment cores showing approximately 1.0 ft (0.3 m) of accumulation in the last 100 years compared to 0.5 ft (0.15 m) accumulation in Lake Monroe), when compared to similar water quality and benthic conditions regionally, lead to a focus on stormwater and vegetation management within the City of DeBary and DeBary Bayou as the most likely avenues for medium to long term ecological improvements in ecosystem condition within DeBary Bayou.

There are also worthwhile gains to be made in addressing clear declines in water quality that impacts ecological health in this system through a series of additional restoration measures targeted at the most likely localized causes of measured ecosystem degradation. For example, remediation of highly organic sediments in Mullet Lake or replanting areas with native vegetation that might be better at sequestering nutrients following invasive vegetation removal. This report therefore ends with a series of restoration actions that may be taken to address the suite of locally-driven restoration objectives where the study team judged improvements might be made. Whereas all concerns were considered, objectives that are unfeasible, impractical or beyond the scope of the problem (i.e., the source of the problem is outside the control of any feasible project), this study does not provide a recommended solution.

10 RESTORATION OBJECTIVES WITH RECOMMENDATIONS

Key locally driven restoration objectives identified previously support the overarching goal to restore and preserve natural resource quality in DeBary Bayou to enhance ecological function, which will enhance tourism and recreational use. The objectives are listed in relative descending priority and magnitude of potential impact. Where possible, estimates of quantities or relative cost are provided for reference. Each restoration objective is presented separately, though recommended remediation actions under each objective can be implemented separately or in combination with other objectives. Implementing restoration activities in a phased approach is recommended, and where appropriate a recommended order of operations is discussed. Opportunistic partnerships for funding or implementation may necessitate piecemeal execution of individual projects or specific Best Management Practices (BMPs) – where possible, the rough impact of each activity alone or in partnership is also discussed.

Address gravity stormwater infrastructure, management and treatment for the City of DeBary to limit nutrient and sediment inputs.

Because there is some evidence of increased sediment supply, addressing the most likely sources of sediment is of the greatest importance. Stormwater appears to be the most likely source which includes nutrient pollution that feeds excessive primary production, followed by resuspension of Mullet Lake sediments. First and foremost, a detailed study to quantify the quantity and quality of gravity stormwater runoff in DeBary Bayou watershed is critical to determine the magnitude of sediment and other pollutant inputs from stormwater and to differentiate this source from resuspended sediment and Lake Monroe sediment inputs.

DeBary is in process of constructing a West Side Emergency Flood Management System (west of US Highway 17-92) with new infrastructure including stormwater storage that should alleviate some of the pressure on existing systems (see discussion above). While quantity, relative frequency and water quality are reasonably well-understood if not entirely treated or treatable for the Eastside and Westside stormwater systems, this information is lacking for existing gravity stormwater infrastructure. These structures are of varying age and condition, many outfalls continue to operate without treatment, and development pressure in the City of DeBary and in Lake Monroe watershed and source waters is only increasing. Additions of excess nutrients, fine sediments, emerging pollutants and other contaminants will only continue.

A comprehensive stormwater feasibility study and stormwater pollution prevention plan should be undertaken to determine the relative contributions of nutrients, sediment and bacteria from gravity stormwater outfalls to DeBary Bayou, with an optimization exercise to focus restoration funding between pollutant sources to result in the best overall water quality in DeBary Bayou. Because both Gemini Springs and Lake Monroe also have impact on water quality in DeBary Bayou, detailed sampling of water quality in Lake Monroe, DeBary Bayou, and Gemini Springs should be combined with sampling at stormwater outfalls and treatment infrastructure for gravity fed and pumped systems where appropriate. A Quality Assurance Project Plan should be developed for this sampling to ensure the appropriate experimental design to answer the following specific questions:

- How does water quantity and quality in DeBary Bayou change over time?

1. Install a gaging station at the mouth of DeBary Bayou to record water quality parameters of interest to determine the patterns of water quality fluctuations relative to storm patterns, Lake Monroe stage and water quality, stormwater pumping activity or periods of reverse flow conditions.
2. Install a similar sampling location upstream from the mouth to represent some average condition within DeBary Bayou that includes impacts from Gemini Springs, stormwater inputs and Lake Monroe.
3. Sample stormwater outfalls at various time intervals to represent stormwater conditions and seasonal or antecedent effects. Sample gravity outfalls at older and newer infrastructure with varied maintenance schedules to assess performance of maintenance activities and to optimize operation and maintenance budgets.

- To what relative extent and with what periodicity is water quality in DeBary Bayou related to or dependent on water quality of Gemini Springs, Lake Monroe, gravity stormwater outfalls and pumped stormwater? Information from this question will reveal potential relative gains in water quality from restoration activities aimed at each of these sources. For example, Lake Monroe quality might be most influential during flood stage in St. Johns River, whereas pumped stormwater may be most influential following recession of Lake Monroe – in this case, treating pumped stormwater during periods of low Lake Monroe stage may be most beneficial.
- What are the differences in proportion of water quality parameters of concern in each of the pollutant source waters? This information can be used to optimize treatment scheduling and allocation. For example, if stormwater contains significantly more bacteria than Gemini Springs, any treatment improvements at the springs may be drowned out during storm periods, so treatment funding should shift to focus on stormwater treatment.
- What is the ongoing ambient water quality in existing lakes, ponds and settling basins between storms? If ambient water quality is low, treatment capability for stormwater will most likely be low. Information from sampling in a selection of these waterbodies should show the general condition of these features, and can be used to optimize use of a number of BMPs to improve and maintain higher antecedent water quality such that there is a buffer for the sudden demand created by stormwater loading.

Addressing stormwater through additional recharge or force mains in existing landlocked lakes should be pursued only if quality is improved through treatment, or optimization shows additional recharge is warranted even if quality is low. Additional settling basins should be installed wherever land areas are available and more aggressive operation and maintenance of current basins is highly recommended to reduce the amount of sediment inputs to DeBary Bayou and associated waters. For example, Riverside Condominiums small stormwater basin definitely requires more frequent maintenance; FDOT maintained this basin until approximately 15 years previous to 2009, though frequency of current management by Riverside Condominiums is unknown. Site visit to this facility in 2009 showed this structure is at capacity. As noted above, this may be due to the combined stormwater flows to this structure. In that case, the length of the I-4 stormwater drainage channel from the Eastside EFMS pump outlet to the DeBary Bayou should be analyzed for any upgrades to augment treatment in combination with the Riverside Condominiums stormwater pond. Additionally, FDOT should consider a maintenance agreement with Riverside Condominiums such that this structure is never allowed to stand full.

Possible discharge of stormwater or beneficial use of sediment material to the FDOT Borrow Pit may be possible with modifications to this structure allowing additional treatment, retention, settling or otherwise sequestering material as needed (e.g., rebuild or reinforce existing berms, implement a sediment removal operation and maintenance plan). Importantly – additional treatment of settled and dredged sediments from stormwater will be required as the quality of these sediments is typically poor. However, there may be beneficial use opportunities for treated sediments that may help recoup expenses if material can be sold rather than transported off site.

Additionally, the City of DeBary should include reduction strategies to limit the quantity or adjust the timing of stormwater runoff. While opportunities for dramatic reduction in stormwater quantities might be limited considering the terrain, reducing or holding steady the proportion of impervious surfaces through zoning and construction regulations or retrofits to existing infrastructure can result in some gains. Gains already underway from FDOT having halted fertilizer use in their rights of way and recent enactment and additional enforcement of the City of DeBary fertilizer ordinance will result in additional nutrient reduction.

Stormwater BMPs can result in dramatic improvements to stormwater quality, removing sediments, nutrients, heavy metals and other pollutants. The International Stormwater BMP Database (http://www.bmpdatabase.org/) is a multi-agency coalition that maintains a database of over 400 BMP studies, including performance results and montiroing guidance designed to help improve design and selection of appropriate BMPs. Studies and results showing effectiveness of many BMPs in reducing various pollutants including solids, metals, bacteria and nutrients are provided, as well as performance and cost information for a selection of structural and non-structural BMPs. For example, evaluation of dozens of studies on nine different BMP categories on reduction efficiency for total suspended solids showed percent removal from 50 to over 80% (Table 7).

Table 7. TSS removal efficiency for selected BMPs, updated May 2011, adapted from International Stormwater BMP Database.

BMP type	TSS In	TSS Out	% Removal	# Studies (in, out)
retention pond	133	24.6	**82**	41, 40
media filter	69.7	19.9	**71**	19, 20
detention basin	118	37.1	**69**	19, 19
bioretention	70.6	24.1	**66**	6, 6
filter strip	75.7	29	**62**	14, 14
manufactured device	128	49.8	**61**	40, 47
wetland basin	49.3	19.4	**61**	15, 16
porous pavement	93.7	38.5	**59**	5, 8
bioswale	42.9	21.4	**50**	17, 19

Address water quality issues and increased nutrient loading in DeBary Bayou where possible to slow the rate of organic matter deposition and eutrophication.

If a comprehensive stormwater and water quality monitoring program is implemented per above discussion, relative timing and distribution of pollutant sources should be better understood and the optimization of treatment options between stormwater inputs and other sources of contamination can be more effectively considered. Most importantly, eutrophication characterizes the system of with the DeBary Bayou is a part. The magnitude of improvement may therefore be limited by the influence of Lake Monroe inputs.

- Resuspension of sediment in Mullet Lake – benefits and potential drawbacks to removal and treatment of these sediments by three different methods has been studied and documented by SJRWMD (2002a, 2003). The depth of nutrient rich organic and fine sediment material in this lake greatly exceeds what should be a natural or historic level (approximately three times accumulation rate in DeBary Bayou channel) and may represent accelerated eutrophication (SJRWMD 2003). Resuspension of these sediments most likely represents an ongoing threat to DeBary Bayou water quality as well as an impediment to a return to a more healthy and sustainable vegetative and animal community. Any removal of material should be balanced against risks to water quality from this activity itself cited in SJRWMD 2003. Additionally, removal of sediment should be combined with both treatment and physical removal of invasive vegetation to limit further introduction of organic material and increases in primary productivity. Though increases in organic matter may not be improved depending on vegetation species, i.e., replanting with native vegetation may not result in any improvement to water quality per se, though there are additional benefits to native vegetation for waterfowl and aquatic animals. This treatment should be coordinated with the existing Gemini Springs Addition Land Management Plan (2006) to ensure monitoring and implementation of any remediation activities is consistent with SJRWMD goals and recommended methods.

- Addition of organic material from vegetation and vegetation treatment. Any "spray and lay" treatment of invasive vegetation in the DeBary Bayou or floodplain by the Corps or SJRWMD should be replaced with physical removal. Similar to nutrient reduction strategies by removing fish, removal of vegetation also results in nutrient and organic material reduction. Whereas this method is labor intensive and may be more expensive, the benefits to improved water quality and reduction in floc or fine sediment accumulation in the system should outweigh the expense, particularly if additional tourism or recreational uses accrue due to improved water quality conditions, reduction in offensive odor from decay of dead plant material, and the appearance of floating dead vegetation are removed. Beneficial use of this material is a possibility if it is not treated with herbicides first – agricultural uses, composting, or other applications should be investigated.

Address water quality issues in Gemini Springs to reduce number of bacteria violations, increase resource use and limit additional loadings to DeBary Bayou.

Because of the high visibility of this area and ongoing violations that limit use of these waters, opportunities for improvements in this public resource can result in educational benefits, added tourism, and improved ecologic function. Any improvements in water quality or quantity achieved in Gemini Springs through addressing stormwater, groundwater recharge, fertilizer ordinances or other activities may not result in water quality at the springs for decades due to residence time in the FAS. However, the impoundment offers a unique opportunity to treat this source prior to outfall to DeBary Bayou, with good potential for partnership and co-sponsorship of a demonstration treatment area. Options should include:

- Treatment by physical removal of invasive vegetation – this is a current practice, but frequency, location and amount of vegetation removed, in addition to types of vegetation targeted, should be incorporated into a new maintenance plan within the impounded area. Spring runs represent a relatively rare habitat type regionally, so should not be actively treated unless clearly warranted.
- Additional aeration at the outfall location should be included as part of the treatment system here.
- Any additional BMPs that might also benefit water quality, such as water fowl exclusion or planting terrestrial buffer areas, should also be considered to increase benefits.

Using Phelps (2006), Walsh (2009) and continued discharge and water quality monitoring by SJRWMD and UGSG as baseline studies, ongoing monitoring of this valuable resource should include sediment accumulation and quality studies similar to those performed in Mullet Lake, DeBary Bayou and Lake Monroe. The extent to which sediment in or from these vents might have formerly influenced benthic sediment quantity or quality in DeBary Bayou might lead to alternative restoration efforts that take this supply into account. Additionally, water quality from Gemini Springs may be closely linked to the type and quality of sediments that form and accumulate in DeBary Bayou by defining conditions under which sediment becomes resuspended or consolidated due to the influence of which type of vegetation is encouraged (planktonic vs macrophytic).

Ensure invasive vegetation is appropriately treated to restore marsh community for wildlife.

Assessment of Lake Monroe levels, I-4 bridge capacity, relative topography and elevations in DeBary Bayou channel and floodplain with those of Lake Monroe, and interpretation of wetland communities combined with transect data through these communities suggest that this area is sufficiently hydrated under the current configuration of I-4 causeway and bridge opening. However, considering sediment cycling, competition with invasive vegetation, and current treatment strategies, various native wetland communities that occur or should occur in the DeBary Bayou floodplain area can be improved. Options should include:

- Eliminate "spray and lay" methods of treatment of invasive vegetation – application of herbicides and addition of organic material that increases BOD, reduces DO and adds organic material to bottom sediments all threaten establishment, growth, survival and sustainability of native vegetative communities. Implement a physical removal program for targeted invasive species.
- Alternatively, chemical spraying could be used in combination with raking or other physical removal techniques – a specific management plan for these techniques should be developed to optimize each type of treatment, considering seasonal concerns and species-specific growth patterns and response to spraying. Storage and treatment areas will need to be identified and secured for disposing of collected plant materials.
- Augment native vegetation to encourage ongoing competition with invasive species. FDOT borrow pit/pond might provide an ideal location for a native nursery for propagation and harvest of native aquatic plant materials for use within DeBary Bayou, Gemini Springs or Mullet Lake. This area could be developed as a demonstration nursery site.

Remove soft sediment within DeBary Bayou to historical levels.

This option should only be pursued if sources of sediment including eutrophication characterization have shown removal of materials combined with treatment of sources will achieve a significant positive improvement. Any program to dredge 1.5 miles of DeBary Bayou as a whole may otherwise be cost prohibitive and would not achieve restoration goals on its own. Considering increases in development such as improvements in Gemini Springs Park and the completion of the SunRail slated for 2013 that will connect Orlando with the City of DeBary, the increase in tourism and recreation opportunities may provide cooperative funding opportunities that make larger scale dredging more feasible. In that regard, SJRWMD transects measured in 2009 offer a very rough estimate of soft sediment depths in DeBary Bayou (Table 8). The following rough quantities could serve as a starting point for developing a dredging estimate for DeBary Bayou should that be a desired strategy.

Note – SJRWMD (2002, 2003) sediment core analysis in Mullet Lake indicated potential for water quality impacts from various sediment treatment and removal options. This does not necessarily preclude dredging, but does indicate special dredging instructions be followed as noted in these documents.

For the approximately 1.5 mi (7,920 ft) estimated channel length, at an average depth of 1.6 ft (0.5 m) of "soft" sediment and an average channel width containing this sediment of 84 ft (25.6 m), roughly 39,500 yd^3 (30217.5 m^3) of soft sediment material could be removed as a short term solution to decreased water depth. This would provide an average channel depth of roughly 3.7 ft (1.1 m) at a Lake Monroe elevation of approximately 0.0 ft, or approximate long term average summer base flow conditions. Current average channel depth to top of "soft" sediment is approximately 2.2 ft (0.67 m)

Table 8. Average channel and soft sediment depths from transect data collected 2009, SJRWMD. All measurements in feet. Values are not intended for use in basing construction estimates – additional measurements and calculations are required.

Transect #	Avg. depth to "soft" sed.	Avg. "soft" sed. depth	Current channel avg. width	Potential channel avg. depth	Notes/Location
1	3.36	2.1	40	5.43	Just below weir at Gemini Springs
2	1.80	1.8	90	3.63	
3	1.30	0.7	65	1.97	
4	1.64	2.2	100	3.87	
5	1.15	1.0	60	2.11	
6	1.55	2.3	120	3.84	
7	0.84	1.3	150	2.15	At River Oaks Estates
8	3.03	1.8	45	4.79	Upstm of I-4 bridge
9	5.36	-	-	5.36	Dnstm of I-4 bridge
Average	2.2	1.6	84	3.7	Average*

*These values are unweighted averages – transect are not evenly spaced along DeBary Bayou. Precise stationing was unknown at the time of this reporting; therefore, no section volumetric estimates were made.

Other considerations include the following:

- Constructing a continuous recording gage at the mouth of DeBary Bayou that includes water quality and sediment sampling with stage-discharge rating development would provide important data required to document actual flow conditions, reverse flow frequency, relationship between stage between DeBary Bayou and Lake Monroe, and sediment concentrations moving into and out of this system. When combined with stormwater data, this information can help determine sources, fates and transport of sediment material in addition to determining the actual flow conditions at which boating access is limited. These are important factors for better estimating the relative benefits and costs of a dredging program.
- A series of monumented cross sections placed through this section, and possibly extending through the I-4 bridge and into Lake Monroe, would facilitate periodic elevation measurements to determine actual time series depths to augment stage information above. Surveys that include sediment sampling can help estimate the locations and quantities of material that is floc, organics or fine sediment “muck” material, and where consolidated bed sediments begin. Comparison with what is happening under the bridge and into Lake Monroe over time will give some indication of system trends and help determine if they are due to Lake Monroe influence rather than DeBary Bayou channel inputs.
- It is important to recognize that sediment processes can play out over long time periods, often on the order of decades. Increased depth shown in 2007 bathymetry just downstream of River Oaks and extending through the I-4 bridge is encouraging evidence sediment transport capacity in this reach. Continued sediment flux might be enhanced by measures that limit additional organic material accumulation and sediment inputs from stormwater and adjacent upland areas and water bodies.

11 PERSONAL COMMUNICATION

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APPENDIXES

Photo Interpretation of Inundation

Photo interpretation of remotely sensed data is a widely used method for indentifying wetlands (Cowardin and Myers, 1974; Tiner, 1977; Brown, 1978; Tiner, 1999). Three criteria are used in indentifying wetlands: 1) inundation/saturation levels, 2) presence of hydric vegetation, and 3) presence of hydric soils. Using photo interpretation to identify hydric soils and vegetation is a complicated and extensive task that is outside the scope of this project. This study will incorporate soil maps, vegetation transects and digital elevation models (DEM) from other studies to aid in photo interpretation of inundation levels.

Remote-sensed data is generally obtained from two platforms: 1) satellite imagery, 2) low/high altitude aerial imagery (Tiner, 1990). When choosing a platform several factors have to be accounted for, including the size of the study area, the spatial and temporal resolution needed, and the amount of data available – just to mention a few. Satellite imagery is commonly used for projects with large study areas that do not require a high level of detail. Aerial imagery is useful when the study area is small and a high level of detail is necessary. For this study aerial imagery was determined to be the ideal platform. The aerial imagery used in this inundation analysis was collected on a Digital Frame Camera, which allows the user to specify color (red, green, blue) or color-infrared (CIR) multispectral imagery. The CIR imagery is composed of three spectral bands: 1) green, 2) red, and 3) near-infrared. The near-infrared band allows for a sharp contrast between water and land, making CIR imagery ideal for identification of inundated areas.

1. Photo interpretation is not a simple task; several concerns need to be addressed before beginning the process:
2. The quality of the imagery is important, because under/over exposed or blurry imagery is not useful.
3. When the imagery was gathered is important. For most locations, early spring is the ideal time to gather imagery, because there tends to be less vegetation coverage, making landforms and other features more discernible. This is generally referred to as “leaf-off” imagery.

Extensive snow or cloud cover can lead to a decrease in mapping accuracy if important features or large areas are affected.

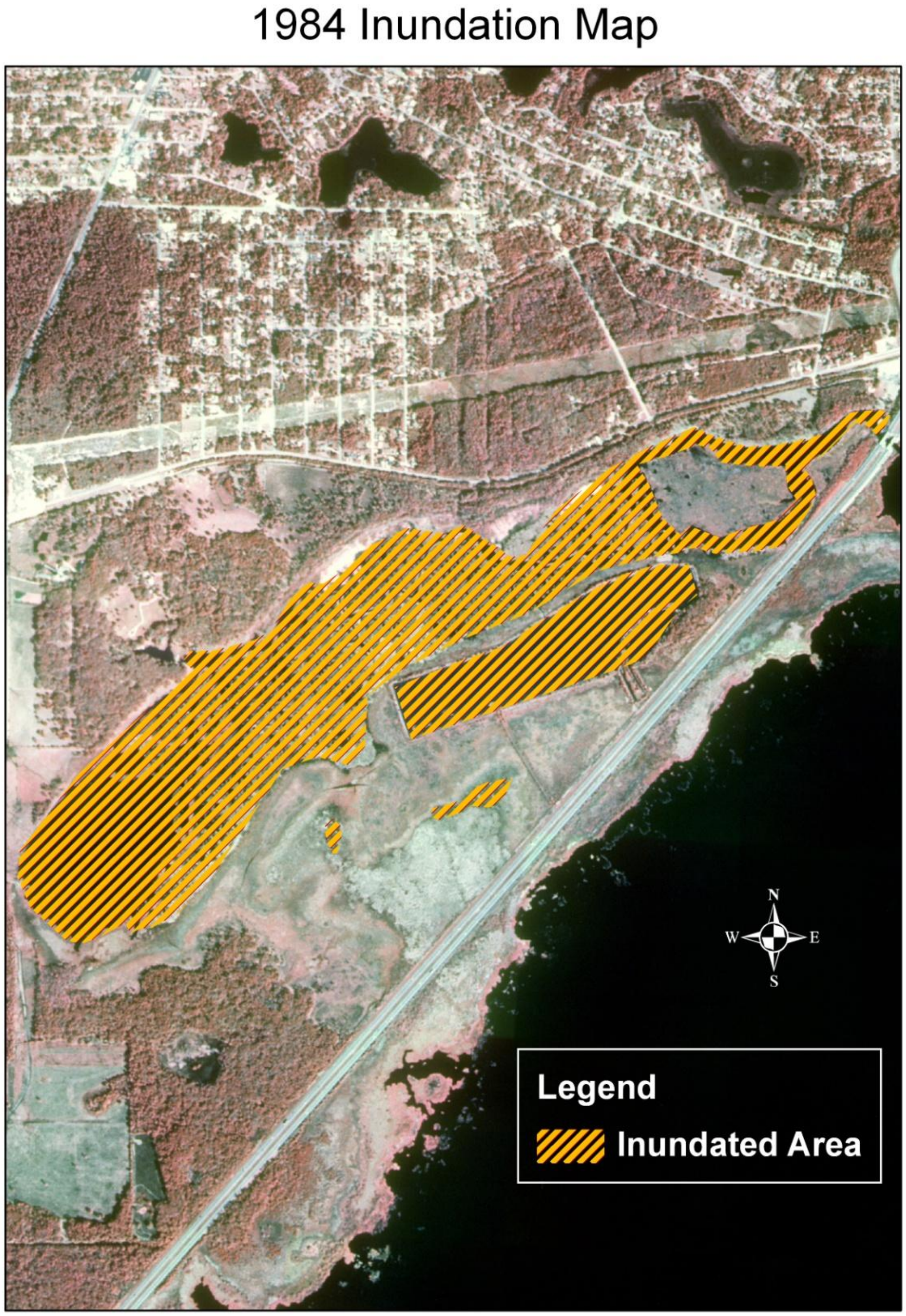
4. The dominant vegetation type is also important, because this can determine the extent of ground visible from the imagery. Coniferous dominated areas are the most difficult to map because they retain canopy cover year round. Deciduous dominated areas can be difficult to map in summer, but imagery taken in the winter or early spring can be useful.
5. The emulsion of the aerial imagery. Emulsion refers to the spectral range of the aerial imagery used (RGB, CIR, Panchromatic). Different spectral ranges are recommended depending on the intended use.
6. The topographic relief of the study area. This is important because shading can lead to misinterpretation of specific features in the study area.
7. The skills of the photo interpreter are paramount to successful, accurate imagery interpretation. Knowledge of how different landscape features appear at different scales and from differing altitude depending on the spectral range, and antecedent knowledge of the study area or features of interest are also helpful.

Digital CIR aerial imagery was available for the following years: 1984, 1995, 1999, and 2009, provided by the St. Johns River Water Management District. Stage at the USGS gaging station at the outlet of Lake Monroe and at St. Johns River at the outlet of Lake Monroe were determined for the date on which the imagery was collected for comparison with known lake level (Table 9). Data were not available for Lake Monroe after 2005, and no data were available for St. Johns River for the 1984 date. Due to the proximity of these two gages at the outlet of Lake Monroe, measured stage at these two gages on any given date typically differs by no more than 0.1 ft and should not affect results at this scale. Additionally, general floodplain and channel topography was assumed to be roughly unchanged in most of the area during the 25-year period covered by this series, at least at the scale of the analysis (some construction and dredging or filling activities may have occurred, but are not significant enough to result in a wholly different pattern of floodplain or channel inundation). Major construction activities within or adjacent to the lowland area during this timeframe included River Oaks Estates starting in 1995 and activities associated with six-laning (widening) of I-4 beginning in 2001 and extending roughly to 2009. Additional expansion within the City of DeBary also occurred, though the precise location and extent is unknown.

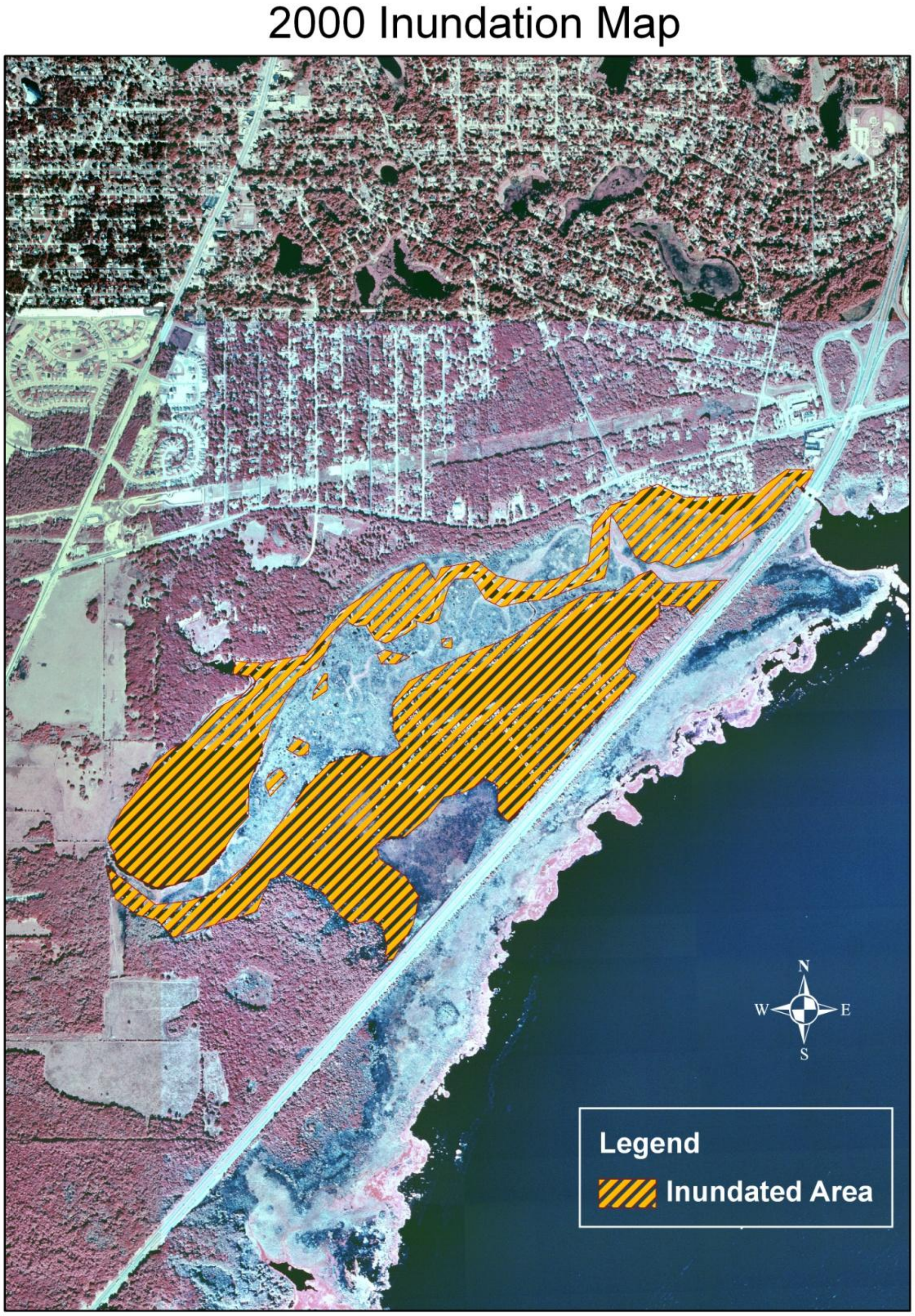
Table 9. Color Infrared imagery for DeBary Bayou with date of collection, corresponding Lake Monroe stage and other Lake Monroe stages of interest for comparison.

Imagery Year	Collection Date	Stage at Lake Monroe (ft)	Stage at St. Johns River (ft)	Rising or Falling Stage	Stage Recurrence or Reference Stage
1984	2 Mar 1984	2.07	no data	Falling, gradual	unknown
1995	4 Apr 1995	1.79	1.84	Falling, gradual	MHW 1.8
1999	26 Jan 1999	1.26	1.32	Falling, gradual	Summer low 1.1
2009	27/28 Oct 1999	no data	4.91 & 4.8	Falling, rapid	unknown
NA	NA	0.1	0.1	Base	Summer base
NA	NA	3.5	3.5	Base	Winter base
NA	NA	9.3	9.3	Peak	100 yr@ DeBary Bayou

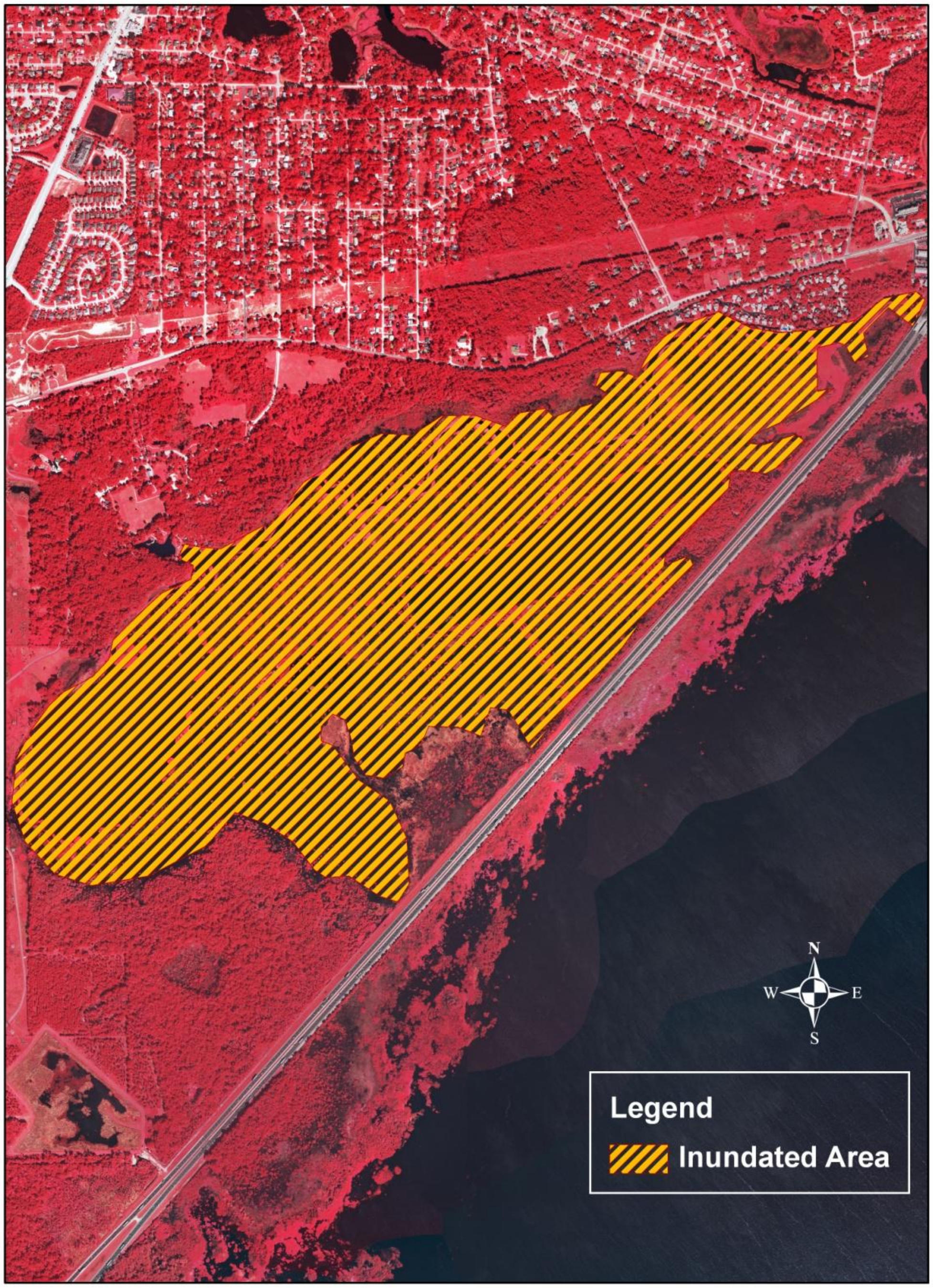
The DeBary Bayou study area south of Dirksen Drive to Lake Monroe is known to be dominated by floodplain marsh and hydric hammock plant communities (SJRWMD, 2006). The floodplain marsh is dominated by grasses and small herbaceous plants. The hydric hammock communities are composed of small to medium sized deciduous vegetation. This vegetation coverage allows for a relatively easy identification of the areas of inundation/saturation. In the CIR imagery the areas of inundation/saturation can be easily identified by their dark color, which is caused by the lack of penetration of the near-infrared spectral band in to water. 1995 Map: Stage at Lake Monroe gaging station = 1.79ft on 4/4/95, stage at St. Johns River = 1.84'2009 Map: Stage at St. Johns River gaging station = 4.85ft on 10/27&28/08, no data for Lake Monroe gage for this date.


1984 Inundation Map
N
W
E
S
Legend
Inundated Area

1995 Inundation Map


2000 Inundation Map
N
W
E
S
Legend
Inundated Area

2009 Inundation Map



Recent Sediment Accumulation in Padgett Creek, Middle St. Johns River Basin

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Final Report

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Introduction

This project was undertaken to evaluate recent sediment accumulation rates at three sites in Padgett Creek, Middle St. Johns River Basin. The study was prompted by concerns that sedimentation rates have accelerated in the recent past and that deposits may soon fill in the creek, impeding water flow and navigation. Sediment cores were collected at three sites that were identified by personnel from Florida DOT as areas of possible concern. Our first objective was to collect intact sediment/water interface cores, measure unsupported ^{210}Pb in contiguous 4-cm sections from the profiles, and determine sample ages if possible, using an appropriate dating model. Such data can enable estimates of sediment accumulation rates that can be used to address concerns about excessive sediment deposition.

Background on ^{210}Pb Dating

Lead-210 (^{210}Pb) is a member of the Uranium-238 (^{238}U) decay series. Uranium-238 and its daughter radionuclides occur naturally in Florida rocks and soils. One of the daughter products, Radium-226 (^{226}Ra), is also found in rocks and soils, where it decays to gaseous Radon-222 (^{222}Rn), some of which escapes to the atmosphere. Radon-222 has a half-life of 3.8 days and undergoes alpha decay, as do its several short-lived daughters, to yield particulate ^{210}Pb. The ^{210}Pb particles are ultimately deposited on land and water surfaces via rainfall and dry fallout.

The particulate ^{210}Pb that is delivered from the atmosphere and ultimately makes its way into aquatic ecosystem sediments comes from several sources: 1) direct deposition on the water surface, 2) stream input, and 3) transport from the catchment. In most cases, direct fallout on the water surface accounts for the vast majority of atmospherically derived ^{210}Pb that enters the water body. This atmospherically derived ^{210}Pb is often referred to as "unsupported ^{210}Pb" or "excess ^{210}Pb." It attaches to particles in the water column and is incorporated quickly into the sediments on the bottom. The stratigraphic distribution of this "unsupported" ^{210}Pb activity in the sediment, often measured as decays per minute per gram (dpm g^{-1}), is used to establish a core chronology, i.e. age/depth relations. Sediments also contain what is called "supported" ^{210}Pb, which is the ^{210}Pb derived from *in situ* decay of ^{226}Ra in the sediment. Dating models use only the "unsupported" ^{210}Pb fraction to determine sediment age, thus "supported" and "unsupported" ^{210}Pb must be distinguished in a sediment core.

^{210}Pb Dating Theory and Models

Pb-210 has a half-life of ~22.3 years. The decay constant "k" is equal to ln 2 ÷ 22.3 yr = 0.03114 yr^{-1}. As a general rule, it is possible to date materials with ages up to about 5-6 times the half-life of the radionuclide used for dating. Thus, ^{210}Pb can be used to date sediment in cores, extending back to about AD 1900, i.e. about 110 years ago. Beyond that age, the original amount of radioactive material has decayed away to the extent that there is too little to measure with accuracy. Unlike radiocarbon, which provides a date for a single carbon-bearing sample, ^{210}Pb activity is measured in contiguous samples from the sediment surface downward, and model dates provide a continuous depth/age relation over the past century. Several models have been developed for dating sediments using ^{210}Pb, two of which are presented here. The Constant Initial Concentration or CIC Model assumes that the ^{210}Pb activity in the surface sediment (i.e. the initial concentration) has always been the same through time. In other words, if bulk sedimentation rate increases, more ^{210}Pb is scavenged from the water column and settled on the bottom. With increasing sediment deposition, ^{210}Pb flux to the sediment changes proportionally, so that ^{210}Pb activity in surface deposits is always the same. The Constant Rate of Supply or CRS Model, however, assumes that the flux of ^{210}Pb to the sediment surface has remained constant through time. Increases in bulk sedimentation dilute the ^{210}Pb content in accruing sediments, and decreases in bulk sedimentation rate lead to greater ^{210}Pb content in sediments.

Selection of a model depends on many factors, among them the reservoir of ^{210}Pb in water, the residence time of water in the system, and the partitioning of ^{210}Pb between particulate and dissolved forms. We use the CRS model in Florida studies because we have found evidence that high sedimentation rates dilute surface sediment ^{210}Pb.

Expressing the CRS Model mathematically, the cumulative residual unsupported ^{210}Pb (A) below sediments of age t varies according to:

$$A_t = A_o \, e^{-kt}, \text{ where:}$$

A_o = total integrated unsupported ^{210}Pb (inventory) in the sediment column

k = the ^{210}Pb radioactive decay constant (0.03114 yr^{-1})

The age of sediment at depth x (preferably expressed as g cm^{-2}) is:

$$t_x = k^{-1} \ln (A_o A_x^{-1}), \text{ where:}$$

A_o = total integrated unsupported ^{210}Pb in the core (dpm cm^{-2})

A_x = integrated activity of ^{210}Pb below depth x ($\int^{\infty}_{x} C_x r_x d_x$) [dpm cm^{-2}]

because C_x = dpm g^{-1}, r_x = g dry cm^{-3}, and d_x = cm

The ^{210}Pb supply rate can be calculated as $P = k(A_o)$, where:

P = the supply rate to the sediments (dpm $cm^{-2}yr^{-1}$)

k = the ^{210}Pb decay constant (0.03114 yr^{-1})

A_o = the total integrated unsupported ^{210}Pb inventory (dpm cm^{-2})

This indicates that the total inventory of ^{210}Pb in the sediments, expressed on an areal basis (dpm cm^{-2}), is directly related to the rate of ^{210}Pb deposition on the bottom, expressed on an areal basis (dpm cm^{-2} yr^{-1}). Although many factors influence the rate of ^{210}Pb deposition, and a range of values has been recorded worldwide, most studies converge on a mean deposition rate of ~1.1 dpm cm^{-2} yr^{-1}, equivalent to a total integrated unsupported ^{210}Pb value of about 35.2 dpm cm^{-2}.

Methods of Measuring ^{210}Pb in Sediments

Alpha spectrometry can be used to count alpha decays of ^{210}Po. The method assumes equilibrium between ^{210}Pb and its granddaughter radionuclide ^{210}Po. The method is destructive and samples must be extracted in acid and plated on silver or copper planchettes before alpha counting. The method also requires "spiking" the extracted sample with a known quantity of ^{209}Po or ^{208}Po, which is measured to assess recovery (plating efficiency) for the sample. When dating by alpha spectrometry, supported ^{210}Pb activity is generally assessed by measuring samples at greater and greater depth, until the activities reach a constant, asymptotic value. This "constant" supported activity is then subtracted from total ^{210}Pb values measured at shallower levels in the core to calculate the "unsupported" (excess) ^{210}Pb activity at each depth. It is assumed that "supported" ^{210}Pb activity has remained constant through time. Alternatively, a separate assay can be done for ^{226}Ra, and supported ^{210}Pb activity can be computed from this measure assuming equilibrium between the two radionuclides.

Direct assessment of ^{210}Pb activity by low background gamma counting presents several advantages. The method is non-destructive, and ^{210}Pb, as well as ^{226}Pb daughters ^{214}Bi and ^{214}Pb are counted simultaneously, so that supported and unsupported ^{210}Pb activities are measured in the same sample on a level-by-level basis. Furthermore, one can use this approach to measure other radionuclides, such as anthropogenic ^{137}Cs, simultaneously, sometimes enabling an independent evaluation of the ^{210}Pb chronology.

Methods

Sediment-water interface cores were retrieved at three selected sites in Padgett Creek, Middle St. Johns River Basin. At each site, water depth was recorded and soft sediment thickness was determined by forcing metered metal rods through the deposits until hard bottom was reached. Soft sediment thickness was figured as the total depth from the water surface to hard bottom minus the water depth. Cores were taken using a piston corer designed to collect undisturbed sediments (Fisher et al. 1992). Four-foot-long polycarbonate core tubes, with a 3” OD and 1/8” wall thickness, were used for core collection. The mud-water interface cores were sampled at 4-cm intervals for ^{210}Pb dating. Cores were extruded upward into a tray attached to the core top and sediment was transferred to pre-weighed, labeled cups for transport to the laboratory.

In the laboratory, sediments for ^{210}Pb dating were weighed in their plastic containers and dried in a Kinetics Thermal Systems Dura-Dry II MP freeze drier. Samples were re-weighed to obtain percent dry mass and water content. Dried samples were ground in a mortar and pestle and transferred to labeled scintillation vials. A subsample from each depth was assessed for organic matter content by weight loss on ignition at 550 °C in a Sybron Thermolyne muffle furnace (Håkanson and Jansson 1983). We calculated sediment density or *rho* (g dry cm^{-3} wet) in each stratigraphic interval using the formula of Binford (1990):

$$p_X = \frac{D(2.5I_X + 1.6C_X)}{D + (1-D)(2.5I_X + 1.6C_X)}$$

where p_X is dry density (g dry cm^{-3} wet), x is depth in the sediment profile (cm), D is proportion of dry mass in wet sediment (i.e. dry mass/wet mass), I is the inorganic proportion of dry mass with density = 2.5 g cm^{-3} dry, and C is the organic proportion of dry material with density = 1.6 g cm^{-3} dry.

Remaining dry sediment was put into pre-weighed plastic Sarstedt tubes to a measured height of ~30mm. Tubes were re-weighed to obtain dry sample mass and sediment was sealed in the tubes with epoxy glue and allowed to equilibrate for at least 21 days. This permits establishment of $^{226}Ra/^{214}Bi$ and $^{226}Ra/^{214}Pb$ (supported ^{210}Pb) equilibrium within the tubes and permits us to use ^{214}Bi and ^{214}Pb activities as proxy measures of ^{226}Ra activity (supported ^{210}Pb activity) in the sediment. It is generally assumed that ^{226}Ra in the sediment is in equilibrium with ^{210}Pb (Brenner et al. 2004). Radium-226 then serves as a substitute variable, or proxy, for "supported" ^{210}Pb. We measured total ^{210}Pb activity and calculated unsupported ^{210}Pb activity for use in the CRS dating model as total ^{210}Pb minus supported ^{210}Pb (Appleby and Oldfield 1983). Samples were measured by direct gamma counting (Appleby et al. 1986, Schelske et al. 1994) using ORTEC Intrinsic Germanium Detectors connected to a 4096-channel, multi-channel analyzer. Unsupported ^{210}Pb was determined and dates and sediment accumulation rates were estimated with the CRS model (Appleby and Oldfield 1983, Oldfield and Appleby 1984). Cesium-137 activity was measured simultaneously in the gamma detectors in an effort to identify the peak period of atmospheric bomb testing *ca.* 1963 (Krishnaswami and Lal 1978) and the Chernobyl accident in 1986.

Results

Three sites were selected for retrieval of sediment cores. In the field, the coring locations were determined with a hand-held GPS unit. Coring locations were numbered 1-3 from east to west and latitude/longitude for the sites were as follows:

Site 1 (28° 52' 08.6"N, 81° 17' 10.9"W)

Site 2 (28° 51' 55.5"N, 81° 17' 57.4"W)

Site 3 (28° 51' 44.8"N, 81° 18' 29.4"W)

The relative positions of the coring sites are shown in Figure 1, and close-up images for sites 1, 2 and 3 are shown in Figures 2, 3, and 4, respectively. Site 1 was picked for its proximity to the I-4 overpass and residential development. Site 2 lies in the middle of the creek and is presumably the least disturbed site. Site 3 lies downstream from the spring run and dam.

Figure 1. Sediment coring sites 1, 2, and 3 (east-west) on Padgett Creek. Each site is indicated by a "pushpin." Image from Google Earth.

Figure 2. Sediment coring site 1, the easternmost site on Padgett Creek. The core site, near the I-4 overpass, is indicated by a "pushpin." Image from Google Earth.

Figure 3. Sediment coring site 2, the middle site on Padgett Creek. The core site is indicated by a "pushpin." Image from Google Earth.

Figure 4. Sediment coring site 3, the westernmost site on Padgett Creek. The core site, just east of the spring and dam, is indicated by a "pushpin." Image from Google Earth.

Coring was done on 27 January 2010. Water depth in Padgett Creek, spud depth (distance from the water surface to hard bottom), soft sediment thickness, and the length of the retrieved core are shown in Table 1. Water depth was shallow at all sites (0.45-1.05 m), indicating that sediments at the locations are probably subject to some disturbance from wind-generated and boat-generated waves. Whereas total soft sediment thickness was comparatively low at sites 1 and 3, 0.90 and 1.25 m, respectively, 3.4 m of soft sediment had accumulated at site 2. Cores retrieved varied in length from a low of 63 cm (site 1) to a high of 98 cm at site 2. Low organic content, and high sand/carbonate concentration impeded greater penetration of the core barrel.

Table 1. Water column depth, sediment thickness, and length of retrieved profiles at core sites 1-3 in Padgett Creek

Site	Water Depth (m)	Spud depth (m)	Soft Sediment Thickness (m)	Core Length Retrieved (m)

1	1.05	1.95	0.90	0.63
2	0.45	3.85	3.40	0.98
3	0.65	1.90	1.25	0.68

The sediment core collected at site 1 displayed very low organic matter (OM) content over most of its length (Table 2). With the exception of the 8-12 and 12-16 cm intervals, in which organic matter content was about 8% and 15%, respectively, the sediments consistently possessed <6% OM. The core displayed high proportion dry weight, much of it having values between 60 and 80%, associated with the high inorganic content of the sediment. The density (dry mass per unit wet volume) of the sediment was also relatively high, typically 1.0-1.6 g dry cm^{-3} wet below 24 cm, as expected for such highly inorganic deposits.

Table 2. Characteristics of the sediment core from site 1 in Padgett Creek

Interval Depth (cm)	Proportion Dry	Proportion Inorganic	Proportion Organic	Rho (g dry/cm^3 wet)	Cumulative Mass (g/cm2)
0-4	0.423	0.968	0.032	0.565	2.259
4-8	0.525	0.961	0.039	0.764	5.315
8-12	0.375	0.923	0.077	0.481	7.239
12-16	0.194	0.848	0.152	0.218	8.112
16-20	0.399	0.957	0.043	0.523	10.205
20-24	0.608	0.976	0.024	0.953	14.019
24-28	0.799	0.996	0.004	1.533	20.151
28-32	0.796	0.997	0.003	1.522	26.238
32-36	0.797	0.994	0.006	1.525	32.340
36-40	0.788	0.994	0.006	1.493	38.312
40-44	0.803	0.992	0.008	1.549	44.507
44-48	0.803	0.998	0.002	1.548	50.699
48-52	0.814	0.997	0.003	1.592	57.066
52-56	0.796	0.993	0.007	1.521	63.152
56-60	0.756	0.982	0.018	1.379	68.669

60-63	**0.646**	**0.948**	**0.052**	**1.045**	**72.850**

The core from site 2 contained sediments with greater organic matter content than was seen at site 1. Topmost deposits were about 36% OM (Table 3). With increasing depth, OM decreased steadily to 20-24 cm (18%), until the trend was reversed, and OM content rose to 24% in the section at 24-28 cm. Below that depth, OM declined to about 6-13% between 28 and 64 cm depth, only to rise again to values comparable to surface deposits (~34-36%) at 64-72 cm depth, and finally fall again to low values in the base of the section. Sediments with higher OM concentration are capable of holding more water and display lower fraction dry content, which ranged overall from about 6% to 44%. Whereas density was high in the core from site 1, 1.0-1.6 g cm^{-3} wet below 24 cm, the highest value attained in the core from site 2 was about 0.6 g cm^{-3} wet near the base of the section.

Table 3. Characteristics of the sediment core from site 2 in Padgett Creek

Interval Depth (cm)	Proportion Fraction Dry	Proportion Inorganic	Proportion Organic	Rho (g dry/cm^3 wet)	Cumulative Mass (g/cm2)
0-4	0.057	0.639	0.361	0.059	0.237
4-8	0.098	0.713	0.287	0.103	0.651
8-12	0.110	0.737	0.263	0.117	1.119
12-16	0.123	0.742	0.258	0.132	1.647
16-20	0.154	0.805	0.195	0.168	2.321
20-24	0.189	0.820	0.180	0.212	3.167
24-28	0.155	0.760	0.240	0.170	3.846
28-32	0.242	0.877	0.123	0.281	4.970
32-36	0.302	0.908	0.092	0.367	6.440
36-40	0.266	0.876	0.124	0.314	7.697
40-44	0.236	0.871	0.129	0.273	8.789
44-48	0.280	0.892	0.108	0.335	10.130
48-52	0.360	0.933	0.067	0.457	11.956
52-56	0.342	0.925	0.075	0.428	13.670
56-60	0.326	0.885	0.115	0.403	15.282
60-64	0.292	0.878	0.122	0.351	16.686

64-68	0.164	0.637	0.363	0.180	17.405
68-72	0.167	0.659	0.341	0.183	18.138
72-76	0.259	0.772	0.228	0.304	19.353
76-80	0.323	0.865	0.135	0.398	20.945
80-84	0.346	0.855	0.145	0.433	22.675
84-88	0.343	0.842	0.158	0.428	24.387
88-92	0.394	0.892	0.108	0.512	26.434
92-96	0.443	0.936	0.064	0.599	28.831
96-98	0.348	0.894	0.106	0.436	30.575

The sediment core from site 3 possesses deposits similar to those at site 2, at least in the uppermost part of the section. Topmost deposits contain about 28-30% organic matter, and then OM declines rather steadily with depth, to values consistently ≤7% below 24 cm. This trend is reflected in the proportion dry content, which is relatively low in uppermost, higher-OM sediments, and then increases with greater depth and the increase in the inorganic fraction of the sediment. Likewise, sediment density (g dry cm^{-3} wet) generally increases with depth in the top half of the core, and correlates positively with the proportion dry mass. Density never exceeds 1.0 g dry cm^{-3} wet. The different nature of the sediment from each site can be summarized by comparing the cumulative dry mass (g) below a square cm of surface at a depth of 60 cm in each core. Those values are 68.7 g cm^{-2} at site 1, 15.3 g cm^{-2} at site 2, and 26.8 g cm^{-2} at site 3.

Table 4. Characteristics of the sediment core from site 3 in Padgett Creek

Interval Depth (cm)	Proportion Dry	Proportion Inorganic	Proportion Organic	Rho (g dry/cm^3 wet)	Cumulative Mass (g/cm2)
0-4	0.075	0.715	0.285	0.079	0.314
4-8	0.089	0.700	0.300	0.093	0.688
8-12	0.120	0.734	0.266	0.128	1.200
12-16	0.160	0.824	0.176	0.177	1.907
16-20	0.155	0.820	0.180	0.170	2.586
20-24	0.183	0.853	0.147	0.205	3.405
24-28	0.291	0.930	0.070	0.352	4.811
28-32	0.426	0.947	0.053	0.570	7.091
32-36	0.623	0.983	0.017	0.992	11.058
36-40	0.430	0.954	0.046	0.577	13.366
40-44	0.336	0.934	0.066	0.419	15.043
44-48	0.519	0.974	0.026	0.752	18.050
48-52	0.472	0.964	0.036	0.657	20.678
52-56	0.533	0.976	0.024	0.782	23.807
56-60	0.514	0.958	0.042	0.740	26.768
60-64	0.522	0.953	0.047	0.756	29.793

64-68	**0.567**	**0.961**	**0.039**	**0.856**	**33.215**

The core from site 1 displayed very low total ^{210}Pb activity in uppermost (0-8 cm) samples, and these levels had no excess ^{210}Pb activity (Table 5). This is atypical for a constantly accruing deposit, but was not entirely unexpected given the very low organic matter content of the topmost sediments (<4%, see Table 2). The only sediment depths with measurable excess ^{210}Pb were from 8-20 cm depth. Pb-210 is particle reactive and adsorbs well to fine organic and inorganic particles. Deposits with sand and shell fragments display low ^{210}Pb activities. Modeled dates for this core are highly tentative and represent dates at the base of the interval. Although it is generally accepted that sediments lacking excess ^{210}Pb activity are >110 years old (i.e. more than about 5 half lives), lack of excess activity even in topmost deposits in this section makes this claim dubious. Total integrated excess ^{210}Pb at site 1 amounts to only 10 dpm cm^{-2}, about one third the value that is expected based on ^{210}Pb fallout rates measured at many sites in Florida. Measurable ^{137}Cs activity below the depth where unsupported ^{210}Pb activity was detected probably represents downward movement of highly soluble ^{137}Cs.

<u>Table 5. Radionuclide activities and dates in the sediment core from site 1 in Padgett Creek</u>

Depth Interval (cm)	Pb-210 Activity (dpm/g)	Ra-226 Activity (dpm/g)	Cs-137 Activity (dpm/g)	Excess Pb-210 Activity (dpm/g)	DATE at given Depth
0-4	0.7	1.1	0.0	0.0	2010.0
4-8	0.8	0.9	0.0	0.0	2010.0
8-12	3.9	1.8	0.2	2.1	1994.2
12-16	7.2	2.8	0.4	4.4	1964.0
16-20	2.3	1.2	0.1	1.2	
20-24	0.8	1.5	0.2	0.0	
24-28	0.2	0.4	0.1	0.0	

The sediment core from site 2 is the most reliably dated of the Padgett Creek profiles. Higher organic matter content in this core enabled efficient adsorption of excess ^{210}Pb to sediment particles and the distribution of excess ^{210}Pb in the core displays a reasonable decay curve (Table 6). The date at 32 cm depth marks approximately the turn of the last century (~1906). This rate of linear sediment accumulation, i.e. about 32 cm in a little more than 100 years (0.3 cm/yr), is consistent with measurements from many lake and wetland sites in Florida (Brenner et al. 1999a, b, 2001, 2006). Likewise, the total integrated excess ^{210}Pb at site 2 amounts to 26.9 dpm cm^{-2}, about the mean value expected based on ^{210}Pb fallout rates measured at many sites throughout the state.

Table 6. Radionuclide activities and dates in the sediment core from site 2 in Padgett Creek

Depth Interval (cm)	Pb-210 Activity (dpm/g)	Ra-226 Activity (dpm/g)	Cs-137 Activity (dpm/g)	Excess Pb-210 Activity (dpm/g)	DATE at given Depth
0-4	15.6	5.1	0.0	10.6	2006.9
4-8	14.2	4.3	0.2	10.0	2000.9
8-12	11.9	4.5	0.2	7.4	1994.9
12-16	12.5	4.4	0.2	8.1	1985.4
16-20	8.4	4.5	0.1	3.9	1977.7
20-24	6.5	4.0	0.0	2.5	1969.9
24-28	10.8	4.2	0.2	6.7	1941.3
28-32	5.4	3.5	0.1	1.9	1905.9
32-36	3.4	2.9	0.0	0.6	1852.6
36-40	2.9	3.6	0.2	0.0	
40-44	3.7	3.5	0.0	0.2	
44-48	2.4	3.6	0.0	0.0	
48-52	1.9	2.8	0.1	0.0	
52-56	2.2	2.8	0.0	0.0	

The core from site 3 also appeared datable. Although unsupported (excess) ^{210}Pb activity was generally low in the section, it did decline fairly uniformly with depth (Table 7). The total integrated excess ^{210}Pb at site 3 was 15.9 dpm cm^{-2}, intermediate between the rates recorded at sites 1 and 2. If the date at 20 cm (1931) is correct, then the mean linear sedimentation rate over the last ~80 years has been about 0.25 cm/yr, just slightly less that what was recorded at site 2 and also consistent with values measured in many Florida waterbodies.

Table 7. Radionuclide activities and dates in the sediment core from site 3 in Padgett Creek

Depth Interval (cm)	Pb-210 Activity (dpm/g)	Ra-226 Activity (dpm/g)	Cs-137 Activity (dpm/g)	Excess Pb-210 Activity (dpm/g)	DATE at given Depth
0-4	12.9	6.4	0.2	6.5	2005.6
4-8	15.4	6.8	0.0	8.6	1997.1
8-12	13.5	6.2	0.0	7.3	1983.2
12-16	8.9	4.4	0.6	4.6	1962.8
16-20	7.9	4.6	0.5	3.4	1931.2
20-24	3.8	3.9	0.4	0.0	
24-28	4.3	3.3	0.0	1.0	
28-32	2.1	2.9	0.1	0.0	

Discussion and Conclusions

Three cores from Padgett Creek provide insights into the nature of sedimentation in this area of the Middle St. Johns River Basin. Cores from sites 2 and 3 were dated using the CRS ^{210}Pb model, and yielded what appear to be reasonable dates. The core from site 1 had highly inorganic sediment, which does not bind ^{210}Pb effectively. If however, the modeled age at 16 cm (1964) is correct, then the site has accumulated 16 cm in about 46 years, for a mean linear sedimentation rate of ~0.35 cm/yr. This value is similar to the long-term average sedimentation rate calculated for site 2 (0.30 cm/yr) and site 3 (0.25 cm/yr). These long-term linear sedimentation rates are consistent with values recorded in many mid-lake sites and wetlands in Florida.

If dates from sites 2 and 3 are considered reliable over the last century or so, some general trends in sedimentation over time can be discerned. In both cores, 4-cm intervals that correspond to the earlier part of the 20th century represent about 30 years of accumulation, whereas more recent deposits show each 4-cm interval represents less than a decade of time. This recent, 3- to 4-fold increase in linear sedimentation rate is due, in part, to lack of compaction in near-surface sediments. This is a common phenomenon in all Florida water bodies, and with time such sediments consolidate. Nevertheless, calculations of mass accumulation rates at sites 2 and 3, suggest that there has been a modest rise in sedimentation at the sites. At site 2, it appears that more rapid accumulation was already established by the late 1960s, whereas at site 3, "modern" sedimentation rates appear to have been established in the last decade. Sites 2 and 3 display similar mass accumulation rates in their topmost (4 cm) samples, 75.4 and 71.1 mg cm^{-2} yr^{-1}, respectively. These values are consistent with very recent sedimentation rates recorded at many lakes in Florida (Brenner et al. 1999a, b, 2001) and lower than values measured in some Florida basins (Brenner et al. 2006). Site 1 is the most difficult to interpret because sediments in the topmost 8 cm were highly inorganic and possessed no measurable unsupported ^{210}Pb. These deposits may represent a recent "slug" of erosional material delivered to the site, as they overlie sediments with unsupported ^{210}Pb. Overall, sediment accumulation rates at sites 2 and 3 in Padgett Creek show modest increases over time, a phenomenon that has been noted in many Florida water bodies. Sedimentation rates at the two sites that yielded reliable dates show are consistent with deposition rates from other aquatic ecosystems in the state.

Table 8. Dates and associated mass sediment accumulation rates

at core sites 2 and 3 in Padgett Creek

Site 2 DATE at given Depth	Mass Sedimentation Rate (mg/cm2/yr)	Site 3 DATE at given Depth	Mass Sedimentation Rate (mg/cm2/yr)
2006.9	75.4	2005.6	71.1
2000.9	69.6	1997.1	43.9
1994.9	77.4	1983.2	37.0
1985.4	55.6	1962.8	34.7
1977.7	88.1	1931.2	21.5
1969.9	108.1		
1941.3	23.7		
1905.9	31.8		

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Appendix 1. Photos of Sediment Cores Retrieved from Padgett Creek

Photo 1. Frank Smith holds the core from site 1 in Padgett Creek

Photo 2. Close-up of the sediment core from site 1 in Padgett Creek

Photo 3. Close-up of the core from site 2 in Padgett Creek

Photo 4. Frank Smith holds the core from site 3 in Padgett Creek

Photo 5. Close-up of the core from site 3 in Padgett Creek