Final Report:

Mapping the Distribution and Vertical Extent of Muck in the Indian River Lagoon

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Nova Southeastern University
Oceanographic Center,
Dania Beach, FL

For the

St. Johns River Water Management District

EXECUTIVE SUMMARY

This report presents the results of a large-scale hydroacoustic survey conducted in Apr-May 2008. The objective of this study was to map the distribution and vertical extent of muck in the Indian River Lagoon, utilizing the data collected during a seasonal drift macroalgae survey. Indian River was surveyed from the Sebastian Inlet to its northernmost extent in the Titusville area. Banana River was surveyed from its convergence with the Indian River northward to the Federal Manatee Zone near Cape Canaveral. The survey vessel was navigated along pre-planned lines running east-west and spaced 200 m apart, except for when muck was indicated by the oscilloscope display, at which point a meandering path was adopted to demarcate the horizontal extent of muck. Hydroacoustic data were collected with a BioSonics DT-X echosounder and two multi-plexed digital transducers operating at 38 and 420 kHz. The vertical extent of muck was derived from the 38 kHz hydroacoustic data, which were processed with Visual Analyzer, a fish-finding software package produced by BioSonics Inc. The software was adapted to integrate echo energy below the water-sediment interface, and a set of post-processing algorithms were developed to translate the sub-bottom echo energy profile into continuous scale estimates of muck thickness. In this manner 500,000+ 38 kHz pings were translated into 88,927 geo-located estimates of muck layer thickness, down to a minimum bottom depth of 1 m. Ground-truthing was conducted in July 2008 at twenty sites within the Indian River. The predictions of muck layer thickness were found to be accurate over the ground-truthed range of 0-3m (r^2 = 0.882, SE=0.52m). The vertical distribution of acoustically-predicted muck demonstrated the tendency for muck to accumulate in deeper areas of the lagoon. For the case of Indian River (excluding navigation channels), muck was not detected in depths shallower than 1.4m and rare in the range of 1.4-2.2 m (only 3.6% of records had a predicted muck thickness greater than 0.5 m). The frequency of muck plateaued between 2.2-3.4 m (9.6%) before making a sharp rise to 82% in the range of 4-5 m. As expected, the mean muck layer thickness was significantly greater within the navigation channels (0.56 m) than outside of them (0.08 m). A significant latitudinal trend of muck thickness was detected within the Indian River navigation channels. The mean muck thickness decreased from 1.38 m in the northernmost Mims segment to 0.83 m in the adjacent TitusvilleA North segment before plateauing at approximately 0.4 m for the remainder of segments. Outside of the main ICW channels, 23 individual muck deposits were identified; 22 in the Indian River and 1 in the Banana River. Factors in descending order of co-occurrence were proximity to causeways or jetties, riverbed depressions, and proximity to shore and drainage channels. In conclusion, this study establishes that a single-beam acoustic survey is a cost-effective and accurate alternative for mapping the distribution and vertical extent of muck deposits in the shallow-water environment of the Indian River Lagoon. Moreover, the temporal consistency afforded by a digital transducer allows for direct and meaningful comparisons between successive surveys.

Team:

Principal Investigator: Bernhard Riegl, PhD
Associate Professor, Nova Southeastern University
Oceanographic Center
8000 N. Ocean Drive, Dania FL 33004
954-262 3671

Principal Surveyor: Greg Foster, PhD Candidate
Research Scientist, Nova Southeastern University
Oceanographic Center
8000 N. Ocean Drive, Dania FL 33004
954-262 3630

Surveyor: Kristi Foster, PhD Candidate
Research Scientist, Nova Southeastern University
Oceanographic Center
8000 N. Ocean Drive, Dania FL 33004
954-262 3630

INTRODUCTION

The primary objective of the 2008 large-scale hydroacoustic survey was to map the distribution and biomass of seasonal drift macroalgae. This was achieved by processing the 38 and 420 kHz data within BioSonics Visual Bottom Typer seabed classification software, merging the two frequencies into a single dataset, and creating a supervised training catalog. In this study only the raw 38 kHz data was utilized for muck detection. The greater power output of the lower frequency transducer increases signal penetration into bottom sediments, both in terms of distance and proportion. The vertical extent of muck was quantified from the vertical profile of sub-bottom echo return intensity (db), obtained by processing the raw 38 kHz data with Visual Analyzer, a fish-finding software package developed by BioSonics Inc. Visual Analyzer was designed to integrate echo intensities across the water column, but by over-riding the bottom-picking algorithm it was possible to integrate across the entire range of depths, i.e. below the water-sediment interface. A series of novel post-processing algorithms were developed to translate the output of Visual Analyzer into continuous scale predictions of muck layer thickness. For this study, muck is loosely defined as accumulations of black, clay-sized, organic-rich sediments. The muck sediments may be depositional or formed *in-situ* from the decomposition of submerged aquatic vegetation. These muck deposits are easily disturbed, and the resulting plume can create localized nutrient overloads and high turbidity, both of which are detrimental to the health of seagrass habitats. Knowledge of the distribution and abundance of muck deposits is important for understanding the factors governing muck deposition, and for optimizing dredging projects aimed at removing muck from the lagoon.

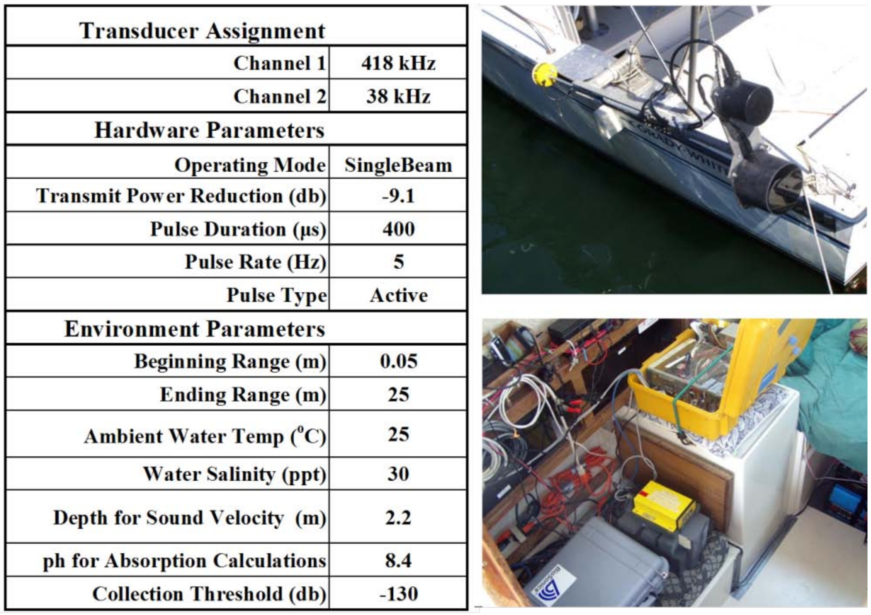
METHODS AND MATERIALS

Survey Area

The acoustic survey was completed between the dates of April 1 - May 21, 2008. Indian River was surveyed from its origin in the Titusville area (28.7664°) southward to Wabasso, just below the Sebastian Inlet (27.8743°) (Appendix A1). Banana River was surveyed from the Federal Manatee Zone near Cape Canaveral (28.4329°) southward to its convergence with Indian River in the Melbourne area (28.1571°). The survey vessel was navigated along pre-planned lines, running east-west and spaced 200 m apart, to a minimum depth of approximately 1 m. When the real-time oscilloscope display indicated the survey vessel was over muck, a meandering path was adopted to demarcate the horizontal extent of the muck deposit.

Sonar Equipment

The survey was conducted from a 7.5 m v-hull boat with a 0.5 m draft. Hydroacoustic data were acquired with a BioSonics DT-X echosounder and two multiplexed, single-beam digital transducers with full beam widths of 10^o (38 kHz) and 6.4^o (420 kHz), operated at 5-Hz sampling frequency and 0.4 ms pulse duration. The 38 kHz data were utilized for muck detection and the 420 kHz data for bathymetry. The Transmit Power Reduction (-9.1 db) option within the BioSonics Visual Acquisition software was used to reduce the onset of reverberation at the shallowest depths. The remaining Visual Acquisition settings are displayed in Figure 1. The two transducers were located on a swing-arm mounted to the gunwale. The GPS antenna was mounted directly above the transducers for optimal integration of acoustical and positional data strings. Global positioning data were collected with a Trimble Ag132 dGPS, differentially corrected against the WAAS signal to achieve positioning accuracies less than 0.9 m horizontal dilution of precision. The dGPS signal was interfaced with HypackMax© to provide real-time monitoring of vessel position with respect to the 2004 DOQQ images and pre-planned survey lines. To avoid turbulence-induced signal contamination, evident as a rolling disturbance on the real-time oscilloscope display, vessel speed was adjusted to maintain a net speed (vessel+drift) of approximately 4.5 knots.



Transducer Assignment	
Channel 1	418 kHz
Channel 2	38 kHz
Hardware Parameters	
Operating Mode	SingleBeam
Transmit Power Reduction (db)	-9.1
Pulse Duration (μs)	400
Pulse Rate (Hz)	5
Pulse Type	Active
Environment Parameters	
Beginning Range (m)	0.05
Ending Range (m)	25
Ambient Water Temp (°C)	25
Water Salinity (ppt)	30
Depth for Sound Velocity (m)	2.2
ph for Absorption Calculations	8.4
Collection Threshold (db)	-130

Figure 1. The critical settings used for the BioSonics DT-X echosounder (Table). Swing-arm in traveling position with 420 kHz (top) and 38 kHz (bottom) transducers and Trimble antenna (Upper Image). Inside V-Berth of survey vessel with (left-to-right) BioSonics DT-X echosounder, Trimble receiver, and acquisition PC (Lower Image).

Data Processing: 420 kHz Bathymetry

The 420 kHz hydroacoustic data were processed with BioSonics Visual Bottom Typer (v1) seabed classification software. The bottom-picks obtained from VBT were corrected for the depth of the transducer face below the waterline (0.61 m) and subjected to a series of filters. The first filter removed records with excessive differential depth between successive pings, typically caused by vessel roll. The next filter removed records with depth-picks less than 1.0 m. The last filter removed records exceeding the 99.5 percentile recorded within a particular survey tile, usually the result of grossly misshapen waveforms. A total 536,334 bottom-picks passed through the series of filters.

Data Processing: 38 kHz Muck Detection

The 38 kHz hydroacoustic data were processed with BioSonics Visual Analyzer 4 software. Originally developed for determining fish sizes and densities, the settings were manipulated in such a manner as to adapt the program from a water column profiler to a sub-surface profiler. Visual Analyzer integrates the echo intensity level (dB) for a grouping of pings, stratified by depth (strata) and segmented by time (reports). Each raw dt4 file was partitioned into 200 strata and 200 reports. The vertical extent of each stratum was (10m-0.5m)(200strata-1) = 0.04774 m per stratum. At the 5-Hz sampling frequency and 30-minute dt4 file cut-off time, each of the 200 reports was the average of approximately 45 pings [(5 pings s^{-1})(60 s min^{-1})(30min)/(200 reports) = 45 pings per report]. This yielded a total of 88,927 geo-located predictions of muck thickness. At the average survey speed of 4.5 knots, the distance travelled between reports, i.e. the spatial resolution, was approximately 20 m.

Before discussing the rationale by which information about the muck layer was extracted from the 38 kHz signal, a brief review of basic hydroacoustic operational theory is presented.

Single-Beam Hydroacoustic Theory

Single-beam acoustic ground discrimination systems are routinely used for benthic habitat assessment. Most studies have employed relatively high frequencies (100-200 kHz), limiting information to the surficial layer of the seabed. Lower frequency transducers, such as the 38 kHz model used in this study, produce a higher energy ping. Combined with low transmission losses (shallow depth) and unconsolidated sediments, the 38 kHz signal was able to penetrate several meters below the surface. Figure 2 displays vertical profiles of 38 kHz signal intensity acquired over (i) a typical Indian River sand bottom and (ii) a thick muck layer over a sand bottom. In both examples the water column is characterized by low signal intensity, as most suspended particles are too small and diffuse to interact with the sound waves (λ = 4.04 cm at 38 kHz). The water-sediment interface is evidenced by a sudden increase in echo intensity, because the greatest amount of energy is reflected back to the receiver as a specular return, i.e. a mirror-like reflection of the sound waves making normal-incident contact with the seabed. BioSonics EcoSAV plant detection software and Quester Tangent's IMPACT seabed classification software both use the maximum rate of rise as a primary criterion for their bottom-picking algorithms. In this study, the maximum rate of rise between strata was also used to define the bottom-pick. Locating the bottom within the output of Visual Analyzer was a critical step in the process of adapting it from a water-column fish-finder to a sub-surface profiler, i.e. from the design intent of looking up from the bottom to looking down from the bottom.

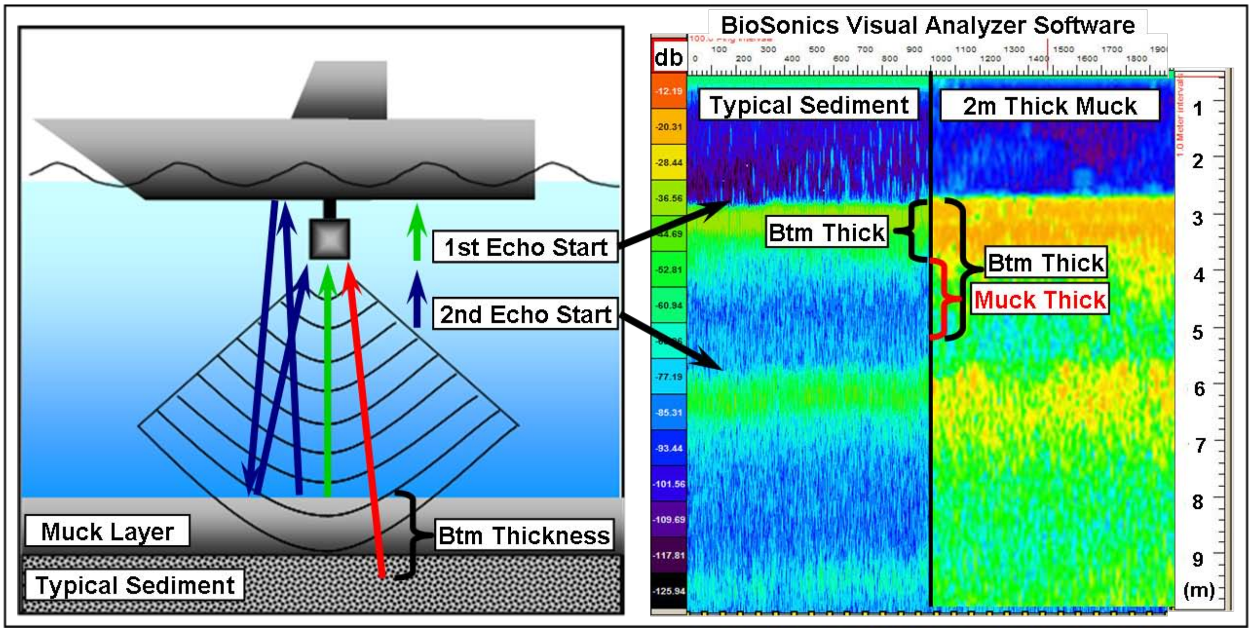


Figure 2. **(left) Specular return of first echo from the water-sediment interface (green arrow) and backscatter caused by signal penetration into muck layer (red arrow). The multi-path second echo (blue arrow) reflects off the air-water interface or vessel and back to the bottom before returning to the transducer. (right) BioSonics Visual Analyzer oscilloscope displays for a "typical" riverbed composed of sand-sized sediments and for a 2m thick deposit of muck. Muck thickness is computed as the difference between the measured acoustic bottom thickness and a constant value of "typical" acoustic bottom thickness.**

As the specular return diminishes, the intensity gradually tails off as the signal comes to be dominated by contributions from incoherent backscatter. The amount of time (or distance, via the speed of sound) it takes for the signal to decay is referred to hereafter as the acoustic bottom thickness. If the bottom surface is hard and smooth the echo return intensity will spike and quickly return to the "noise" baseline. If the bottom surface is rough and soft the echo return intensity will persist longer, due to a combination of increased backscatter and signal penetration into the sediment. These two scenarios are represented in the two oscilloscope displays of Figure 2.

A second echo return is created when the first echo reflects off the survey vessel or air-water interface and contacts the bottom a second time before returning to the transducer. For this reason, the second echo returns at approximately twice the depth of the first echo.

Quantifying Muck Thickness

The acoustic bottom thickness was calculated for each hydroacoustic record as the difference between the bottom depth (i.e. water-sediment interface) and the depth at which signal intensity dropped below -40 db. There is no physical significance to -40 db; the value was arrived at by reviewing a large number of catalog samples. The bottom depth was defined as the maximum rate of rise in echo return intensity, computed as the maximum value of (dB_n – dB_{n-1}) for strata 1 through 200. The vertical extent of the muck layer was then calculated as the measured acoustic bottom thickness minus a constant value of "typical" acoustic bottom thickness (Figure 3). The typical acoustic bottom thickness was obtained from a sub-set of ground-validated catalog samples collected for the drift macroalgae project. 45 catalog samples, consisting of a 30-90 second hydroacoustic file and a concurrent drop-cam video file, were selected on the basis that they were generally devoid of epibenthic biota and constituted of the sand-sized particles typical of the majority of Indian and Banana River riverbeds. 33 of the catalog samples were collected during the Apr-May 2007 BioSonics trial and the remaining 12 were collected during the 2008 lagoon-wide survey. The 45 catalog files were processed in Visual Analyzer, yielding a total of 500 records, which was reduced to 329 after removing records that appeared either irregular or as if the bottom was too soft. The acoustic bottom thickness of the remaining records averaged 18 strata, or 0.86 m (Figure 3). A multiple linear regression ($r^2 = 0.044$, n=329) demonstrated that the acoustic bottom thickness was independent of bottom depth (p=0.001) and year of acquisition (p=0.041), coded as -1/1. The latter observation is particularly important as a validation of the temporal consistency afforded by digital transducers, which will allow for direct and meaningful comparisons between successive surveys

Maximum Detectable Muck Thickness

The presence of the second echo imposed a constraint on the maximum vertical extent of muck that could be detected. If the transducer pings into muck, the signal intensity of the second echo will comingle with any of the first echo signal continuing to emanate from the muck layer. Since the second echo is known to start at twice the depth of the first echo, the maximum detectable muck thickness is equal to the depth at the start of the second echo, minus the sum of the bottom depth and the typical acoustic bottom thickness of 0.86 m (Figure 3, upper left). The maximum detectable muck layer thickness increases from 0.62 to 3.0 m as water column depth increases from 1. 5 to 4.0 m (Figure 3, upper right). The ratio of (detected muck thickness):(maximum detectable muck thickness) was calculated for each hydroacoustic report, to identify records where the reported muck thickness was constrained by water column depth.

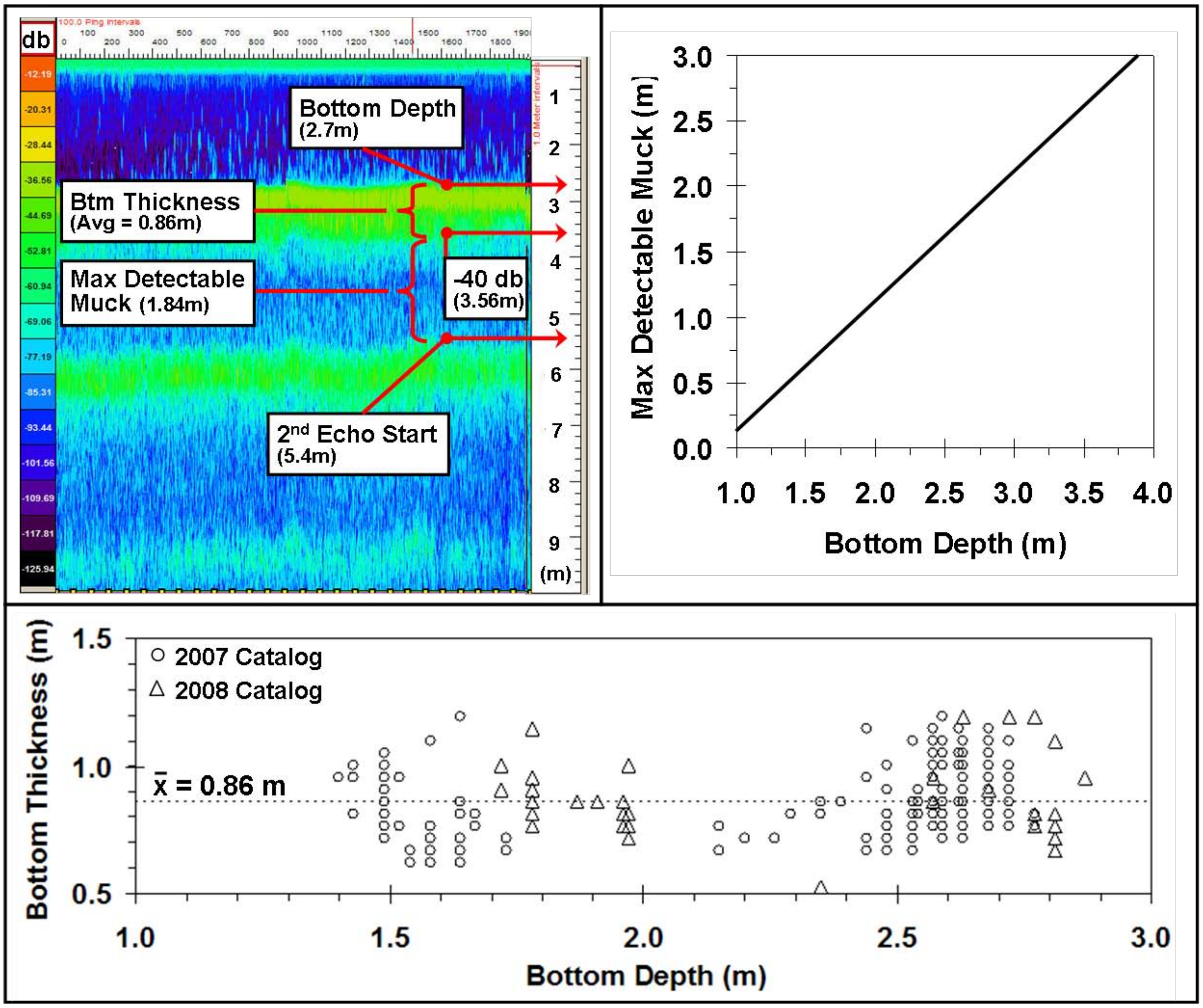


Figure 3. (upper left) BioSonics Visual Analyzer display of a "typical" riverbed. Maximum Detectable Muck Thickness is equal to [Start of 2nd Echo - (Bottom Depth + Typical Bottom Thickness)]. (upper right) Maximum Detectable Muck Thickness as a function of Bottom Depth. (bottom) Computation of the average Acoustic Bottom Thickness from 45 sonar catalog samples collected in the Indian and Banana Rivers.

Muck Metadata

Using the methods described above, the 500,000+ 38 kHz pings were post-processed into 88,927 geo-located records. A brief explanation of each field follows:

> MYDEPTH: The bottom-depth obtained from 38 kHz output of Visual Analyzer, equal to the lower-end of the depth range of the stratum at which the maximum rate of rise of signal intensity occurred.
>
> STRATA_TI: The gross acoustic bottom thickness in units of strata, computed as the number of strata (out of 200) below the bottom depth with a signal intensity greater than the threshold intensity of -40 dB.
>
> STRNRM_TI: The net acoustic bottom thickness in units of strata, computed as the gross acoustic bottom thickness minus the typical acoustic bottom thickness (18 strata, or 0.86 m).
>
> MUCKZ_M: The thickness of the muck layer in units of meters, computed as the product of the net acoustic bottom thickness (STRNRM_TI) and the stratum depth increment (0.04774 m).
>
> STRNRM_T_1: The ratio of (detected muck thickness):(maximum detectable muck thickness). A value of 1 indicates that all strata available for analysis were identified as muck, and that the actual muck thickness may be greater than reported.

Data Analysis

The 88,927 geo-located acoustic muck records were joined with a SJRWMD shapefile of Indian River Lagoon segments (IRL_Segments.shp) in ArcMap v 9.0. These records were further sub-divided by clipping to a SJRWMD shapefile of navigation channels (ICW.shp). The segment-average muck thickness was calculated as the simple average of records falling within a particular segment, either within or outside of navigation channels (any records acquired while demarcating muck deposits were removed, so as not to over-represent the abundance of muck). The vertical extent of muck was further described by computing the percentage of records falling into four ranges of thickness; 0.0-0.5, 0.5-1.0, 1.0-2.0, and > 3.0 m. The actual area surveyed within each segment was obtained by clipping the segment shapefile to a shapefile of the acoustic survey extent.

Polygons were drawn around individual muck deposits that (i) were located outside of the main ICW navigational channel, (ii) had an average acoustically-derived muck thickness greater than 0.5 m, and (iii) spanned multiple survey tracks (identified post-survey) or were demarcated during the survey (identified in real-time from oscilloscope display). The perimeter of each deposit was estimated using the trackplots of acoustically-derived muck thickness and the 420 kHz bathymetry as guides. The average muck thickness and bottom depth was computed for each deposit as the simple average of records falling within the polygon (records acquired while demarcating muck deposits included). Images of each of deposit were exported from ArcMap at a scale of 1:10,000. Factors suspected to relate to the spatial distribution of muck were noted, including; proximity and orientation to the main navigation channel, causeways and jetties, spoil areas, and drainage outlets, and the nearest distance to the shore (without crossing the main navigation channel).

Ground Truthing

The acoustically-derived muck thickness was ground-truthed on July 17, 2008, with the assistance of scientists from SJRWMD (J. Steward, L. Morris, and L. Hall). Twenty sites of varying predicted muck thickness (0 to 3 m) were selected for ground-truthing, located within three clusters along the Indian River. The vertical extent of the muck layer was measured by probing the riverbed with a tee-handled, open-ended PVC pipe, calibrated in 1.0 cm increments. The pipe was driven through the muck layer at a near-normal angle of incidence until the consolidated sediment lying beneath could be felt. After pulling the pipe back on deck a thick coating of muck remained on the PVC pipe. The depth of the muck layer was recorded as the maximum interface between clean pipe and muck. Three replicate probings were taken at each site. The vessel was re-positioned to the target coordinates and the actual GPS coordinates were recorded for each replicate, just as the pipe was driven into riverbed. The three acoustically-derived muck thickness records nearest to the center-point of the three replicates were queried in ArcMap. The ground-truthed and acoustically-derived muck thicknesses were reported as the simple average of the three probings and the three acoustic records, respectively. The performance of the acoustic method was evaluated by simple linear regression of the acoustic and ground-truthed averages, forcing the constant to zero.

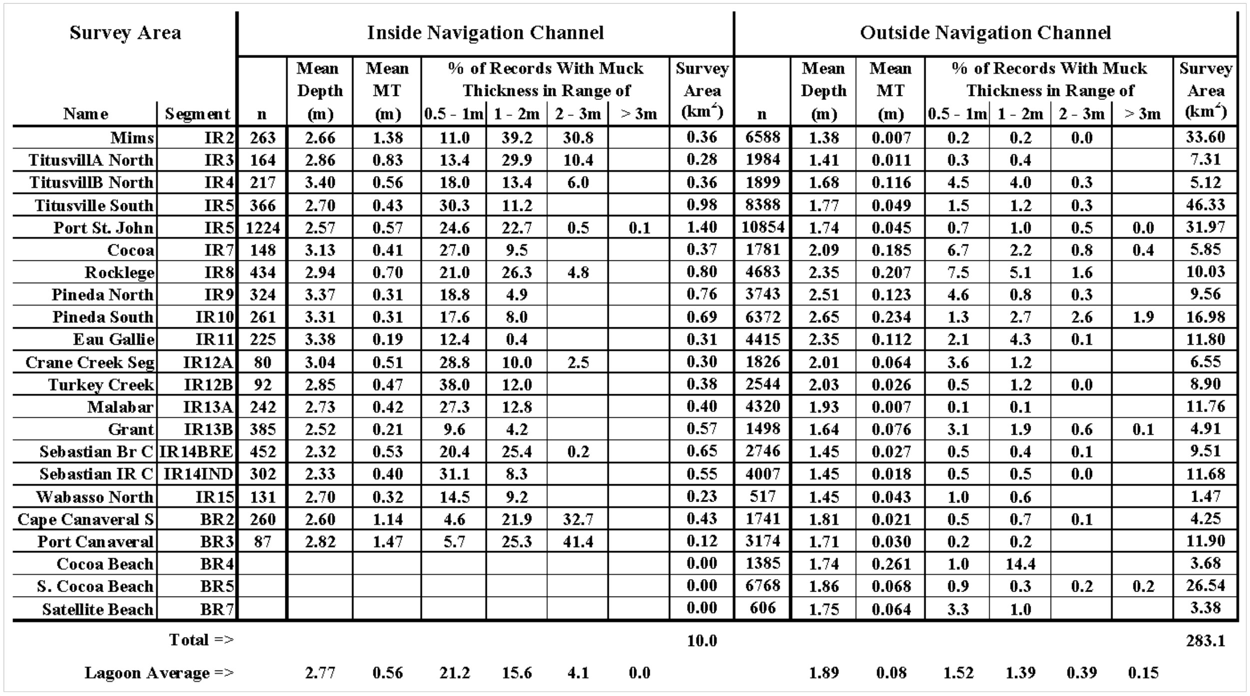
RESULTS

Spatial Distribution of Muck

The 500,000+ 38 kHz pings were post-processed into 88,927 geo-located estimates of muck thickness and plotted over the 2004 DOQQ's (Appendices A1-A5). The mean values of muck thickness by IRL segment, within and outside of navigation channels, are reported in Table 1 (off-track records acquired while demarcating muck deposits were removed, so as not to over-represent muck abundance). An independent samples t test was performed to assess whether a difference in mean muck thickness existed between (1) records from within the navigation channels versus records from outside of navigation channels, or (2) records from the navigation channels of Indian River versus records from the navigation channels of Banana River. The Levene test showed a significant difference between the variances of both comparisons, so the unequal variances version of the t test was used. The mean muck thickness was greater within the navigation channels (M=0.56m SD=0.62, n=5657) than outside (M=0.08m SD=0.30, n=81839), and the difference was found to be statistically significant ($p<0.001$, two-tailed). The 95% CI around the difference between these sample means ranged from 0.46 to 0.49m. The mean muck thickness within the navigation channels of Banana River (M=1.22m SD=0.97, n=347) was greater than that of Indian River (M=0.51m, SD=0.57, n=5310), and the difference was also found to be statistically significant ($p<0.001$, two-tailed). The 95% CI around the difference between these sample means ranged from 0.60 to 0.81m.

The author considers navigation channels to be ideal features for spatial comparisons of muck deposits. Their depth, orientation, and areal extent are generally consistent throughout the lagoon, making them a natural sediment trap from which to base comparisons. There was a significant latitudinal trend in muck thickness within the navigation channels of Indian River (Figure 4). The mean muck thickness was 1.38 m within the northernmost segment (Mims) and 0.83 m in the adjacent segment (TitusvilleA North), compared to an average value of 0.42 m for the remaining Indian River segments. This suggests that the watershed within the Mims segment is a major source of muck sediments for Indian River.

Table 1. **Summary of the muck layer thickness (MT) derived from the 38 kHz hydroacoustic signal, broken down by SJRWMD segments and by proximity to navigation channels. Excludes off-track records acquired while demarcating muck deposits.**



Survey Area		Inside Navigation Channel								Outside Navigation Channel							
			Mean Depth	Mean MT	% of Records With Muck Thickness in Range of				Survey Area		Mean Depth	Mean MT	% of Records With Muck Thickness in Range of				Survey Area
Name	Segment	n	(m)	(m)	0.5 - 1m	1 - 2m	2 - 3m	> 3m	(km^2)	n	(m)	(m)	0.5 - 1m	1 - 2m	2 - 3m	> 3m	(km^2)
Mims	IR2	263	2.66	1.38	11.0	39.2	30.8		0.36	6588	1.38	0.007	0.2	0.2	0.0		33.60
TitusvillA North	IR3	164	2.86	0.83	13.4	29.9	10.4		0.28	1984	1.41	0.011	0.3	0.4			7.31
TitusvillB North	IR4	217	3.40	0.56	18.0	13.4	6.0		0.36	1899	1.68	0.116	4.5	4.0	0.3		5.12
Titusville South	IR5	366	2.70	0.43	30.3	11.2			0.98	8388	1.77	0.049	1.5	1.2	0.3		46.33
Port St. John	IR5	1224	2.57	0.57	24.6	22.7	0.5	0.1	1.40	10854	1.74	0.045	0.7	1.0	0.5	0.0	31.97
Cocoa	IR7	148	3.13	0.41	27.0	9.5			0.37	1781	2.09	0.185	6.7	2.2	0.8	0.4	5.85
Rocklege	IR8	434	2.94	0.70	21.0	26.3	4.8		0.80	4683	2.35	0.207	7.5	5.1	1.6		10.03
Pineda North	IR9	324	3.37	0.31	18.8	4.9			0.76	3743	2.51	0.123	4.6	0.8	0.3		9.56
Pineda South	IR10	261	3.31	0.31	17.6	8.0			0.69	6372	2.65	0.234	1.3	2.7	2.6	1.9	16.98
Eau Gallie	IR11	225	3.38	0.19	12.4	0.4			0.31	4415	2.35	0.112	2.1	4.3	0.1		11.80
Crane Creek Seg	IR12A	80	3.04	0.51	28.8	10.0	2.5		0.30	1826	2.01	0.064	3.6	1.2			6.55
Turkey Creek	IR12B	92	2.85	0.47	38.0	12.0			0.38	2544	2.03	0.026	0.5	1.2	0.0		8.90
Malabar	IR13A	242	2.73	0.42	27.3	12.8			0.40	4320	1.93	0.007	0.1	0.1			11.76
Grant	IR13B	385	2.52	0.21	9.6	4.2			0.57	1498	1.64	0.076	3.1	1.9	0.6	0.1	4.91
Sebastian Br C	IR14BRE	452	2.32	0.53	20.4	25.4	0.2		0.65	2746	1.45	0.027	0.5	0.4	0.1		9.51
Sebastian IR C	IR14IND	302	2.33	0.40	31.1	8.3			0.55	4007	1.45	0.018	0.5	0.5	0.0		11.68
Wabasso North	IR15	131	2.70	0.32	14.5	9.2			0.23	517	1.45	0.043	1.0	0.6			1.47
Cape Canaveral S	BR2	260	2.60	1.14	4.6	21.9	32.7		0.43	1741	1.81	0.021	0.5	0.7	0.1		4.25
Port Canaveral	BR3	87	2.82	1.47	5.7	25.3	41.4		0.12	3174	1.71	0.030	0.2	0.2			11.90
Cocoa Beach	BR4								0.00	1385	1.74	0.261	1.0	14.4			3.68
S. Cocoa Beach	BR5								0.00	6768	1.86	0.068	0.9	0.3	0.2	0.2	26.54
Satellite Beach	BR7								0.00	606	1.75	0.064	3.3	1.0			3.38
	Total =>								10.0								283.1
	Lagoon Average =>		2.77	0.56	21.2	15.6	4.1	0.0			1.89	0.08	1.52	1.39	0.39	0.15	

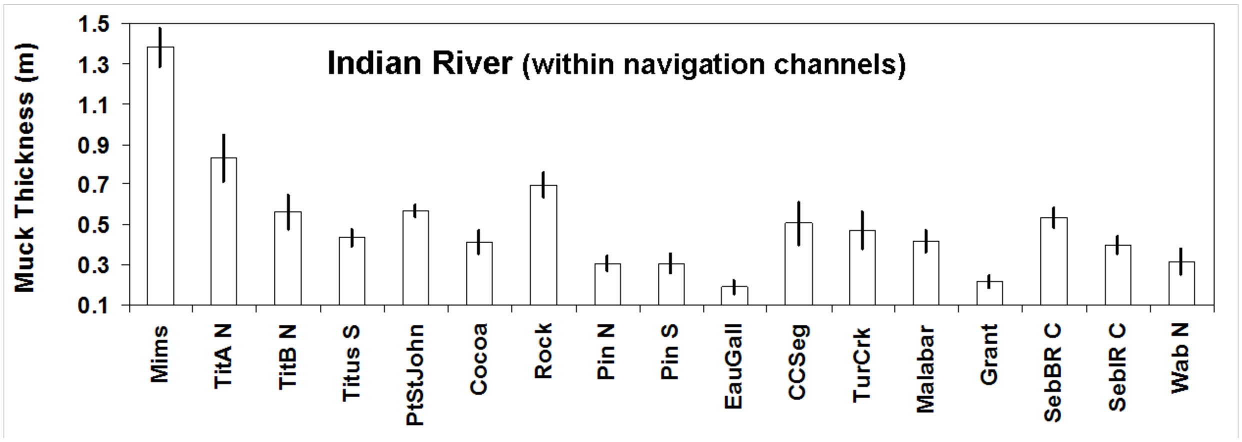


Figure 4. **Mean values of acoustically-derived muck thickness acquired within the navigation channels of Indian River, broken down by SJRWMD segments. Error bars = 95% CI.**

Vertical Extents of Muck

The vertical extents of muck deposits within the SJRWMD segments were further described by tallying the percentage of records falling within four ranges of muck thickness (Table 1). Within the navigation channels of Indian River, the Mims segment had the greatest percentage of records in the 2-3m category (30.8%), followed by the two adjacent segments TitusvillA North and TitusvillB North (10.4 and 6.0%, respectively). Of the 14 remaining Indian River segments, only four had any records in the 2-3m category, and only two were greater than 1%. The only two Banana River segments with navigation channels, Cape Canaveral S and Port Canaveral, also had high percentages of records in the 2-3m category, 32.7% and 41.4%, respectively.

Muck Deposits (Outside of Main Navigation Channels)

A total of 23 muck deposits were identified, demarcated and described (Table 2, Appendices B1-B2). 22 of the deposits were located in the Indian River, and of these, only one small deposit was located south of Crane Creek. 16 of the 23 muck deposits were in close proximity to a causeway or jetty; of these 10 were north of the causeway or jetty and 6 were south. 12 of the deposits were located in a depression, and 9 of these were also in close proximity to a causeway or jetty. Twelve of the deposits were encountered while making turns; 11 were within 500 m of the shore. 4 deposits were near drainage outlets, and only 2 deposits were in close proximity to spoil islands.

Table 2. Summary of muck deposits outside of main ICW navigation channel. Includes off-track records acquired while demarcating the horizontal extent of deposits.

Muck Deposit	Survey Area		Centerpoint of Muck Deposit		Avg Depth	Area	Avg Muck	Which Side of	Distance to Shore	In Pit?	Near Jetty/Causeway?			Near Spoil Area?		Near Drainage
Shapefile	Name	Segment	Lat	Lon	(m)	(km2)	(m)	ICW	(m)	Y / N	Y / N	Dir	(m)	Y / N	Dir	Outlet?
Muck01	TitusvillB North	IR4	28.6487	80.7916	2.06	0.0440	1.12	E	315	Y	Y	S	85	N		Y
Muck02	Titusville South	IR5	28.6185	80.7993	2.37	0.0363	0.90	W	220	N	Y	S	30	N		N
Muck03	Titusville South	IR5	28.5864	80.7948	2.41	0.0197	1.40	W	415	Y	N			N		N
Muck04	Titusville South	IR5	28.5611	80.7287	2.18	0.1550	0.88	E	765	N	N			N		Y
Muck05	Titusville South	IR5	28.5306	80.7622	2.86	0.0777	1.68	E	2900	Y	Y	N	265	N		N
Muck06	Port St. John	IR5	28.4854	80.7659	2.48	0.1458	1.30	W	340	Y	Y	S	420	N		N
Muck07	Port St. John	IR5	28.4676	80.7545	2.06	0.0251	0.88	W	620	N	Y	S	25	N		N
Muck08	Port St. John	IR5	28.4058	80.7332	2.47	0.0268	1.25	E	1265	Y	Y	N	210	Y	SW	N
Muck09	Rocklege	IR8	28.3553	80.7140	1.59	0.0364	0.60	E	545	N	Y	S	40	N		N
Muck10	Rocklege	IR8	28.3515	80.7206	2.15	0.0181	0.94	W	82	N	N			N		N
Muck11	Rocklege	IR8	28.3477	80.7130	2.15	0.0957	1.09	E	790	N	N			N		N
Muck12	Rocklege	IR8	28.3345	80.7085	2.80	0.0371	1.81	E	895	N	N			N		N
Muck13	Pineda North	IR9	28.2380	80.6715	2.01	0.0066	1.01	W	125	Y	N			N		N
Muck14	Pineda North	IR9	28.2081	80.6569	2.60	0.0064	1.64	W	445	Y	Y	N	200	N		N
Muck15	Pineda South	IR10	28.2041	80.6431	4.11	0.0528	3.14	E	375	Y	Y	S	135	N		N
Muck16	Pineda South	IR10	28.2004	80.6540	3.58	0.0266	2.58	W	525	Y	Y	S	400	N		N
Muck17	Pineda South	IR10	28.1355	80.6136	3.19	0.1173	1.33	E	990	N	Y	N	15	N		N
Muck18	Eau Gallie	IR11	28.1335	80.6101	2.66	0.2182	1.41	E	336	Y	Y	S	35	N		N
Muck19	Eau Gallie	IR11	28.0872	80.5854	2.58	0.0871	1.40	E	625	N	Y	N	5	N		N
Muck20	Crane Creek Seg	IR12A	28.0784	80.5928	2.41	0.2859	0.51	W	475	N	Y	S	15	N		Y
Muck21	Crane Creek Seg	IR12A	28.0842	80.5869	2.20	0.0307	1.25	E	1010	N	Y	S	60	N		N
Muck22	GRANT	IR13B	27.9674	80.5412	2.82	0.0090	1.25	W	100	Y	N			Y	SW	Y
Muck23	S. Cocoa Beach	BR5	28.2119	80.6321	4.03	0.0741	2.46	W	535	Y	Y	N	120	N		N
	Yes / North / East							12		12	16	6		2		4
	No / South / West							11		11	7	10		21		19

Muck versus Bottom Depth

It is reasonable to assume that muck tends to accumulate in the deeper areas of the lagoon, where it is less likely to be re-suspended by wind shear or boat traffic. Of the 23 muck deposits identified in the Indian and Banana Rivers, 12 were located in riverbed depressions (both man-made and natural). The tendency for muck to migrate towards sinks was further examined by quantifying the probability of encountering muck as a function of bottom depth, using the 69,000+ acoustic records from the Indian River (excluding navigation channels). This was accomplished by dividing the number of records with a measured muck thickness greater than 0.5 m by the total number of records within a particular range of bottom depth (Figure 5). The records were binned into 21 bottom depth increments, ranging from 1.0 to 5.0 m. Muck was not detected at bottom depths less than 1.4 m. In the range of 1.4 – 2.2 m, the proportion of records with muck thickness greater than 0.5 m was only 3.6%. The proportion plateaued at roughly 10% for bottom depths in the range of 2.2 – 3.4 m before beginning a sharp upward trend. In the range of 4- 5 m, an average of 82% of acoustic records were classified as having muck greater than 0.5 m thick. These trends support the idea that muck sediments tend to accumulate in the deeper areas of the lagoon.

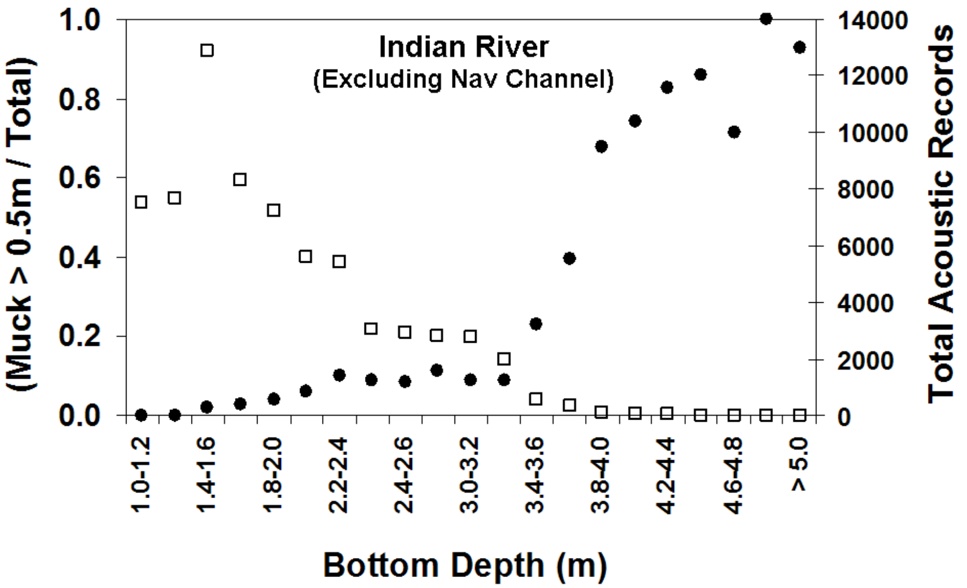
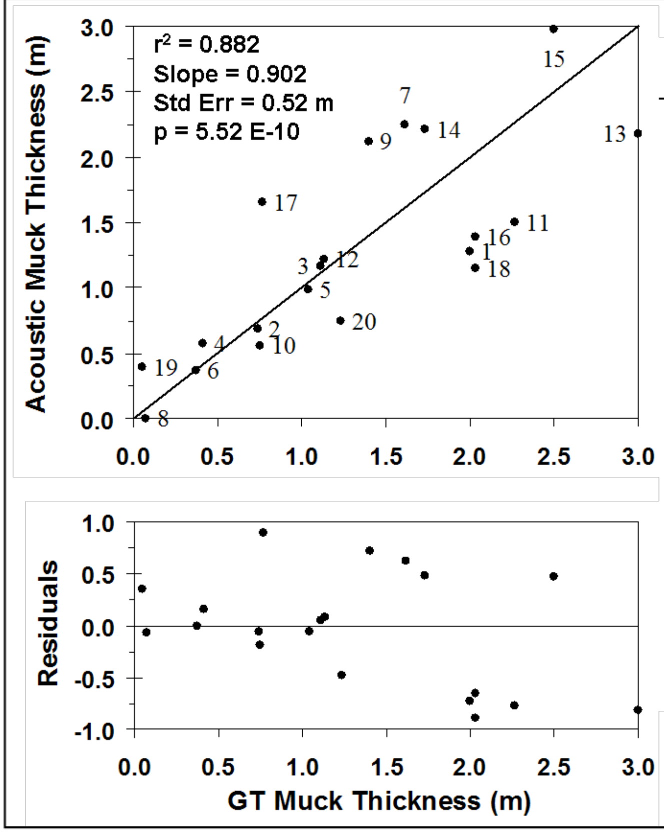


Figure 5. (●) Probability of encountering muck as a function of bottom depth, computed as the number of records with measured muck thickness greater than 0.5 m divided by the total number of records. (□) Total number of acoustic records within depth increments.

Ground-Truthing

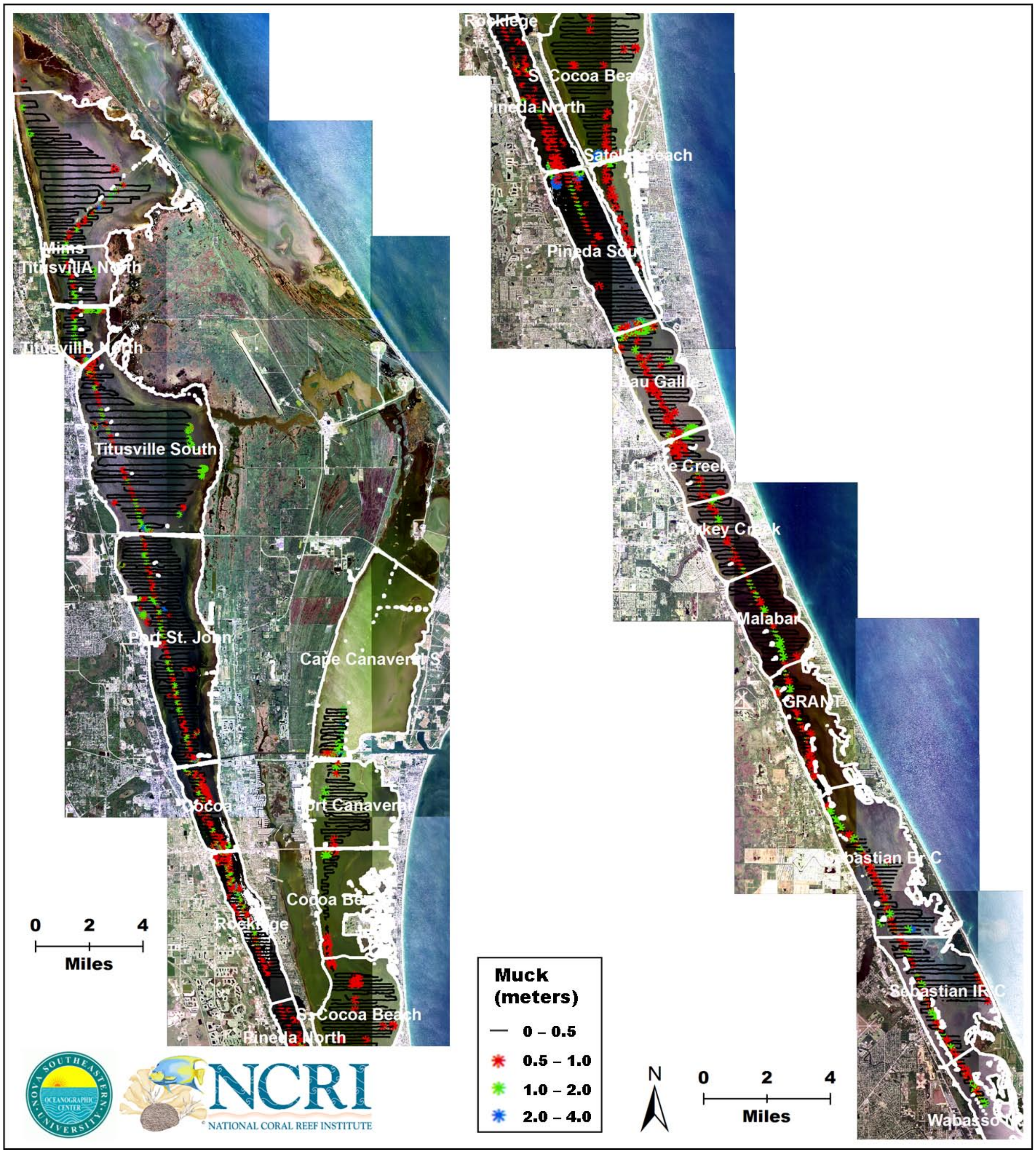
The acoustically-derived muck thickness agreed closely with ground-truthing (n=20, r^2 = 0.882, SE=0.52m), and only slightly under-predicted the thickness of the muck layer (b=0.902). Three of the five samples with the largest under-predictions (1, 11, 13) were constrained by bottom depth, i.e. the ratio of (detected muck thickness):(maximum detectable muck thickness) was close or equal to 1. In another of these samples (16), the muck layer was capped by a thin layer of highly compacted sand. This caused a large portion of the signal to be reflected off the surficial layer, and the subsequent under-prediction of muck thickness. Otherwise the agreement between predicted and ground-truthed muck thickness was satisfactory.



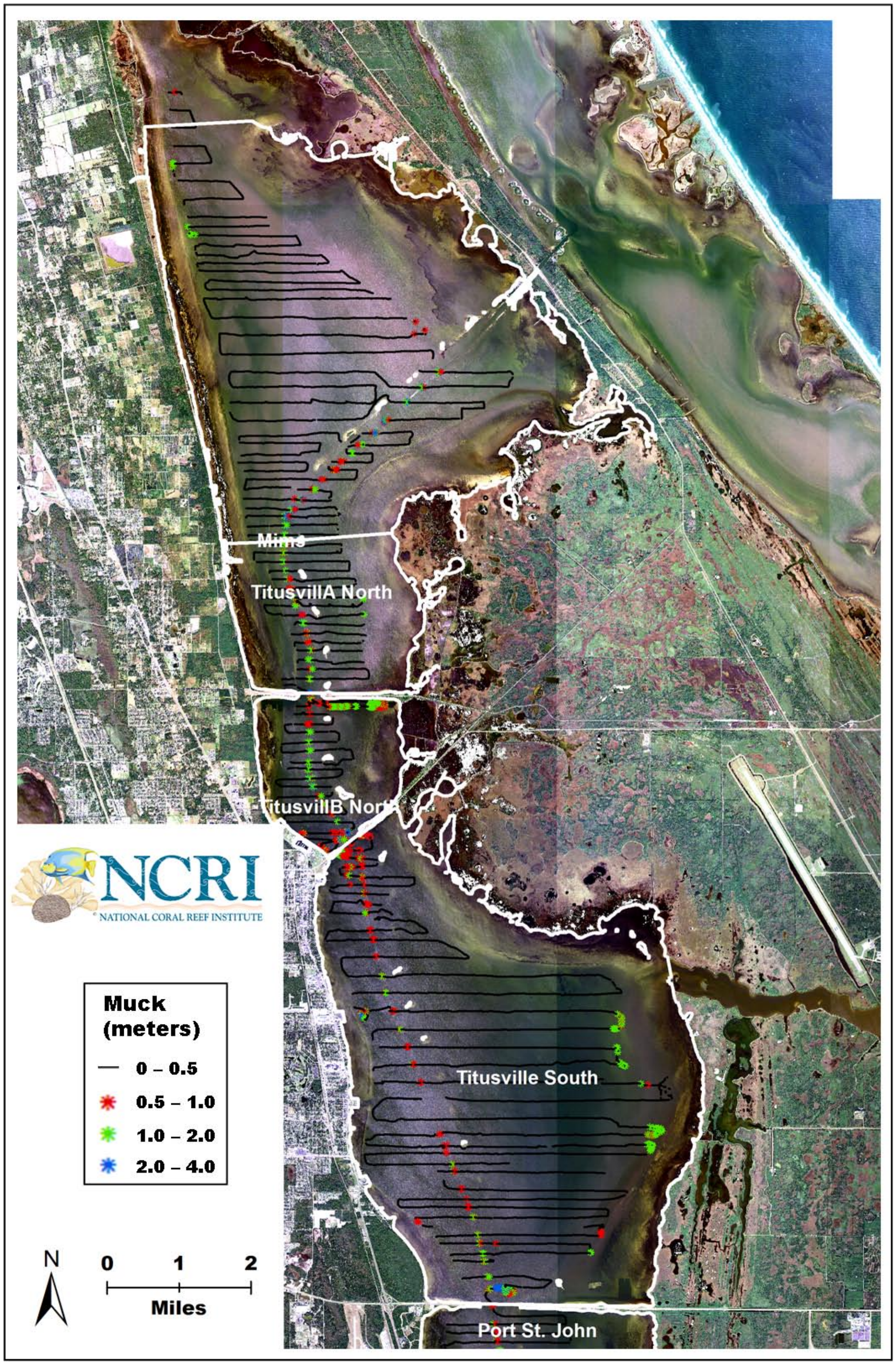
Sample	Sample Location Lat	Sample Location Lon	Depth (m)	Muck Thickness GT	Muck Thickness Acoustic	MT / MT_{Max}
1	28.3555	80.7149	2.15	2.00	1.27	0.988
2	28.3515	80.7201	2.18	0.74	0.68	0.525
3	28.3513	80.7204	2.26	1.11	1.16	0.829
4	28.3512	80.7211	2.37	0.41	0.57	0.374
5	28.3431	80.7130	3.50	1.04	0.99	0.374
6	28.3376	80.7117	3.67	0.37	0.37	0.130
7	28.3372	80.7099	3.13	1.62	2.24	0.993
8	28.3357	80.7066	0.85	0.08	0.00	0.000
9	28.3338	80.7082	2.97	1.40	2.12	1.000
10	28.3337	80.7076	2.28	0.75	0.56	0.390
11	28.2379	80.6713	2.36	2.27	1.50	1.000
12	28.2324	80.6624	3.20	1.13	1.22	0.521
13	28.2083	80.6571	3.04	3.00	2.18	1.000
14	28.2000	80.6543	3.21	1.73	2.21	0.940
15	28.1997	80.6539	3.94	2.50	2.98	0.963
16	28.0866	80.5886	3.09	2.03	1.38	0.618
17	28.0860	80.5898	3.17	0.77	1.66	0.717
18	28.0843	80.5954	2.07	2.03	1.15	0.948
19	28.0823	80.5943	1.91	0.05	0.40	0.299
20	28.0769	80.5932	2.25	1.23	0.75	0.540

Figure 6. Results of July 2008 ground-truthing of muck layer thickness, accomplished by probing bottom sediments with a calibrated probe. MT/MT_{Max} is the acoustically-derived muck thickness divided by the maximum-detectable muck thickness. Ground-truthed muck thickness reported as the average of three replicates. Acoustic muck thickness reported as the average of the three records nearest the centerpoint of three ground-truthing replicates.

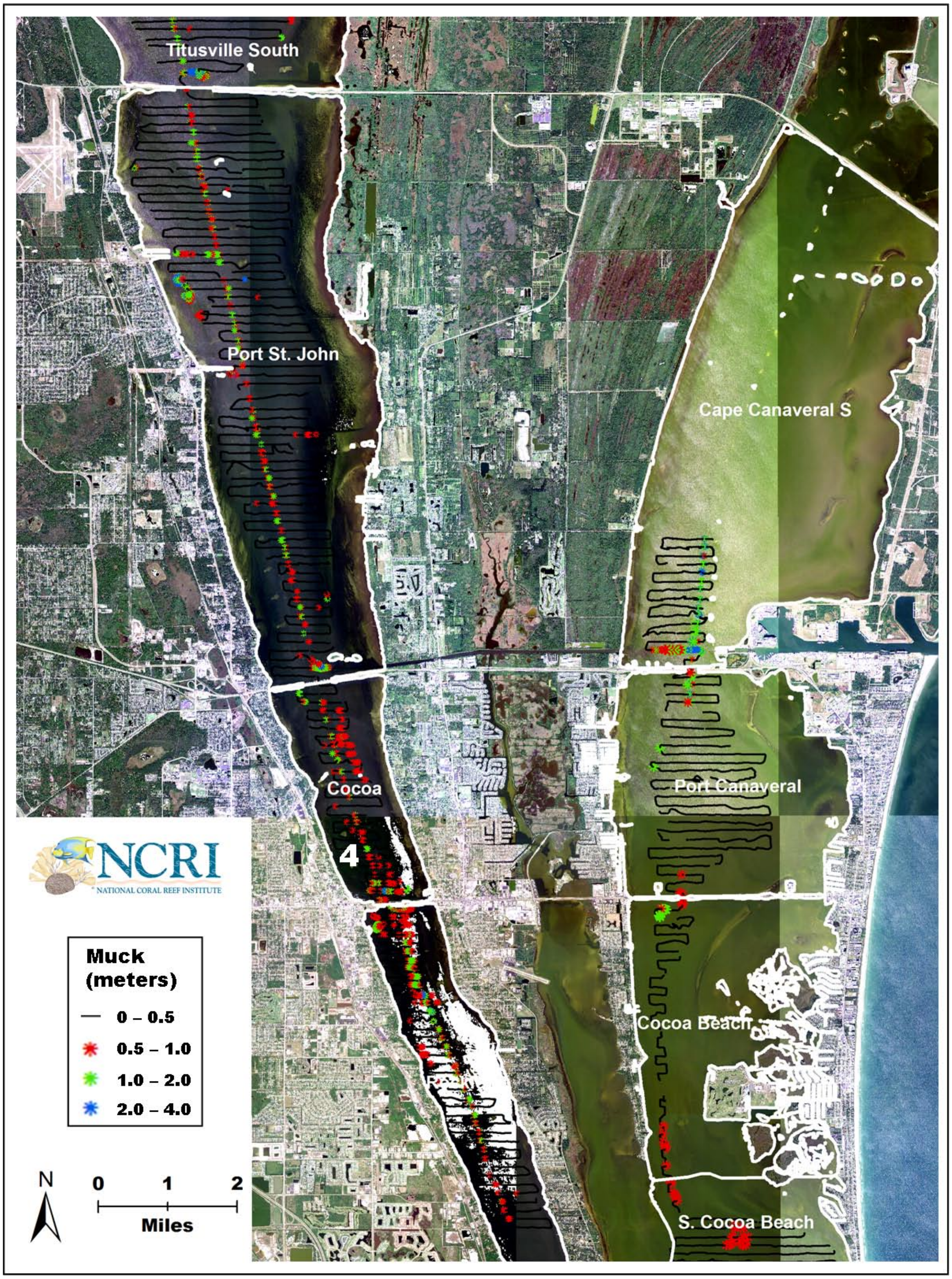
APPENDIX



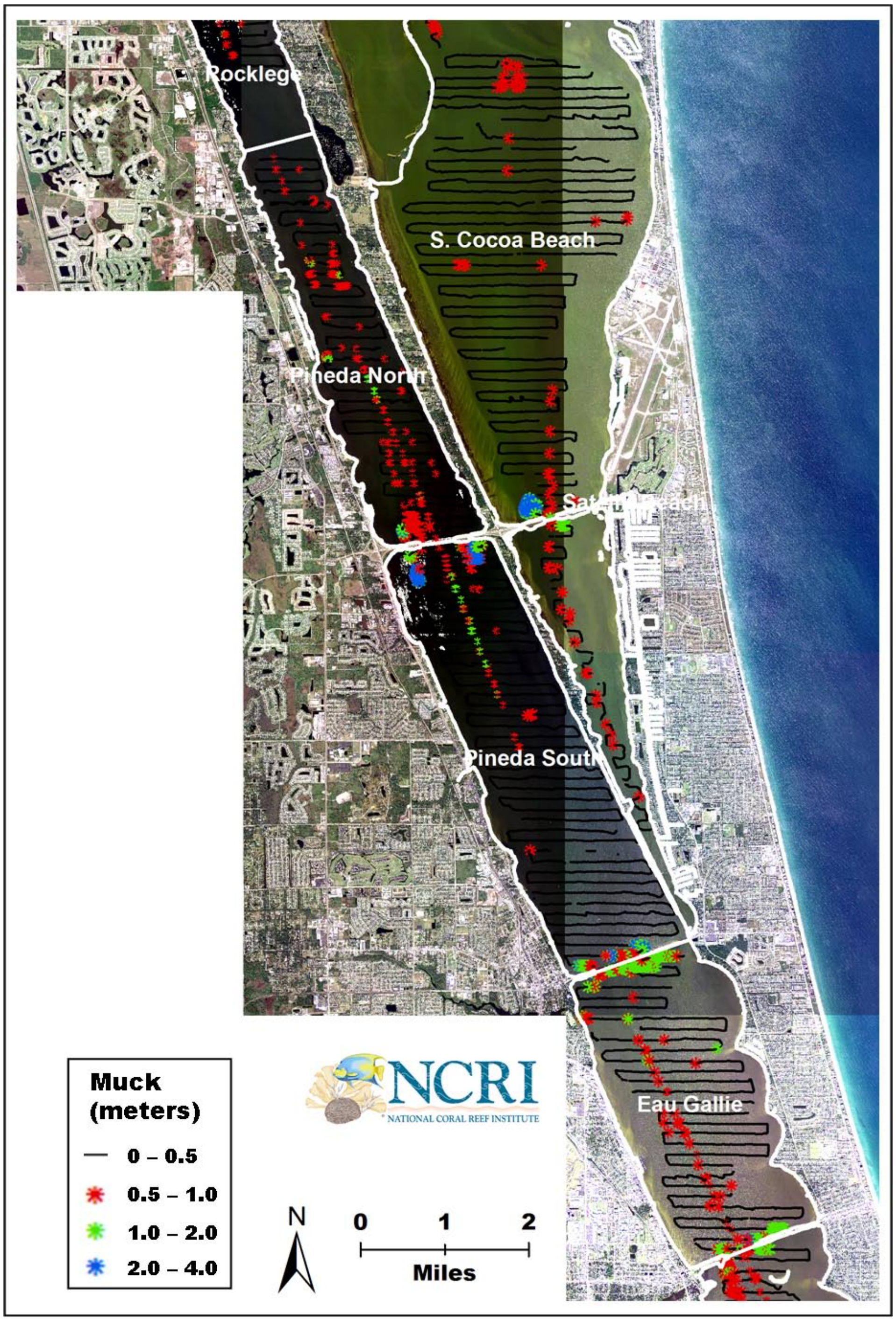
Appendix A1. Extent of the 2008 hydroacoustic survey, displayed as the trackplot of muck layer thickness predictions, which were derived from the 38 kHz hydroacoustic signal. The Indian River was surveyed from its origin in the Titusville area southward to Wabasso. The Banana River was surveyed from the Federal Manatee Zone near Cape Canaveral southward to its convergence with Indian River in the Melbourne area.



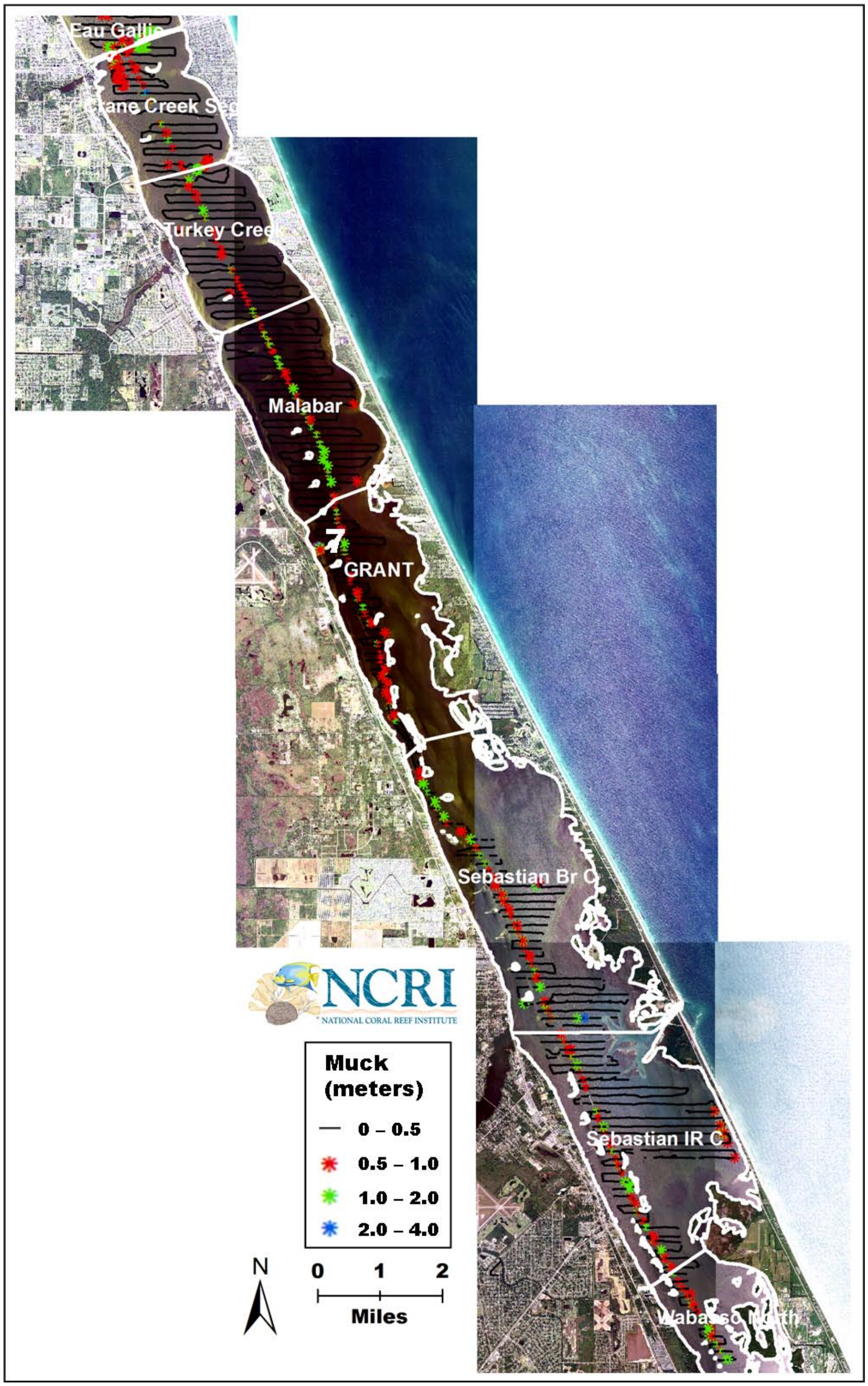
Appendix A2. **(Titusville area) Trackplot of the 2008 hydroacoustic survey. Records are displayed as predictions of muck layer thickness, derived from the 38 kHz hydroacoustic signal.**



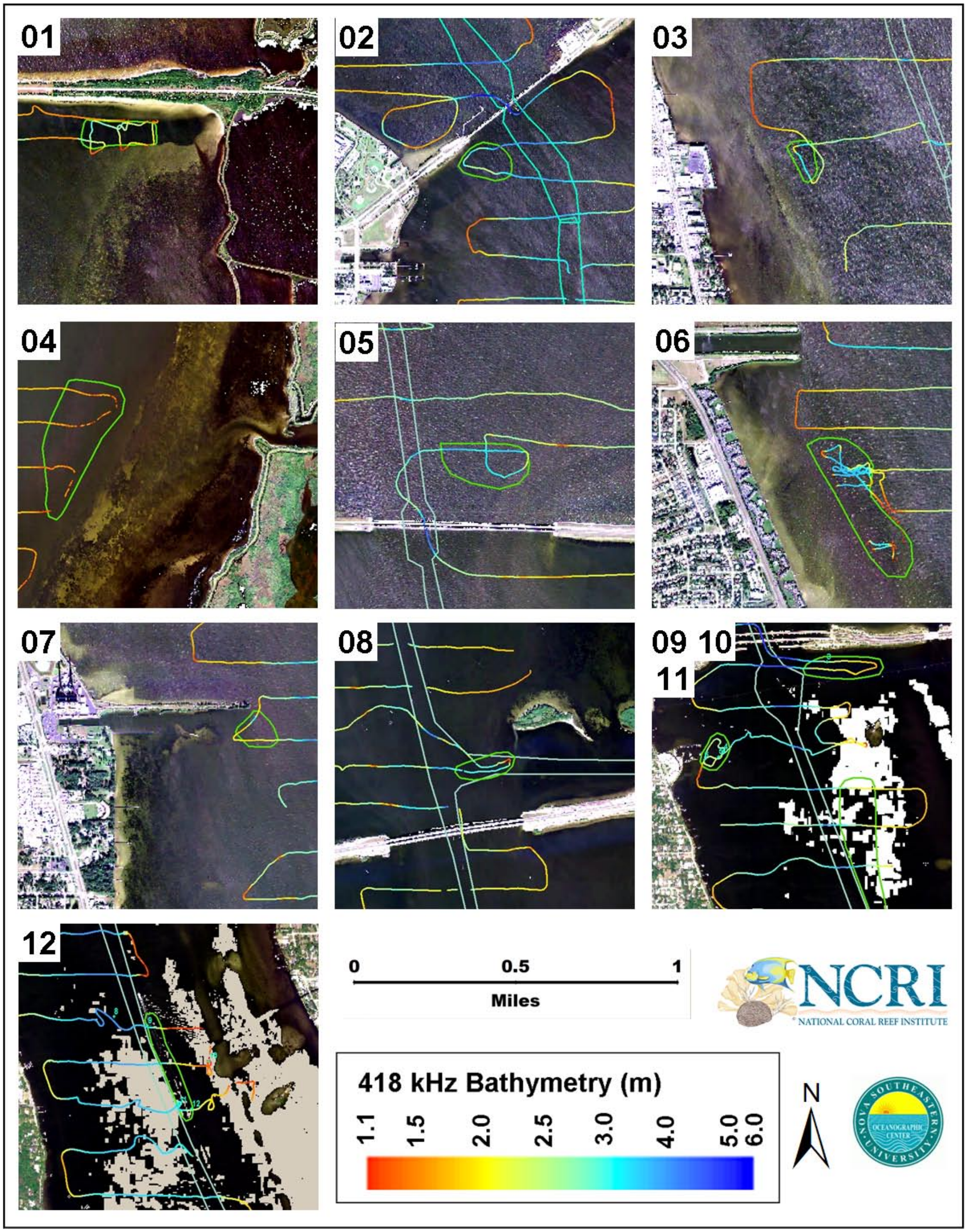
Appendix A3. **(Port St John to Cocoa Beach) Trackplot of the 2008 hydroacoustic survey. Records are displayed as predictions of muck layer thickness, derived from the 38 kHz hydroacoustic signal.**



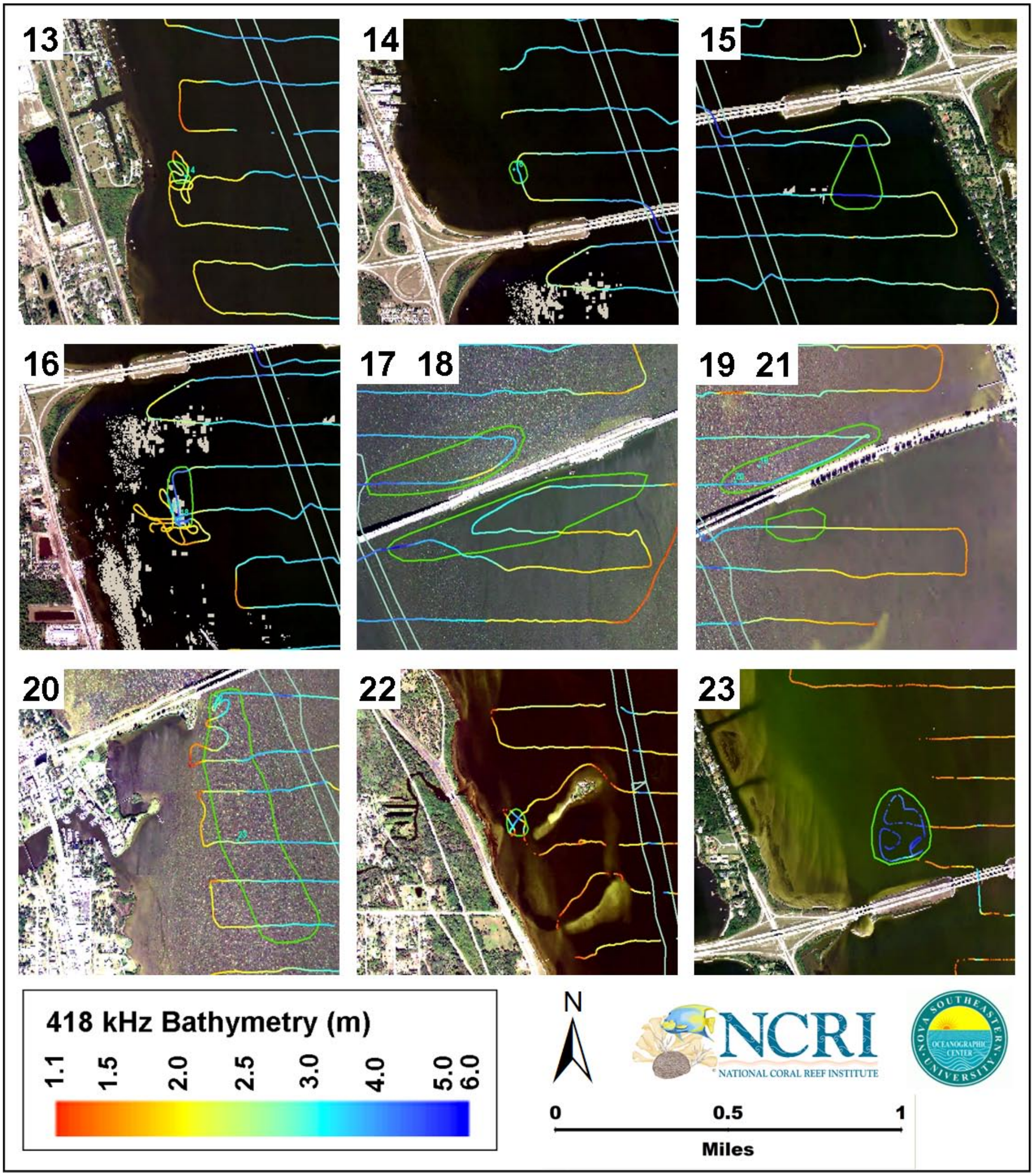
Appendix A4. (Rocklege to EauGallie) Trackplot of the 2008 hydroacoustic survey. Records are displayed as predictions of muck layer thickness, derived from the 38 kHz hydroacoustic signal.



Appendix A5. (Crane Creek to Wabasso) Trackplot of the 2008 hydroacoustic survey. Records are displayed as predictions of muck layer thickness, derived from the 38 kHz hydroacoustic signal.



Appendix B1. Demarcations (green polygons) of muck deposits (1-12 of 23) identified in the Indian and Banana Rivers, displayed over 2004 DOQQ's (map scale = 1:10,000). Also displayed are the trackplots of the 420 kHz bottom picks and the ICW shapefile (cyan polygons).



Appendix B1. Demarcations (green polygons) of muck deposits (13-23 of 23) identified in the Indian and Banana Rivers, displayed over 2004 DOQQ's (map scale = 1:10,000). Also displayed are the trackplots of the 420 kHz bottom picks and the ICW shapefile (cyan polygons).