Assessment of LIDAR for Simulating Existing and Potential Future Marsh Conditions in Casco Bay

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BACKGROUND

Light Detection and Ranging (LIDAR) topographic data has revolutionized the rapid collection and subsequent analysis of highly accurate coastal topography. LIDAR data can be collected over relatively large geographic areas, and has been typically used to support mapping of a variety of different shoreline features, along with post-storm impacts.

Previous LIDAR flights have been conducted along southern coastal Maine. These include flights for the NOAA Coastal Services Center in 2000 and 2004. The Maine Geological Survey (MGS) has used extensively available 2004 LIDAR data in conjunction with aerial orthophotographs to support a variety of its shoreline mapping efforts within the State of Maine, mostly in inspecting coastal features along the shoreline such as dunes and beaches (MGS links at references section). The RMSE vertical accuracy of the NOAA 2004 LIDAR was 6.7 cm, with an overall vertical accuracy of 13.4 cm, with a 2 meter point spacing (NOAA CSC, 2004).

MGS has also used the 2004 NOAA LIDAR and aerial imagery as part of a demonstration project to inspect the impacts of sea level rise on coastal floodplains and inundation levels (Slovinsky and Dickson, 2006). As part of this project, MGS simulated the impacts of sea level rise on tidal inundation levels, and also used tidal elevations as proxies for existing coastal wetland boundaries. For example, high marsh species, which dominate most of southern Maine marshes, typically exist between mean high water and highest annual tide tidal elevations, while low marsh species typically are found below mean high water and above mean sea level (Gehrels, 1994; Frey and Basan, 1985; Jacobson and Jacobson, 1989). These tidal elevations were calculated by MGS using NOAA NOS Tide Charts (NOS, 2009a), and benchmark data sheets for Portland, Maine (NOS, 2009b). LIDAR raster data was used to create simulations of both existing marsh conditions, and potential future marsh conditions after sea level rise.

2006 FEMA LIDAR Data

In 2006, the Federal Emergency Management Agency (FEMA) conducted aerial Light Detection and Ranging (LIDAR) flights in southern Maine to support Flood Insurance Rate Map remapping efforts for the FEMA Flood Plain Map Modernization Program. The data collection efforts were to provide FEMA compliant elevation, topography and contour maps of Cumberland and York County in Maine, in addition to bare earth (vegetation removed) topographic data of the coastal region of Cumberland and York County, Maine. The area of LIDAR coverage included communities that surround Casco Bay (Appendix A, Figure 1).

The LIDAR data had to meet certain standards to be determined adequate for FEMA use (FEMA, 2002), such as data needing to have a vertical Root Mean Square Error (RMSE) that does not exceed 15 cm (this is considered to be 30 cm accuracy at the 95% confidence interval, or about 1 vertical foot). Interestingly, metadata supporting the FEMA LIDAR listed an 18.5 cm RMSE for the bare earth data, or an overall 37 cm, which is outside listed standards.

The LIDAR topographic data, including TINs, bare earth grids (.xyz format files), and first and last return raw .xyz format files, were provided to the Maine Office of

Global Information Systems (MEGIS) by the FEMA contractor; MEGIS provided the LIDAR data to MGS at our request.

PROJECT PURPOSE

Because of potential inaccuracies in the 2006 LIDAR data as evidenced by the higher than standard RMSE and overall vertical accuracies, MGS was requested to conduct field investigations to compare LIDAR elevation data with field recorded Real Time Kinematic Global Positioning (RTKGPS) data collected at specific field sites. Subsequent comparisons between the LIDAR and groundtruthing RTK data could help determine whether or not the 2006 FEMA data was adequate for using tidal elevations to simulate existing marsh surfaces within select locations, and conducting subsequent mapping simulations of the potential impacts of sea level rise on those marsh surfaces.

METHODOLOGY

Real Time Kinematic Global Positioning System Surveys

With guidance from staff at CBEP, MGS selected two separate marsh areas for groundtruthing studies within Casco Bay, and received data from CBEP for a third location as part of its efforts. The study areas were selected to coincide with available FEMA LIDAR data, and were meant to cover different geographic regions of Casco Bay. They included:

1. finger marsh system at Cousins River, Yarmouth,
2. fringing marsh system at Back Cove, Portland; and
3. finger marsh system at Thomas Bay, Brunswick

The locations of the different study areas are provided in Figure 2.

At all field sites, GPS data was collected using Ashtech Z-Xtreme RTKGPS rover and base units with Ashtech Geodetic IV antennae and Tripod Data Systems (TDS) SurveyPro software and stored on a TDS Ranger data collector. HDOP and VDOP (horizontal and vertical dilution of precision) values were monitored in the field to ensure that values, to the maximum extent practicable, remained between 1 and 2 (ideal to excellent), and not record values above 3 (good), if at all possible. These grades of precision are required for highest or most demanding data needs. Data was transferred to PC via TDS SurveyLink software into formats compatible with GIS analysis. Raw GPS data was stored in SurveyLink proprietary (.RAW) formats.

GPS points were converted to UTM NAD83 Zone 19 (GEOID99 orthometric elevations were converted to GEOID03 orthometric elevations using the geoidal separation between the 2 geoids for the 2 study locations provided from the NOAA National Geodetic Survey (2009)). Thomas Bay, Brunswick GPS data was provided in GEOID03.

Cousins River, Yarmouth

There were several goals in undertaking a field study at the Cousins River site in Yarmouth. This study was considered a "pilot" in determining whether or not the LIDAR datasets could be used for successfully mapping existing marsh features and subsequently simulating the potential impacts of sea level rise. In that regard, our goals for the study were to:

- identify and map the extent of the Highest Annual Tide (HAT, 6.4 ft NAVD), which occurred on January 12, 2009 and reached a verified elevation of 6.56 ft NAVD;
- capture additional elevation data of the existing marsh surface while in the field;
- compare the field identified HAT with that derived from 2006 FEMA LIDAR data; and
- compare field measured marsh elevations with those extracted from LIDAR topographic data.
- compare the horizontal spatial difference between the HAT derived from LIDAR and the field mapped HAT.

In order to meet the first goal, field studies were conducted during early January, 2009, under difficult conditions, including deep snow and extensive ice cover on both upland and marsh surfaces. Horizontal and vertical survey control, along with base point establishment, was completed using numerous survey benchmarks within the area. Control work and base point setting was completed from January 9 through January 12, 2009. Due to snow, ice and stormy weather conditions, field GPS data was collected on January 13, 2009 – a day after the higher tide was measured. However, field efforts needed to be undertaken as close to the time of highest tide regardless of field conditions in order to capture the higher tidal event. Data was collected on a cold, windy day with considerable cloudiness.

Verified tidal data available from NOAA CO-OPS showed that the high tide reached an elevation of 6.56 ft NAVD at 11:42 am on January 12, 2009 (Image 1, following page in text). This was slightly higher than the predicted HAT, which was 6.4 feet (based on Prince's Point, Yarmouth; Dickson, 2009).

Field data collected included the demarcation of the "wet-dry" line, which marked the extent of the HAT from January 12, 2009, on both the north and south sides of Interstate 295, in addition to elevation data along the high marsh surface on the northern side of I-295.

Although difficult to continuously delineate due to snow and ice cover and ice rafting, there was a notable wet-dry line observed in the field that could be followed somewhat consistently during field efforts, especially on the south side of I-295. On the north side, field definition of the boundary was more difficult. Examples of the visible wet-dry line representing the limits of the HAT are shown in Photographs 1 and 2.

Marsh elevations were also recorded, to the maximum extent practicable. The ice surface was too thick to break through on a consistent basis, so random points were recorded at locations where there were apparent holes in the ice, or where the

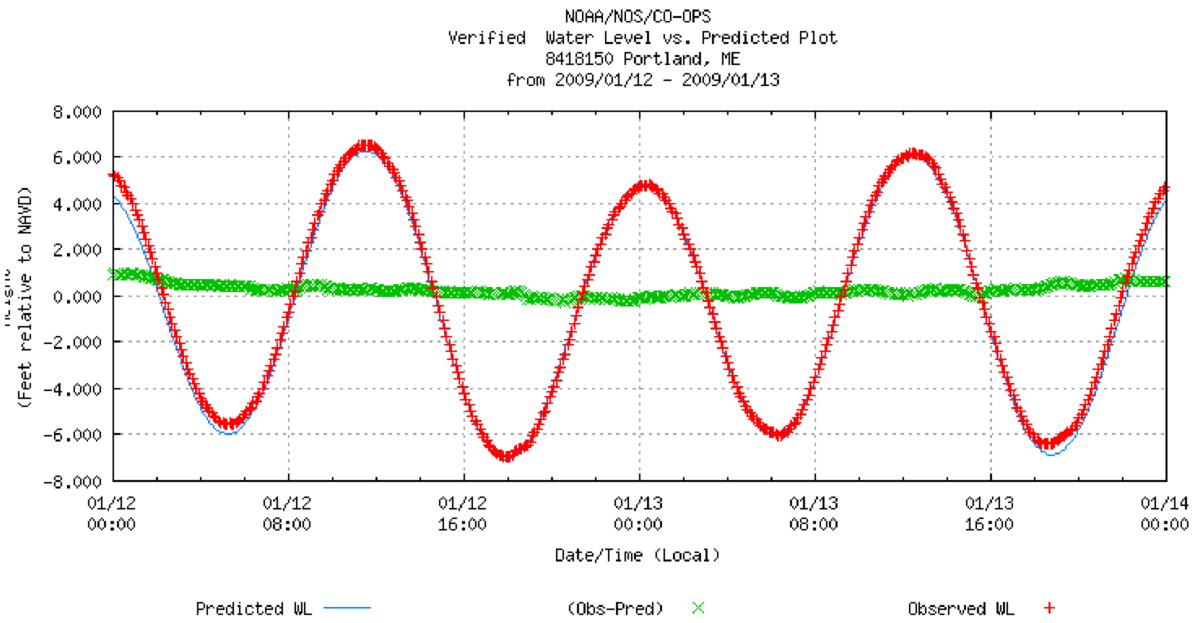

Image 1. Verified tidal data (observed vs. predicted) for 1/12-1/13/2009. The tide reached 6.56 ft at 11:42 am on 1/12/2009, and left a distinct mark on ice and snow. Data from NOAA CO-OPS, http://tidesandcurrents.noaa.gov

survey pole could be punched through to the frozen marsh. It was noted that GPS signal quality varied during the survey, especially adjacent to tree-lined uplands.

A total of 118 GPS points were collected to define the field extent of the HAT, while an additional 182 points defined the elevation of the high marsh, and 43 points were collected to inspect elevations of the "low marsh". GPS signal quality was relatively good, but not ideal. The resulting data points for all surveyed elevations are shown overlain on 2001 aerial orthophotographs (MEGIS, 2001) in Figure 3.

Back Cove, Portland

The field study at Back Cove was undertaken to inspect the elevations of an "urban" marsh. Back Cove has a relatively large area of fringing marsh along Baxter Boulevard, and low marsh comprises a much higher percentage of the marsh than at the Cousins River site. The purposes of the study here included:

- identify and map in the field the high marsh-low marsh boundary;
- capture additional elevation data of the existing marsh surface and some surrounding uplands;
- compare the field identified boundary between the high and low marsh vegetation with LIDAR derived mean high water (4.21 ft NAVD);
- compare field measured marsh elevations with those extracted from LIDAR topographic data.

Horizontal and vertical survey control, along with base point establishment, was completed using numerous survey benchmarks within the area. Control work and base point setting was completed in late August 2009, and field GPS data was collected on September 2, 2009.

Photograph 1. View of definitive wet-dry line on the south side of I-295 which was used to establish the limits of the highest annual tide. Photo by P.A. Slovinsky, 1/13/2009.
Photograph 2. View of wet-dry line between upper marsh and uplands on a section of the north side of I-295, which was harder to delineate in some areas. Photo by P.A. Slovinsky, 1/13/2009.

Field data collected included the demarcation of the boundary between the high marsh (dominated by *Spartina* patens and *Juncus* gerardi) and low marsh (dominated by *Spartina* alterniflora). In some areas, the boundary was difficult to delineate where pockets of low marsh incurred into dominant areas of high marsh; in these areas, best field judgment was used. The boundary between these two marsh types is generally approximated by the "mean high water" line (calculated to be 4.21 ft NAVD in 2009 using data from NOAA CO-OPS and the Portland tide gauge; Dickson, 2007; 2009).

We also collected elevation data along shore perpendicular transects, which started in the uplands (usually across Baxter Boulevard), and continued into the low marsh. Due to softness of the marsh surface, it was impossible to continue surveying into lower portions of the low marsh and onto the adjacent mudflats.

GPS quality during the survey was very good. A total of 212 GPS points were collected to define the field extent of the boundary between the low marsh and high marsh, and an additional 102 points were collected as part of 8 roughly equally spaced shore-perpendicular transects (40 points were in the "upland" and 62 points extended onto the high and low marsh surfaces). Resulting survey data points are shown overlain on 2001 aerial orthophotographs in Figure 4.

Thomas Bay, Brunswick

Collected GPS data was provided to MGS by the Estuary Partnership from survey work completed on May 6, 2009. Data was collected using a Trimble 5700 GPS receiver with Zephyr antenna. Base station data was provided by the Maine Technical Source Continuous Operating Reference Station (CORS, point YMTS), which was held as a fixed control point. A total of 100 points were collected by the University of Southern Maine GIS laboratory, mostly within the marsh area adjacent to the north and south side of Adams Road in Brunswick (Figure 5).

FEMA LIDAR Data Processing

For each of the study site locations, available LIDAR data from the FEMA LIDAR dataset were processed so that later comparisons between field collected GPS elevations and associated LIDAR elevations could be made. Initial analysis of the data showed that the bare-earth .xyz files were actually at approximate 2 foot (not 2 meter) spacing and represented ground elevation data with vegetation removed. Data was provided in NAD1983 Maine State Plane Coordinate System (feet, Maine West, 1802), and referenced to NAVD88 (feet) orthometric elevations. ESRI ArcToolbox was used to transform data to UTM NAD83 Zone 19.

Bare Earth XYZ files

Applicable bare-earth .xyz files were converted to ASCII raster format using an executable file. One specifies an input format (including header file, no data), and desired output format (including cell size, and floating point or integer output). Two meter (6 foot) output point spacing and floating point output was specified. Once this was completed ArcToolbox>Spatial Analyst Tools>Extract>Extract Values to Points command was used to find the *nearest* LIDAR data points to the collected GPS data. No interpolation was used; the nearest central grid value was taken.

TIN files
It was determined in discussions with Dr. Matthew Bampton and Dr. Vinton Valentine of the GIS Department at the University of Southern Maine, who had preliminarily inspected the LIDAR datasets, that extracted nodes from the TIN files may better represent bare earth topographic values for comparing LIDAR with GPS elevation values. Using available TIN data, elevation data nodes were extracted using ArcToolbox>3D Analyst Tools>Conversion>from TIN>TIN node command.

This creates a 2D feature class of the extracted TIN nodes with an optional spot elevation field associated with each node. After nodes were extracted, the nearest node to each GPS point was joined using ArcToolbox>Analysis Tools>Overlay> Spatial Join.

Tidal Elevation Processing
Additional LIDAR processing was completed to derive the Highest Annual Tide (HAT) and Mean High Water boundaries for comparison with field collected GPS data for the Cousins River and Back Cove study sites, respectively. Applicable bare earth raster datasets were queried to find all cells with values below the HAT (6.4 ft for the Cousins River) and MHW (4.21 ft for Back Cove) elevations. The same routines were carried out for creating the existing and future marsh surfaces, albeit at specified elevation ranges, discussed later in the report.

<u>LIDAR and GPS data Comparison</u>
Vertical Comparison
Collected GPS elevation data was subtracted from the nearest extracted LIDAR data points (both TIN nodes and raster values) to determine the difference in elevations.

Horizontal Comparison
We also compared the horizontal spatial variation of a field delineated boundary, such as the HAT, and the same boundary defined using extracted LIDAR data. Extracted LIDAR data was used to create a polyline representing the landward limits of the subject boundary and was compared with the GPS delineated boundary. To do this comparison, the ArcGIS Digital Shoreline Analysis System (DSAS) extension, developed by the USGS (Thieler et al., 2009) was used. A baseline was set on the marsh side of the delineated boundaries, and transects were cast at 5 m intervals in a landward direction along the length of the boundaries. The net difference between the two "shorelines" indicates the horizontal offset between the two boundaries. In areas where the LIDAR delineated boundary was marshward of the GPS delineated boundary, net difference values were negative; where the GPS delineated boundary was located marshward of the LIDAR boundary, net difference values were positive.

Slope Analysis
For analysis at the pilot site (Cousins River), ESRI Spatial Analyst was used to calculate the slopes, in degrees, of the LIDAR data (using the gridded raster as an input). An output raster of slope data was created.

Hawth's Tools (Beyer, 2009) ArcMap extension was then used to analyze adjacent upland slopes where DSAS transects were cast. Transects were cast at lengths of

20 m, at a 5 m interval, in order to match the DSAS transect locations and capture the slopes of the adjacent uplands. The tool calculates a Length Weighted Mean (LWM, in degrees), Maximum, Minimum, and Standard Deviation slope values.

RESULTS AND ANALYSIS

Cousins River, Yarmouth

The overall averaged data quality, as recorded by GPS in the field, is included in Table 1 (values converted to feet).

Feature delineated with RTKGPS	HRMS		VRMS		HDOP		VDOP	
	X'(ft)	δ(ft)	X'(ft)	δ(ft)	X'(ft)	δ(ft)	X'(ft)	δ(ft)
HAT Boundary (South side)	0.18	0.18	0.17	0.08	1.70	0.75	1.97	0.40
HAT Boundary (North side)	0.14	0.10	0.23	0.11	1.80	0.96	2.78	1.10
HAT Boundary North side (filtered)	*0.12*	*0.05*	*0.20*	*0.04*	*1.47*	*0.15*	*2.30*	*0.29*
HAT Boundary (All, non filtered)	0.16	0.16	0.19	0.10	1.75	0.85	2.30	0.88
High Marsh	0.12	0.12	0.22	0.06	1.39	0.53	2.25	1.03
High Marsh (filtered)	*0.11*	*0.13*	*0.21*	*0.06*	*1.18*	*0.15*	*1.84*	*0.25*
Low Marsh	0.13	0.02	0.16	0.02	1.56	0.44	1.97	0.35
All Data combined (non-filtered)	0.14	0.13	0.20	0.08	1.53	0.67	2.24	0.92
All Data combined (filtered)	*0.13*	*0.13*	*0.19*	*0.07*	*1.38*	*0.46*	*1.93*	*0.31*

Table 1. GPS data quality during the survey at Cousins Marsh, Yarmouth.

It is clear that there were some data quality issues during the survey; we attribute this to tree cover adjacent to steep slope uplands, considerable cloud cover, and satellites consistently lower on the horizon during the survey. This resulted in some difficulties establishing good satellite reception during the study. Average HDOP values were typically less than 3 (values should remain between 1 and 2, "ideal" to "excellent", with 3 being "good"). VDOP values exceeded 3 for 41 points, the majority of which were located in the northern portion of the study area (along the high marsh and HAT boundary). This resulted in slightly higher than normal HRMS and VRMS values. Compounding these errors was the weather and field conditions, which made identification of exact features quite difficult due to snow and ice cover.

As a result, GPS data was filtered to remove some of the error introduced. We illustrate the impacts of filtering the data for this pilot study area in Tables 1 and 2. In order to provide a baseline for comparison of data quality with the other main study site (Back Cove), we chose to filter the data.

Vertical Comparison and Analysis

We found that, in general, LIDAR topographic data – either sourced from the bare earth grid format or the extracted TIN node data – was quite accurate in representing ground conditions when compared with field collected RTKGPS topographic data in this study region. For the total 343 GPS points collected (not filtered) the mean differences between the LIDAR data and GPS data was +0.15 ft (δ=0.45 ft) for data extracted from TIN nodes, and +0.16 ft (δ=0.41 ft) for the rasterized data. Comparing these mean values to the filtered data – overall – did not greatly improve the overall accuracy. The overall statistics are shown in Table 2.

Feature delineated with RTKGPS	GPS			LIDAR (node)		LIDAR (grid)		ΔElev. (node-GPS)			ΔElev. (grid-GPS)		
	n	X'(ft)	δ(ft)	X'(ft)	δ(ft)	X'(ft)	δ(ft)	X'(ft)	δ(ft)	RMSE(ft)	X'(ft)	δ(ft)	RMSE(ft)
HAT Boundary (South side)	68	6.55	0.21	6.66	0.57	6.69	0.48	0.10	0.57	0.58	0.14	0.49	0.51
HAT Boundary (North side)	50	6.27	0.26	6.48	0.67	6.55	0.61	0.20	0.74	0.76	0.28	0.66	0.71
HAT Boundary North side (filtered)	*37*	*6.30*	*0.25*	*6.40*	*0.64*	*6.46*	*0.59*	*0.11*	*0.69*	*0.70*	*0.15*	*0.62*	*0.64*
HAT Boundary (All)	118	6.43	0.27	6.58	0.62	6.63	0.54	0.15	0.65	0.66	0.20	0.57	0.60
High Marsh	182	5.24	0.23	5.34	0.28	5.32	0.27	0.10	0.27	0.29	0.09	0.26	0.28
High Marsh (filtered)	*156*	*5.20*	*0.22*	*5.29*	*0.26*	*5.28*	*0.25*	*0.09*	*0.26*	*0.27*	*0.08*	*0.26*	*0.27*
Low Marsh	43	4.21	0.34	4.53	0.38	4.53	0.38	0.32	0.37	0.49	0.32	0.32	0.45
All Data combined (not filtered)	343	5.52	0.78	5.66	0.84	5.68	0.84	0.15	0.45	0.47	0.16	0.41	0.44
All Data combined (filtered)	*304*	*5.50*	*0.81*	*5.62*	*0.84*	*5.63*	*0.84*	*0.13*	*0.44*	*0.45*	*0.13*	*0.40*	*0.42*

Table 2. Statistics associated with comparison of GPS and LIDAR datasets for filtered and unfiltered data. Note that X' denotes the mean value, δ is standard deviation, and RMSE is Root Mean Square Error.

The published overall vertical accuracy of the 2006 FEMA LIDAR data from available metadata was +-37 cm (1.25 ft total, RMSE 18.5 cm or 0.6 ft). It seems that both sets of LIDAR data – bare earth grids and data created from TIN nodes – generally meet or exceed this accuracy, *especially for representing the marsh surfaces*, even using unfiltered data. The HAT boundary elevation relationship (differences between LIDAR and GPS data) was *slightly improved* by using filtered data.

Comparison of Marsh Elevations – Low Marsh

Only a small portion of low marsh was surveyed for comparison with LIDAR values (43 points). This area was concentrated at the northern end of the marsh system, adjacent to small tidal channels. The average elevation of the low marsh was near 4.21 ft, which corresponds with the 2009 published Mean High Water elevation value for the Portland Harbor area (4.21 ft). Both LIDAR datasets appeared to be quite good at representing actual low marsh elevations, with a slight positive bias near +0.3 ft (Figure 6). This may well be due to snow and ice cover encountered in the field, or the routines used for removing vegetation from the LIDAR data.

Comparison of Marsh Elevations – High Marsh

GPS data of high marsh elevations within the northern marsh area showed that the average high marsh elevation was near 5.2 ft for both filtered and unfiltered data. Comparison of GPS and LIDAR data showed that the LIDAR data was quite accurate in representing real ground conditions, with a mean difference of +0.09 to +0.10 ft, and standard deviations and RMSE values near 0.3 ft for both filtered and unfiltered data. There is a very slight positive bias in the data, indicating that the LIDAR data overestimates the actual ground elevations. The spatial variation of the differences within the high marsh area is shown in Figure 7.

Comparison of Vertical Differences - Highest Annual Tide

As part of the analysis, we compared the field delineated HAT boundary (6.56 ft) with that of the extracted LIDAR data (6.4 ft) for both the marsh systems on the south and north sides of I-295. This comparison included both elevation as derived from the LIDAR vs. GPS, and horizontal spatial difference between the boundary formed by the collected and extracted data points.

For the south side marsh area, GPS measured HAT averaged 6.55 ft – extremely close to the observed NOAA tidal elevation of 6.56 ft. In comparing the GPS data with extracted LIDAR data, we found that the mean difference was relatively small for both LIDAR datasets (just over 0.1 ft mean difference). *It appears that since values are slightly positive, both LIDAR datasets slightly overestimate the ground* *elevation as recorded by GPS in the field.* This may be an artifact of ice and snow conditions during field work. Figure 8 shows the variation in the mean difference for the southern portion of the study area.

On the north side, the HAT boundary averaged near 6.30 ft for both filtered and unfiltered data. This is slightly below the verified water levels from the NOAA tide data, but within data the range of data error based on standard deviation values from the collected data. This difference may be attributed to field induced errors associated with difficult to define limits of the HAT due to field conditions (i.e., snow and ice). *However, due to tidal restrictions caused by U.S. Route 1 and I-295, it is possible that this lower value may be representative of constrained limits of tidal inundation, including HAT levels on this portion of the marsh system.*

When comparing the GPS data with extracted LIDAR data, we notice slightly greater error in this area. The mean difference was between +0.2 ft and +0.3 ft for unfiltered data, with a much higher variance (on the order of 1 ft, and RMSE values near 0.75 ft). This increased error may relate to the lack of an easily definable boundary in the field, pockets of less quality GPS data (i.e., HDOP or VDOP near 3 or above), or the role of steeper sloped terrain which may cause more errors in the LIDAR data since data is averaged over 2 m (6 ft) grids. For this reason, we compared filtered with unfiltered GPS data in Figure 9. The filtered data increases accuracy of the LIDAR to near +0.1 ft (mean value).

Overall, the mean difference between the LIDAR and GPS data for the entire HAT boundary within both portions of the study area was around +0.20 ft (δ and RMSE near 0.6 ft). This is within the overall error of the LIDAR data.

Comparison of Horizontal Differences – Highest Annual Tide

The mean horizontal difference (in meters) of the HAT boundary for the south and north marsh areas and both combined, as determined using the LIDAR vs. GPS data, is summarized in Table 3. The table also shows the adjacent slope – from the marsh into the uplands, calculated as the Length Weighted Mean (LWM) in degrees, and the associated standard deviation.

	Net Difference (LIDAR-RTK)			Adjacent Slope	
Feature delineated with RTKGPS	Transects	M (m)	δ (m)	LWM (°)	δ (°)
HAT Boundary (South side)	71	-0.11	1.38	16.23	3.83
HAT Boundary (North side)	101	0.86	2.86	28.74	10.50
HAT Boundary (All)	172	0.46	2.43	23.58	10.45

Table 3. Difference, in meters, in the horizontal distance between the LIDAR-derived HAT boundary and the field-determined HAT boundary. Associated slope data is included.

Figures 10 and 11 show the boundary relationships analyzed using DSAS for the southern and northern portions of the study area, respectively.

The mean net horizontal distance between the LIDAR and GPS defined boundaries within the southern portion of the study area was relatively low. LIDAR data generally well represented what was mapped in the field; the mean net difference between the GPS defined boundary and LIDAR boundary was slightly negative, indicating that there was a slight bias for the LIDAR boundary to be *marshward* of field determined boundary. This makes some sense since the verified tidal elevation was 6.56 ft, while the LIDAR data used the predicted elevation of 6.4 ft.

In the northern portion of the study area, the mean difference between the two boundaries was higher, and was positive, indicating that the LIDAR HAT boundary was more consistently *landward* of the field delineated boundary (Figure 11).

It is important to note it appears that the LIDAR HAT boundary tends to overestimate (positive values) the extent of inland inundation along heavily vegetated wooded areas, and underestimates (negative values) the inundation along more open areas (Figure 10). This likely has to do with routines used to remove vegetation along the shoreline from the raw LIDAR data

However, statistically there is less than a 0.5 m mean horizontal difference between the two boundaries when combining both portions of the study area.

We wondered if the difference in the location of the HAT noted between the two portions of the study areas related to adjacent upland slopes, i.e., if shallower or steeper slopes generally led to the closeness of the LIDAR in depicting the field delineated boundary. We extracted the maximum slopes along each DSAS transect used in calculating the Length Weighted Slope from Hawth's Tools.

Overall, the maximum slopes in the southern portion were lower than along the northern portion of the study area. We found little direct linear relationship between slope and the net difference between the HAT boundaries in the southern or northern areas. However, especially in the southern area which has a very good mix of relatively steep, vegetated and unvegetated shorelines, it seems that once the maximum slopes of adjacent uplands exceed 40 degrees, the LIDAR data well underpredicts (becomes more negative) the actual inland extent of a boundary – thus underpredicting the potential inundation (Figure 12).

Additional Statistics of LIDAR and GPS Data

In general, we would expect extracted LIDAR data, both grid values and TIN nodes, to have extremely good correlation with groundtruthed GPS data points for the different types of features that were delineated. We would expect almost a linear relationship between these data types.

Simple linear regression analysis showed that the gridded LIDAR data was slightly better at being a proxy for GPS elevations than the extracted TIN node data (Figure 13). TIN node data had an R^2 value of 0.72, while the gridded LIDAR data had a value of 0.77.

We attribute the slightly lesser quality of the relationship than expected to difficulties in the field for delineating the boundary of the HAT due to snow and ice conditions, especially within the northern portion of the study area, where the boundary was more difficult to evaluate, in addition to some added errors caused by GPS signal quality experienced during the survey.

Summary of Cousins River, Yarmouth Pilot Study Findings

It appears, based on the analysis of the Cousins River, Yarmouth site that:

- Either extracted TIN nodes or gridded bare earth raster data can be used to relatively accurately represent field conditions.

- There appears to be a slightly better relationship between on-the-ground elevations and gridded bare earth data.

- As expected, heavily vegetated areas cause more difficulty for LIDAR post-processing to accurately create bare earth elevations; this is evidenced in the vertical and spatial analysis.

- It appears that LIDAR data consistently overestimates the actual on-the-ground elevations, especially along the base of heavily wooded areas.

- Overall, the LIDAR overestimates elevations on the order of +0.1 to +0.2 feet, more noticeably so within the marsh system on the north side of I-295.

- Tidal restrictions may play a role in impacting the physical elevations that can be attained by the highest annual tide (or any tidal elevation), thus causing discrepancy between a predicted tidal elevation and on-the-ground measurements

- Some inaccuracies in GPS measurements (based on a possible combination of field misinterpretation of features, cloud cover, snow and ice ground cover, heavily treed areas, and variable satellite quality) may have impacted the study results, as precision results are less than what we typically expect of RTKGPS.

Back Cove, Portland

Vertical Comparison and Analysis

At the Back Cove study area, we delineated several different features, including the Mean High Water (MHW) boundary, located in the field as the boundary between dominant low and high marsh species of vegetation. We also recorded additional spot elevations along transects within the uplands and marsh areas.

Unlike the study at Cousins River, field conditions were warm, sunny, and satellite reception was very good. This was reflected in the subsequent overall precision of GPS measurements (Table 4). The distribution of the GPS data points collected at the site was shown in Figure 4.

Overall, GPS quality during data collection was quite good, with generally very low errors. However, several data points did need to be filtered out to account for high errors in HRMS, VRMS and extremely high VDOP values. Filtering included:

Low Marsh: No data removed.
Marsh (MHW) Boundary: 2 points due to high VRMS; 2 due to high VDOP.
High Marsh: No data removed.
Upland: No data removed.

	HRMS		VRMS		HDOP		VDOP	
Feature delineated with RTKGPS	**X'(ft)**	**δ(ft)**	**X'(ft)**	**δ(ft)**	**X' (ft)**	**δ (ft)**	**X' (ft)**	**δ (ft)**
Low Marsh	0.031	0.003	0.055	0.008	1.221	0.140	1.839	0.326
Marsh Boundary	0.075	0.457	0.138	1.000	1.173	0.690	1.821	1.030
Marsh Boundary (filtered 4 points)	*0.038*	*0.094*	*0.066*	*0.045*	*1.122*	*0.345*	*1.709*	*0.350*
High Marsh	0.160	0.160	0.190	0.100	1.750	0.850	2.300	0.880
Upland	0.032	0.006	0.064	0.024	1.370	0.180	2.198	0.434
All Data combined (filtered 4 points)	*0.036*	*0.078*	*0.064*	*0.038*	*1.181*	*0.315*	*1.799*	*0.390*

Table 4. Quality of GPS data collection at Back Cove, Portland.

Based on results from the Cousins River pilot site, for this site, we chose to use the LIDAR bare earth files to create rasters of elevation data for Back Cove. This was used as the basis for comparison with field captured GPS values. Table 5 shows the overall results of the collected field data and differences between the field measured and LIDAR derived elevations.

		GPS data		LIDAR grid data		Difference LIDAR-RTK (grid)		
Feature	**n**	**X'(ft)**	**δ (ft)**	**X'(ft)**	**δ (ft)**	**X'(ft)**	**δ (ft)**	**RMSE (ft)**
Low Marsh	27	3.67	0.62	3.59	0.50	-0.07	0.49	0.49
Marsh Boundary (filtered)	*208*	*4.00*	*0.28*	*4.01*	*0.38*	*0.01*	*0.35*	*0.40*
High Marsh	34	4.88	0.59	5.01	0.78	0.13	0.49	0.50
Upland	40	10.74	1.97	10.34	1.94	-0.39	0.62	0.73
All Data (filtered)	*309*	*4.94*	*2.39*	*4.91*	*2.28*	*-0.03*	*0.45*	*0.47*

Table 5. Comparison of collected field GPS data and LIDAR grid data, including removal of bogus GPS data.

Overall, gridded bare earth data appears to represent on-the-ground conditions very well, especially for the different marsh surfaces and marsh boundaries, with low mean difference values, and relatively low (less than ½ foot) standard deviation and RMSE values. The LIDAR data had a bit more difficulty in representing upland ground conditions, which were concentrated mostly along Baxter Boulevard.

Comparison of Marsh Elevations – Low Marsh
Twenty seven GPS points were used to establish elevation points within the low marsh, which was defined as those GPS points collected seaward of the field delineated boundary between dominant high marsh and low marsh species. These were extracted from 8 shore perpendicular transects which were conducted starting on Baxter Boulevard.

The mean low marsh elevations were quite close (Table 5). Comparison with LIDAR grid data was good. Data indicates that GPS measurements were slightly *higher*, overall, than the extracted LIDAR data. The largest deviation occurred along a central transect – the GPS data along this transect was of slightly less quality (HDOP 1.3-1.8, VDOP 2.1-2.75) but not poor enough to remove the point. Figure 14 shows a graphical depiction of the relationship of the GPS and LIDAR data and differences amongst the collected points in the low marsh.

Comparison of Vertical Differences – High-Low Marsh and Mean High Water
The boundary between dominant low and high marsh species was established in the field using 212 GPS points; 4 of which were removed due to poor GPS signal quality. The change from low to high marsh generally represents the Mean High Water (MHW) line, which is at elevation 4.21 ft NAVD based on NOAA NOS tide data. Low marsh species typically thrive up until about this elevation before high marsh species become dominant.

Both the GPS and LIDAR data had equivalent values for this boundary (4.00 ft) and standard deviation values were quite similar. The mean difference value was quite low at 0.01 ft (δ and RMSE at 0.35 and 0.40 ft, respectively). The elevations of this boundary varied along the shoreline in comparison with the defined MHW of 4.21 ft (Figure 15).

The comparison of elevations along this boundary spatially is quite interesting (Figure 16). Firstly, a single GPS point is clearly low compared with the LIDAR data – this point was not removed due to poor GPS signal – it appears to be adjacent to a newly cut tidal channel at one of the discharge pipes. Secondly, there is a spatial pattern where the GPS elevations are *higher than the LIDAR* (indicated by negative values) in the southern end of the Cove, and transition distinctly to where the GPS elevations are *lower than the LIDAR* (positive values) data. The nodal point is located at a culvert opposite the end of Mackworth Street (marked by arrow).

Although it is not clear, this may represent spatial patterns of erosion (i.e., where difference values are positive, or the RTK data is lower than the LIDAR data) and subsequent accretion of the marsh. This pattern may have been driven by storms that hit the area since the time the LIDAR data was collected (2006), and the GPS data was recorded (2009). It is difficult to ascertain whether or not this is the case, since aside from the LIDAR data, we have no baseline for comparison. *However,* *this could indicate that short-term erosion and accretion patterns within marsh systems could be monitored using subsequent LIDAR flights, or LIDAR combined with field GPS surveys.*

Comparison of Horizontal Differences - High-Low Marsh and Mean High Water

We already observed a vertical difference (on the order of -0.2 ft) between the predicted MHW boundary (4.21 ft) and the observed boundary delineated (4.00 ft) by the difference in vegetation using GPS techniques. Elevations along the LIDAR extrapolated boundary were very close to the GPS elevations.

Next, we analyzed the horizontal spatial relationship of the GPS measured boundary to the LIDAR MHW boundary using similar methodology from the Cousins River marsh site for comparison of the HAT boundary. DSAS transects were cast at 5 m intervals along the boundary. Results of this additional horizontal analysis are shown in Figure 17. The difference in the horizontal position of the two boundaries has a mean value of +1.8 m (δ = 4.2 m). This indicates a positive bias, i.e., the GPS derived boundary is actually seaward of the LIDAR derived boundary. This inherently makes sense, since the MHW elevation used to define the LIDAR boundary was 4.21 ft (based from extraction methods using that tidal elevation), and the average elevation measured along the GPS defined boundary was 4.00 ft.

The difference between the positions varies spatially. Within the southern portion of the Cove (through Transect 92), data shows the GPS boundary is seaward of the LIDAR boundary; interestingly, from Transect 92-155, the LIDAR boundary is actually seaward of the GPS boundary. From here northwards, the GPS boundary is back to being the more seaward boundary. The transition matches with the location of the changes seen in LIDAR-GPS elevations along the marsh boundary at Mackworth Street. *Thus, the horizontal comparison of LIDAR and GPS values may help indicate erosion and accretion of the edge of the marsh.*

As previously discussed, the Mean High Water elevation for Portland, based on 2009 tide data, was 4.21 ft. The field delineated boundary, based on differences in salt marsh vegetation, was 4.00 ft (δ=0.28 ft). It appears that the marsh system in Back Cove is somewhat unique – it has a higher percentage of low marsh than most systems in southern Maine (which are typically 90% or more high marsh, similar to the Cousins River site). This is reflected in the field collected GPS data, with the difference in elevation resulting in subsequent horizontal difference. *Thus, using the published MHW elevation as a proxy for the boundary between the high marsh and low marsh, at least at Back Cove, may not be accurate; local corrections (on the order of -0.2 feet) may be needed*

Comparison of Marsh Elevations – High Marsh

Thirty-four GPS points were collected representing the high marsh; these points were established landward (upslope) of the MHW boundary amongst vegetation dominated by *Spartina* patens and *Juncus* gerardi, and downslope of vegetated uplands and steep slopes. LIDAR derived elevations were slightly higher on average by around +0.15 ft than GPS measurements (Figure 18).

Additional Statistics of LIDAR and GPS Data
At the Back Cove site, there is a strong linear relationship ($r^2 = 0.96$) between field collected GPS elevations and extracted LIDAR raster elevations (Figure 19). This is in comparison with the Cousins River site, which had a lower correlation coefficient. It is quite possible that the relationship at Back Cove is better portrayed due to a larger range in elevation of the data collected and extracted (i.e., low marsh up through the uplands), while at the Cousins River pilot site, data was only collected within the marsh areas up to the HAT boundary.

Summary of Back Cove, Portland Study Area Findings
Based on our analysis of GPS and LIDAR elevation data, it appears that:

- Field collected GPS data quality was excellent at this study area.

- Bare earth gridded raster LIDAR was very good at representing field elevations derived from GPS, especially within the marsh area.

- GPS and LIDAR derived elevations and horizontal boundaries may potentially be used to compare and analyze the erosion and accretion patterns within a marsh system.

- There is a consistent offset predicted MHW tidal elevations (4.21 ft) and the field verified boundary between the high marsh and low marsh (4.00 ft). This adjustment could be used in mapping existing and simulating potential future marsh areas and conditions in response to sea level rise using LIDAR data.

- Comparisons of LIDAR and GPS elevation and horizontal difference data may be used to potentially analyze patterns of marsh erosion and accretion.

Thomas Bay, Brunswick

Vertical Comparison and Analysis

Field-collected GPS data provided to MGS by CBEP was used to analyze the relationship between GPS and LIDAR elevations. Elevation data was converted from meters into feet for comparison with the other sites. A total of 100 points were provided; data was filtered to remove data where the Relative Dilution of Precision (RDOP) values exceeded 4, as such a value can signify poor satellite reception and subsequent lower precision values. The remaining 74 points were analyzed for GPS precision accuracy (Table 6) and in comparison with gridded LIDAR data, consistent with the other sites. For this site, we did not differentiate between high marsh, low marsh, and upland, since these features were not noted in the GPS GIS files.

	Horiz. Precis.		Vertical Precis.		RMS		RDOP	
Feature delineated with RTKGPS	X'(ft)	δ(ft)	X'(ft)	δ(ft)	X' (ft)	δ (ft)	X'	δ
Thomas Bay Marsh North	0.022	0.012	0.046	0.023	0.033	0.010	2.938	0.691
Thomas Bay Marsh South	0.032	0.040	0.063	0.063	0.043	0.016	2.570	0.500

Table 6. Quality of GPS data collected at the Thomas Bay site.

The study area was divided into two portions – one south of the Adams Road tidal restriction, and the one north of the restriction (Figure 19), to see if there was a noted impact of the restriction on collected GPS and extracted LIDAR elevation data. Summaries of data statistics are shown in Table 7.

		GPS data		LIDAR grid data		Difference LIDAR-RTK (grid)		
Feature	n	X'(ft)	δ (ft)	X'(ft)	δ (ft)	X'(ft)	δ (ft)	RMSE (ft)
Thomas Bay Marsh North	42	4.65	1.47	5.21	1.15	0.56	0.71	0.90
Thomas Bay Marsh South	32	4.37	1.89	4.75	1.79	0.38	0.52	0.64

Table 7. Summarized statistics for the two different portions of the study site.

Figure 20 shows several points in the northern portion that have high positive difference values (indicating LIDAR data was significantly higher than GPS data). Even with these points removed, the average GPS elevation of the northern portion of the study area is still consistently higher than the south on the order of around +0.2 to +0.25 feet. The difference in the extracted LIDAR data is even higher.

It appears that the LIDAR data at this site overpredicts the ground elevation on the order of +0.4 ft in the southern portion, and closer to +0.6 ft in the northern portion. This result may be slightly skewed by the inclusion of upland elevations within the analysis. Thus, elevations along the road surface within both areas were removed. This results in the following:

		GPS data		LIDAR grid data		Diff. LIDAR-RTK (grid)	
Feature	n	X'(ft)	δ (ft)	X'(ft)	δ (ft)	X'(ft)	δ (ft)
Thomas Bay Marsh North	38	4.47	0.53	5.01	0.66	0.54	0.47
Thomas Bay Marsh South	30	3.97	1.08	4.41	1.25	0.44	0.45

Table 8. Comparison of statistics with upland data removed.

Although all mean values generally decrease, there is still a +0.5 ft difference between the southern and northern marsh elevations, based on GPS values. This trend is mirrored by the LIDAR data, which is still consistently higher than the GPS elevation data, again by +0.5 ft.

Summary of Thomas Bay, Brunswick Study Findings

Based on our analysis of GPS and LIDAR elevation data, it appears that:

- There is a discrepancy between the tidal marsh elevations recorded in the southern and northern portions of the study area on the order of +0.5 ft. The tidal restriction caused by Adams Road may be responsible for this discrepancy.

- LIDAR data consistently overpredicts the measured ground elevations using GPS.

- The over-prediction for the marsh surfaces only (uplands removed) is approximately +0.5 ft in the northern portion of the study area, and +0.45 ft in the southern portion.

- Based on comparison with other results from the Cousins River and Back Cove study areas, this overprediction appears relatively high. We are unsure of the cause of this systematic offset, but some of it may be due to the use of different GPS equipment or distance to base/control points.

- A LIDAR to GPS elevation correction of around -0.5 ft could potentially be applied for this study area, but may warrant further study.

SIMULATION OF EXISTING MARSH CONDITIONS

Cousins River, Yarmouth

The nearest location where tidal elevation data was calculated is Princes Point, Yarmouth (Dickson, 2009).

At the Cousins River site, analysis of data showed that LIDAR data was consistently slightly higher than the field recorded GPS data. The difference for the whole site was on the order of 0.15 ft, but this easily fell within the standard deviation of the data. Our field delineations of the HAT boundary showed that the southern portion of the study area matched well with the observed high water (6.54 ft), while in the northern area, field delineated high water was below this elevation (mapped near an average of 6.30 ft).

Additionally, our horizontal analysis of the LIDAR vs. GPS derived HAT boundary showed that the LIDAR data was quite good in representing the position of the boundary on the south side, but less so on the north side. It is unclear whether or not this difference is due to combined data error, field errors in delineating the boundary, or the slight decreased quality of GPS signal which was observed. *However, it is quite possible that this difference is due to the tidal constriction caused by the Route 1 and Route 295 roadways.*

Therefore, we are not comfortable applying any corrections to the LIDAR data at this location for our simulations at this point, and will proceed using the tidal elevations shown in Table 9. A second survey, carried out during warmer weather and hopefully better GPS positioning quality (not constrained by a specific day due to tidal regime), may be warranted to further constrain this difference, and will be undertaken by MGS as part of a no cost agreement with CBEP, if permitted.

Feature	Tidal Range	Elev Range (ft)	Existing Area (sq.km)	Future Elev Range (ft)	Future Area (sq.km)	Difference (sq.km)	Percent Change
High Marsh	MHW-HAT	4.21-6.40	0.37	6.21-8.40	0.06	-0.31	-84.23
Low Marsh	MSL-MHW	-0.31-4.21	0.10	1.69-6.21	0.44	0.34	328.84
Open Water	<MSL	<-0.31	0.10	<1.69	0.13	0.03	24.50

Table 9. Existing and potential future marsh conditions in Cousins River, Yarmouth. Tidal elevations derived from Prince's Point, Yarmouth (Dickson, 2009).

Please note that for this analysis, the study area raster was clipped to include portions of the south and north marshes so that boundaries could be easily constrained in analyzing changes to the marsh.

Using the values in Table 9, the overall breakdown of marsh area was calculated. The Spatial Analyst Raster Calculator was first used to calculate the raster values for each range of elevations associated with each marsh type. Next, the raster was appropriately sampled, and then converted to polygons. Finally, areas of each representative marsh surface were calculated.

The marsh system here is dominated by high marsh, which is at an almost 4:1 ratio with existing low marsh. Broad expanses of high marsh exist, extending right up to steeper sloped, wooded uplands. Areas of low marsh are concentrated as narrow fringes of vegetation along tidal channels (Figure 21).

The Cousins River marshes could undergo dramatic changes at this location, with the *high marsh undergoing loss of over 84% of its area in response to sea level rise* (Figure 22). Subsequently, the low marsh has areas of low sloped high marsh upon which to transgress, and can increase by over 325% of existing conditions. Open water increases by about 25%. There appears to be very little room for the high marsh to expand. These areas are concentrated mainly in the upper reaches of the tidal creeks associated with the River, but growth is constrained by steeper sloped uplands.

<u>Back Cove, Portland</u>

The tidal elevations associated with different marsh types (including open water) for the Back Cove study area are listed in Table 10. We have applied a -0.2 ft correction to LIDAR data for the MHW elevation by adjusting expected inundation levels, based on the results of the analysis of LIDAR-derived MHW elevations in reference to the field-defined boundary between the low marsh and high marsh.

Feature	Tidal Range	Elev Range (ft)	Existing Area (sq.km)	Future Elev Range (ft)	Future Area (sq.km)	Difference (sq.km)	Percent Change
High Marsh	MHW-HAT	4.01*-6.30	0.86	6.01-8.30	0.44	-0.42	-49.21
Low Marsh	MSL-MHW	-0.31-4.00	1.16	1.69-6.01	1.33	0.17	14.49
Open Water	<MSL	<-0.31	21.81	<1.69	22.40	0.59	2.71

Table 10. Existing and potential future marsh conditions in Back Cove, Portland. Tidal elevations derived from NOS tide data (NOS, 2009a). *A correction of -0.2 ft was included for the MHW boundary.

Existing conditions illustrate the dominance of open water and low marsh within the area. High marsh is concentrated as a thin fringe adjacent to the walking path around Baxter Boulevard, and comprises less than 1 sq. km. Existing marsh conditions are represented in Figure 23. Note that the area of shown existing high marsh within the soccer field at the southeastern end of Back Cove does not actually exist as colonized marsh.

Under the scenario of 2 feet of sea level rise, there is a *potential dramatic decrease in high marsh, close to 50%, while there is a 15% increase in low marsh and an almost 3% increase in the area of open water.* Potential future conditions are shown in Figure 24. It appears that existing high marsh will be pinched out against adjacent steeper sloped uplands by a transgressing low marsh and open water. The existing soccer field (at the southeast side of the Cove) appears to be the only area where the high marsh may have room to transgress, along with smaller finger marshes at the northwestern side of the Cove. Of additional note is potential flooding of portions of the commercial facility on the northeastern side of Tukey's Bridge. It does not appear that Baxter Boulevard itself would be impacted by potential future inundation levels associated with normal expected HAT after sea level rise.

Thomas Bay, Brunswick

Tidal ranges used for the Thomas Bay site were taken from tidal elevation data from nearby Wilson Cove, in Middle Bay. The ranges are similar to elevations from the Cousins River site. No correction was applied to the LIDAR data for this simulation. The study area was clipped in order to provide spatial control for calculation of marsh areas. Existing and future marsh area changes are in Table 11.

Feature	Tidal Range	Elev Range (ft)	Existing Area (sq.km)	Future Elev Range (ft)	Future Area (sq.km)	Difference (sq.km)	Percent Change
High Marsh	MHW-HAT	4.21-6.40	0.125	6.21-8.40	0.032	-0.093	-74.52
Low Marsh	MSL-MHW	-0.31-4.21	0.078	1.69-6.21	0.177	0.099	128.05
Open Water	<MSL	<-0.31	0.010	<1.69	0.030	0.020	196.44

Table 11. Existing and potential future marsh conditions at Thomas Bay, Brunswick. Tidal elevations derived from NOS tide data (NOS, 2009a). A 3rd decimal place was added due to small calculated areas.

Figure 25 shows the existing conditions at the marshes in the area. Similar to the Cousins River study site, the area is dominated by high marsh in the northern and southern portions of the area. Low marsh is confined mostly to the southernmost portion of the southern study area, and as a thin fringe along the tidal channels through both sections of the study area.

After sea level rise, the study area undergoes dramatic changes to all simulated areas. The high marsh decreases by almost 75%, while low marsh increases near 130%. Open water increases close to 200% of existing conditions. It appears there are only several small areas where the high marsh can transgress into adjacent uplands – these are lower lying areas adjacent to the upper reaches of the tidal creek, and an area of wooded uplands to the west (Figure 26).

ADDITIONAL DISCUSSION

Local tidal levels can vary due to the complex geography of Maine's coast. Casco Bay is spatially complex with multiple large islands, deep channels, meandering estuarine channels, and bathymetric shoaling in estuaries. Shoaling of estuaries can affect tidal elevations and may be a cause of some of the differences between a tidal datum calculated from the Portland tide gauge with local corrections to a nearby NOS tidal station. Lincoln and FitzGerald (1988) demonstrated that friction reduced tidal amplitude in salt marshes of the upper reaches of the Ogunquit River and four other small tidal systems in Maine. Conversely, tides are amplified up the Penobscot River from Belfast to Bangor. The HAT in Bangor is 2.2 feet higher at the mouth of the river due to the constriction of the river in its inland reaches (Dickson 2009). Local effects may be identified by high-resolution GPS field surveys of marsh system boundaries and elevations as was demonstrated herein.

From one year to the next the predicted Highest Annual Tide in Portland may vary by one or two tenths of a foot. For example, the HAT for 2009 in Portland was 0.1 ft lower than it was in 2008. Furthermore, over a period of several years the Mean High Water elevation gradually rises or falls due to astronomical forces that have an 18.6 year periodicity (Gratiot et al., 2008; Pugh, 1987). Thus, interannual variability in tides may fluctuate faster than responding lateral migration of salt marsh plant communities. So field surveys of marsh boundaries - the higher edge of the high salt marsh or the high-low marsh boundary - may diverge from the HAT of a current year based on recent trends.

CONCLUSIONS

Overall, we find that LIDAR is an excellent data source for simulating impacts of sea level rise on Maine salt marsh ecosystems. Results are most accurate if combined with field-verified elevation data of current marsh system boundaries.

Some elevation adjustments were potentially found for the study areas. These are due to the distance from the Portland tide gauge and to local modification of tidal amplitude in upper estuaries. Some estuarine tidal variability may be due to tidal constrictions from road overpasses while others may be due to increases or decreases in tidal amplitude from channel friction that constricts or dissipates flow.

Best results were obtained in open areas when snow/ice cover was absent. Areas with minimal upland forest vegetation adjacent to the highest tides do not yield as accurate results as wetlands adjacent to open, non-forested uplands.

Given the large expanse of the salt marshes studied, the horizontal displacements that were found comparing LIDAR data to GPS-based field surveys were small. The use of LIDAR data to simulate sea level rise inundation is very sound and can yield useful results for studying local impacts of climate change.

Even with the small uncertainties noted in this study, there are dramatic consequences to salt marsh systems from a sea level rise of two feet. Many of southern Maine's marsh systems – in the past several thousand years – were at one point dominated by low marsh, instead of today's existing high marshes (Belknap et. al, 1989). With measured increases in global and relative sea level and accelerations in rates of sea level rise, simulations of future conditions give a better understanding of the potential responses of the marsh systems.

Our simulations do not include changes in topography due to sediment deposition or erosion but are rather static inundation models. Depending on the rate of sea level rise, marsh systems may undergo different sedimentary conditions so a static scenario is best used as a planning tool to understand potential ecological consequences of sea level rise.
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The most dramatic changes in the three simulated locations were:

Cousins River, Yarmouth	50% loss of high salt marsh
Back Cove, Portland	84% loss of high salt marsh
Thomas Bay Brunswick	75% loss of high salt marsh
Cousins River, Yarmouth	325% increase of low salt marsh
Back Cove, Portland	15% increase of low salt marsh
Thomas Bay Brunswick	130% increase of low salt marsh

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APPENDIX A

Note: All base GIS imagery is courtesy of Maine Office of GIS.

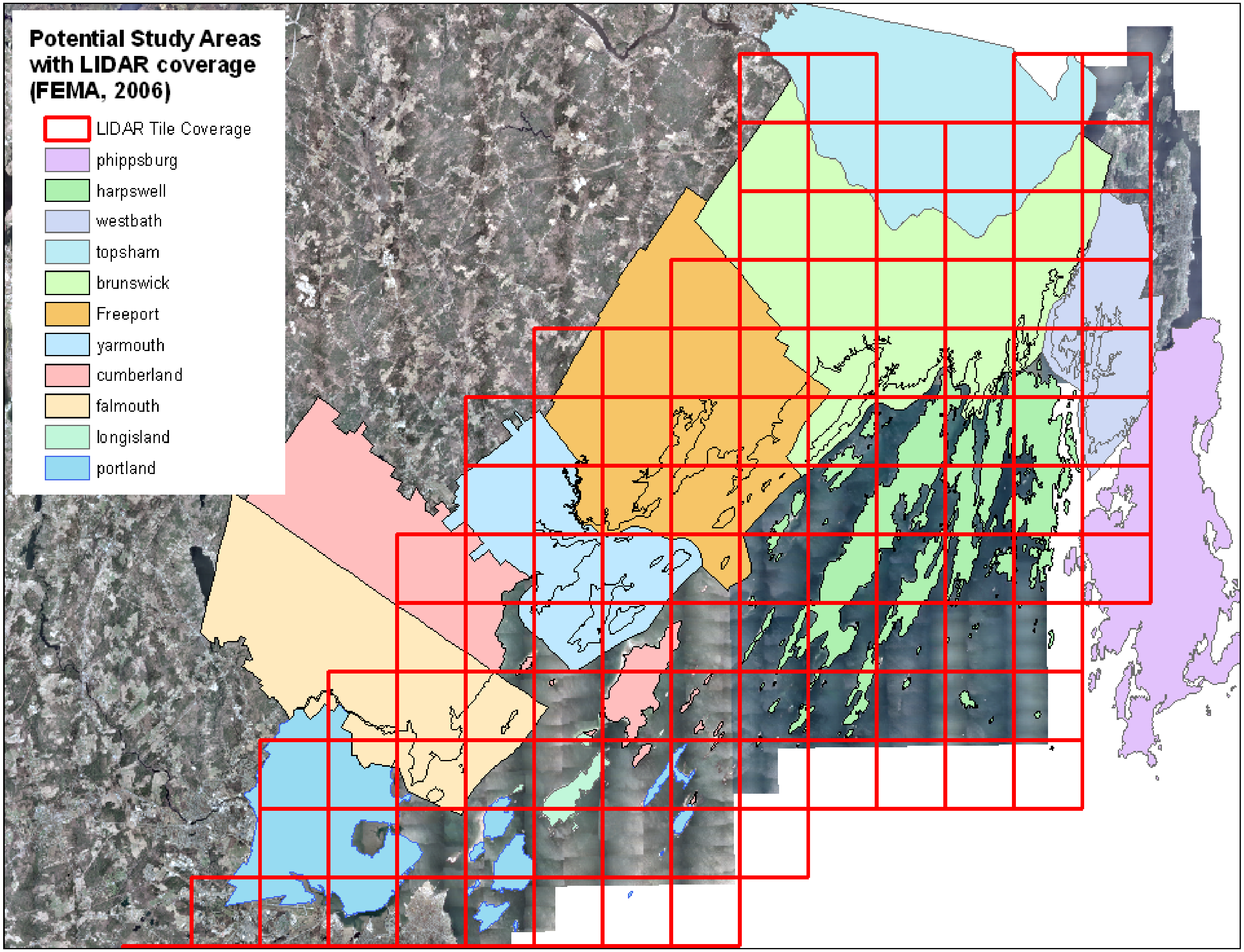


Figure 1. Spatial distribution of 2006 FEMA LIDAR coverage.

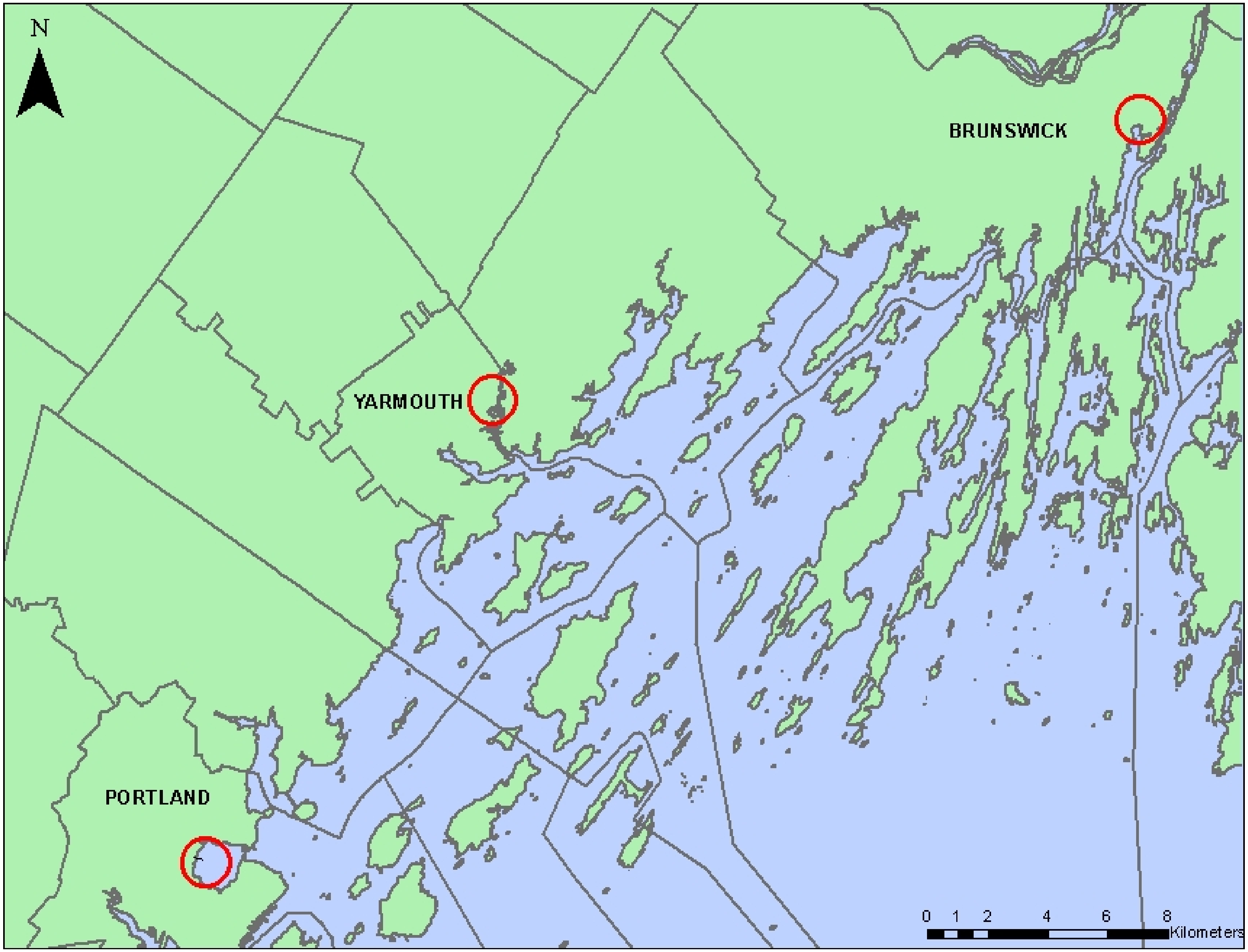


Figure 2. Locations of the 3 study areas: Cousins River, Yarmouth; Back Cove, Portland; and Thomas Bay, Brunswick.

Figure 3. Collected GPS data at the Cousins River study area. The study area can be divided into southern and northern portions.

Figure 4. GPS data collection at Back Cove, Portland.

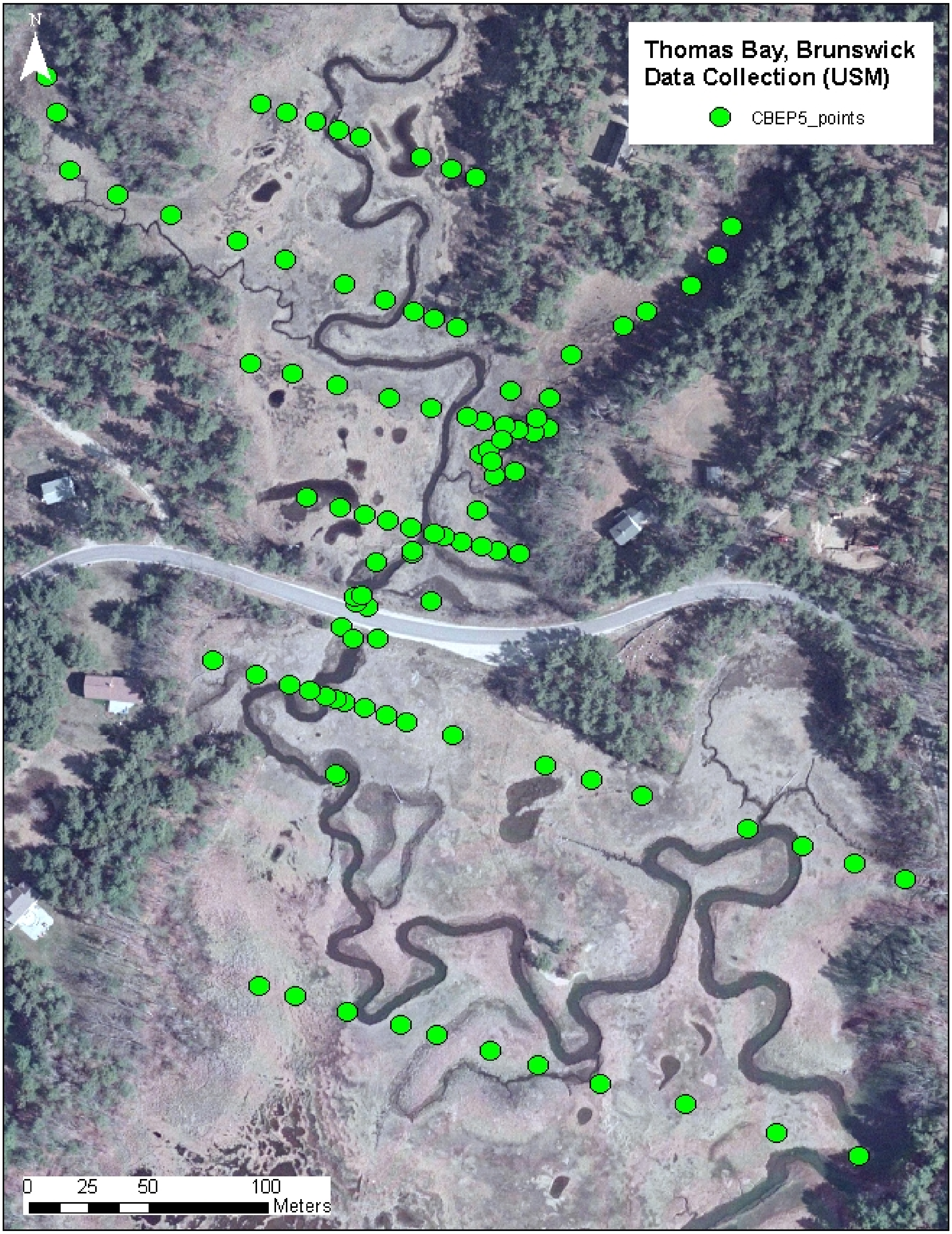


Figure 5. GPS data collection by USM GIS Laboratory at Thomas Bay marshes, Brunswick.

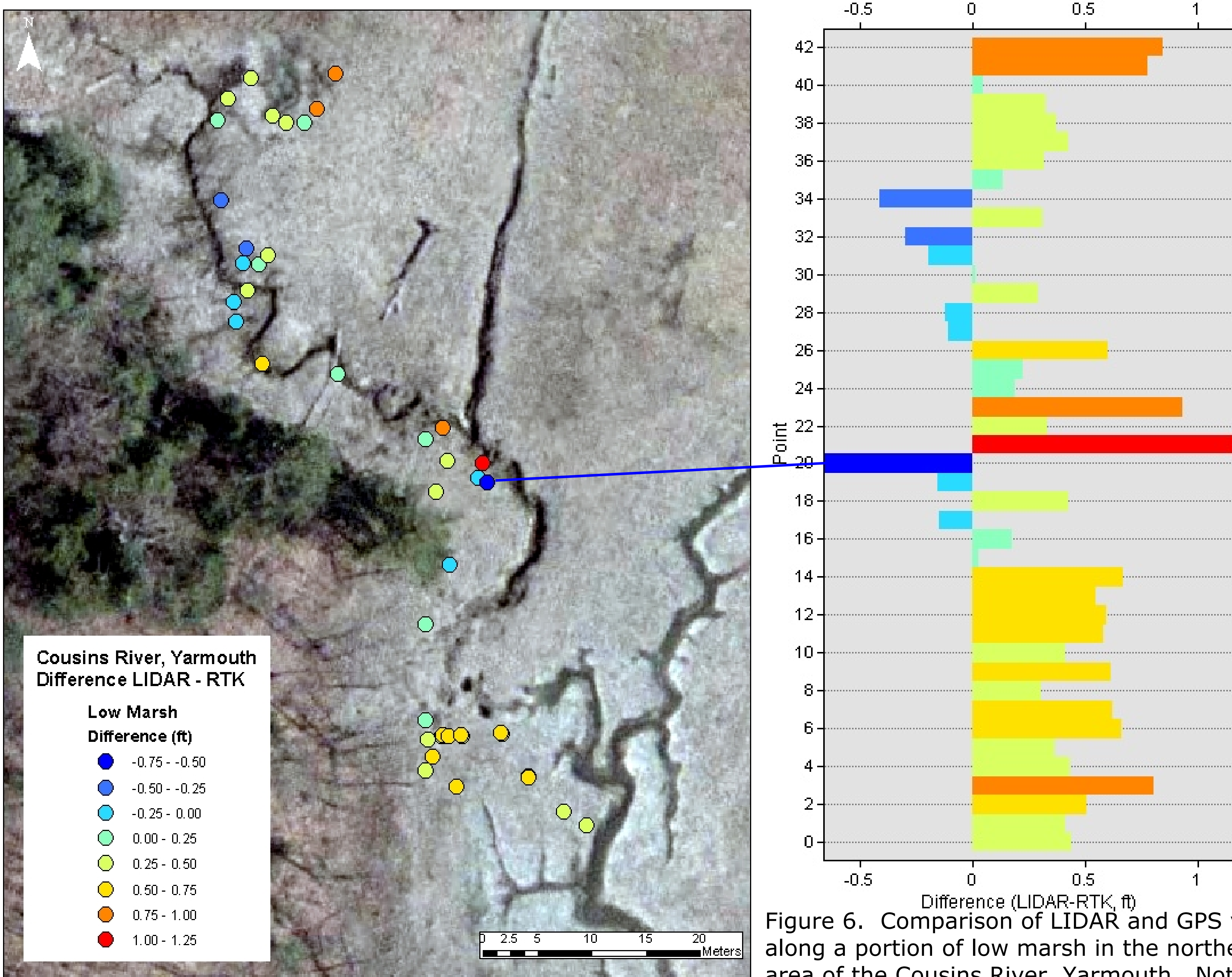


Figure 6. Comparison of LIDAR and GPS values along a portion of low marsh in the northern study area of the Cousins River, Yarmouth. Note positive bias.

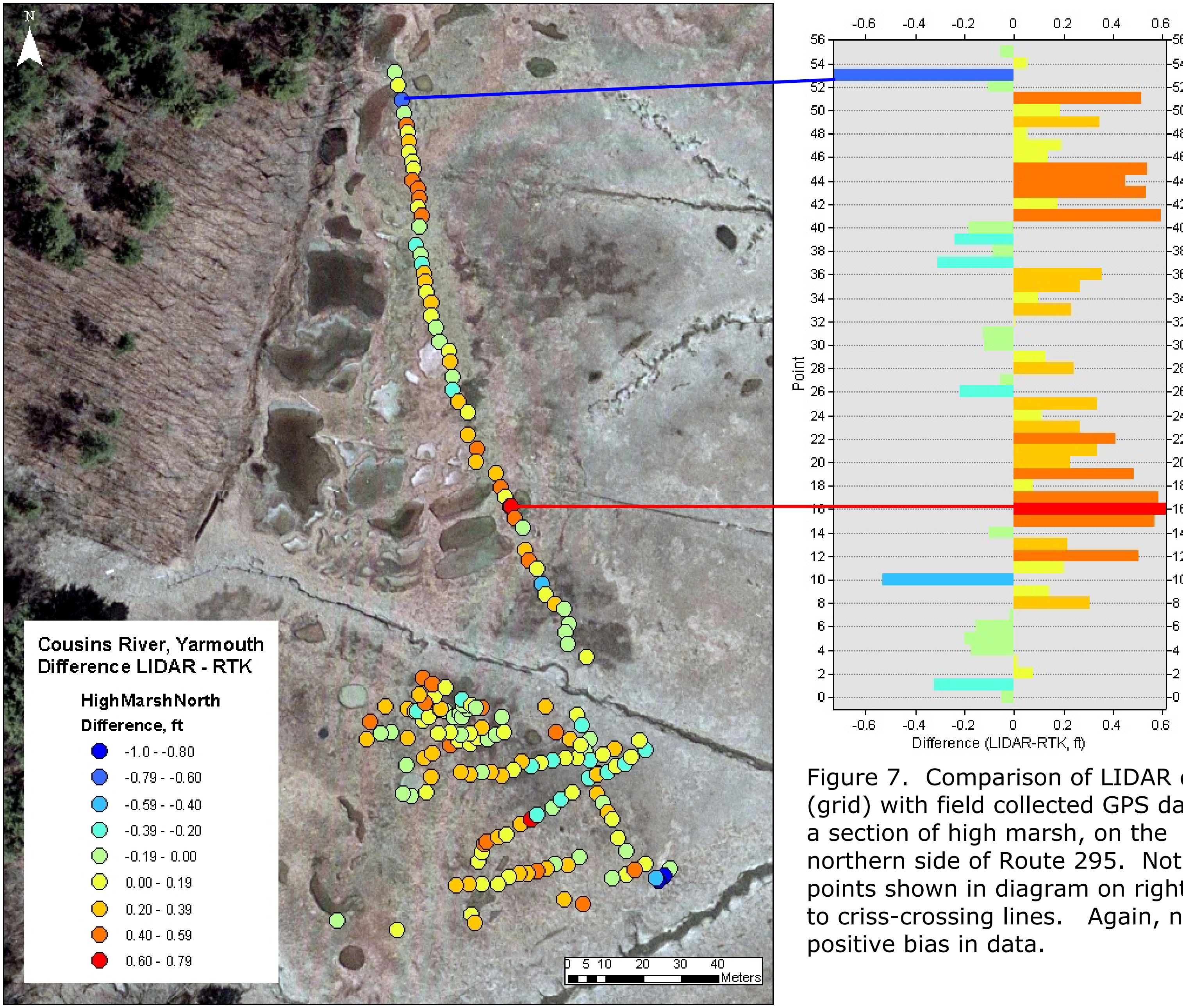


Figure 7. Comparison of LIDAR data (grid) with field collected GPS data for a section of high marsh, on the northern side of Route 295. Not all points shown in diagram on right due to criss-crossing lines. Again, note positive bias in data.

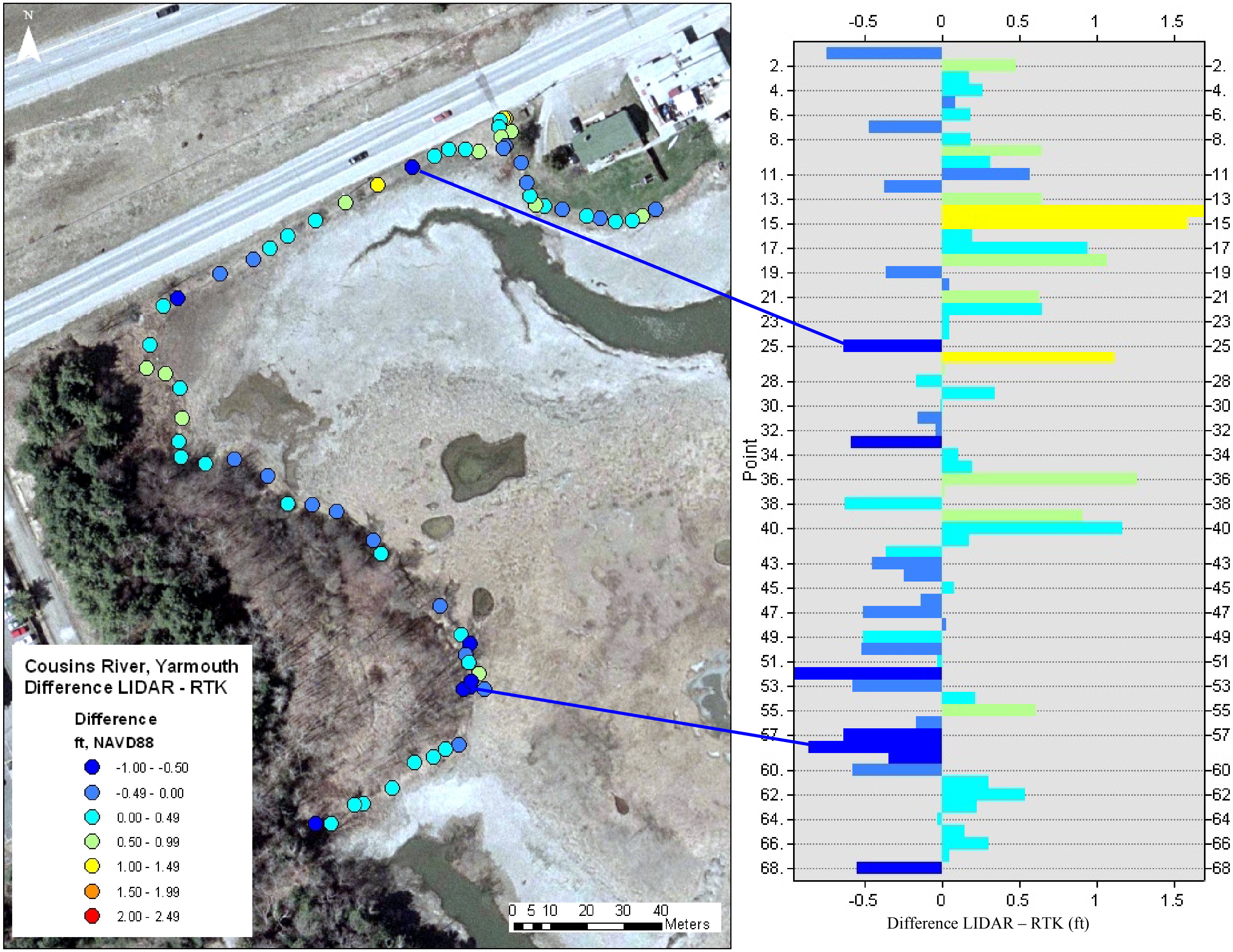


Figure 8. Variation of difference in elevations of the HAT boundary for the southern area.

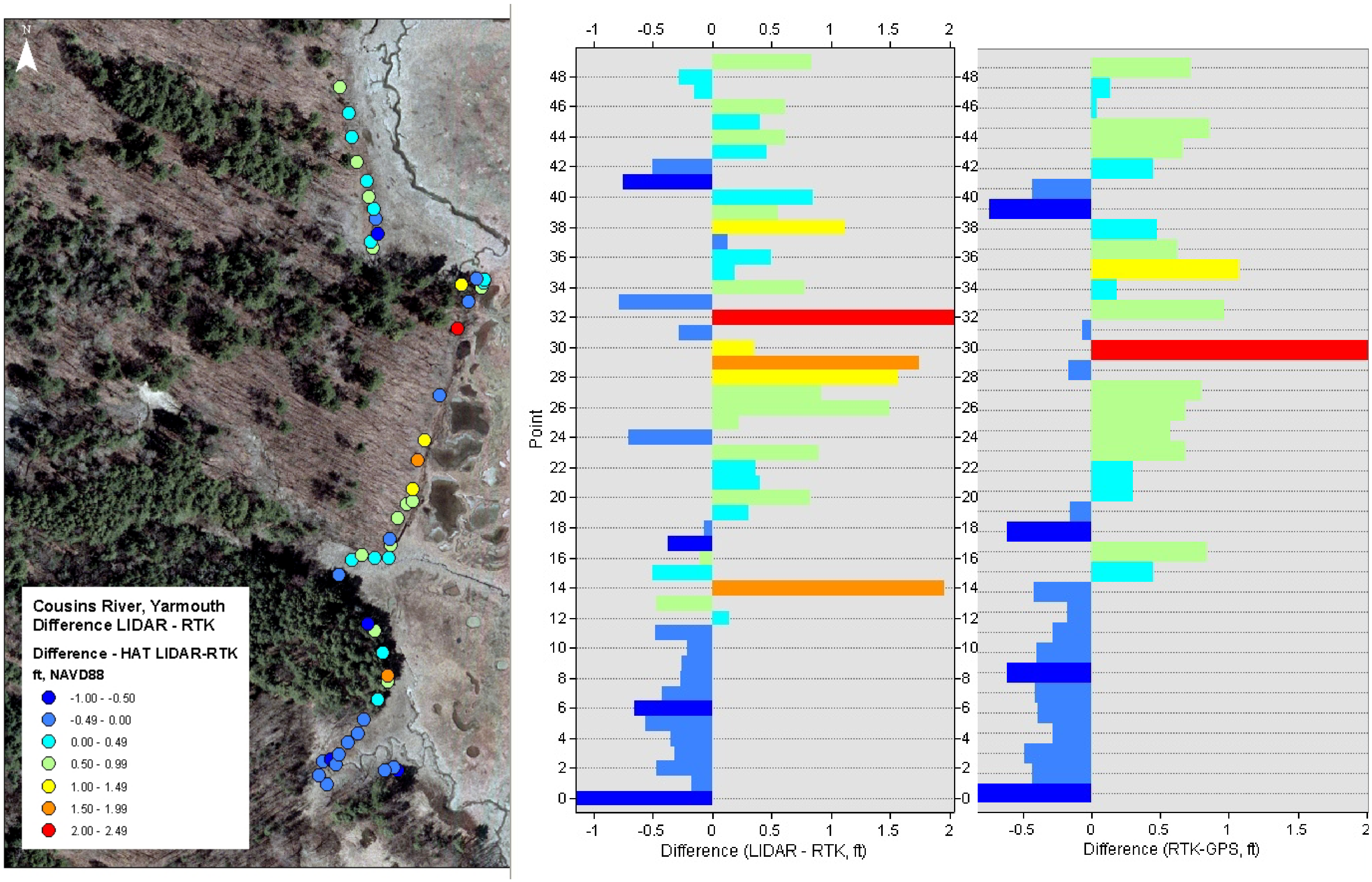


Figure 9. Comparison of unfiltered (center) and filtered (far right) LIDAR data at the HAT boundary in the northern marsh. Filtered GPS data decreased the overall difference between LIDAR and GPS to an average near +0.1 ft.

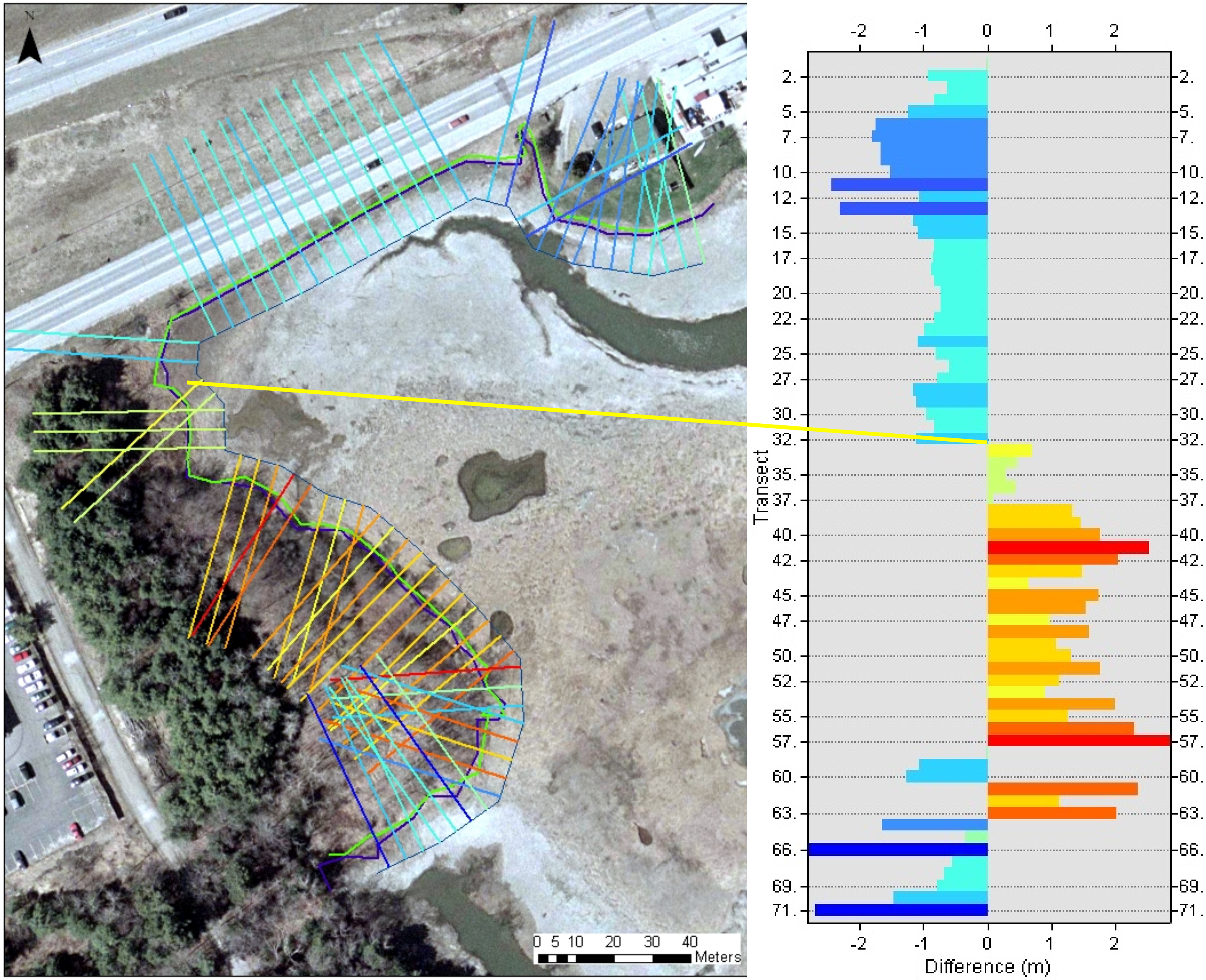


Figure 10. Difference in horizontal position of HAT boundary extracted from LIDAR (blue line) and field mapped boundary (green line) for the southern marsh area. The LIDAR overestimates (positive values, too far landward) the boundary along wooded areas, and underestimates the boundary (negative values, seaward) along the more open areas.

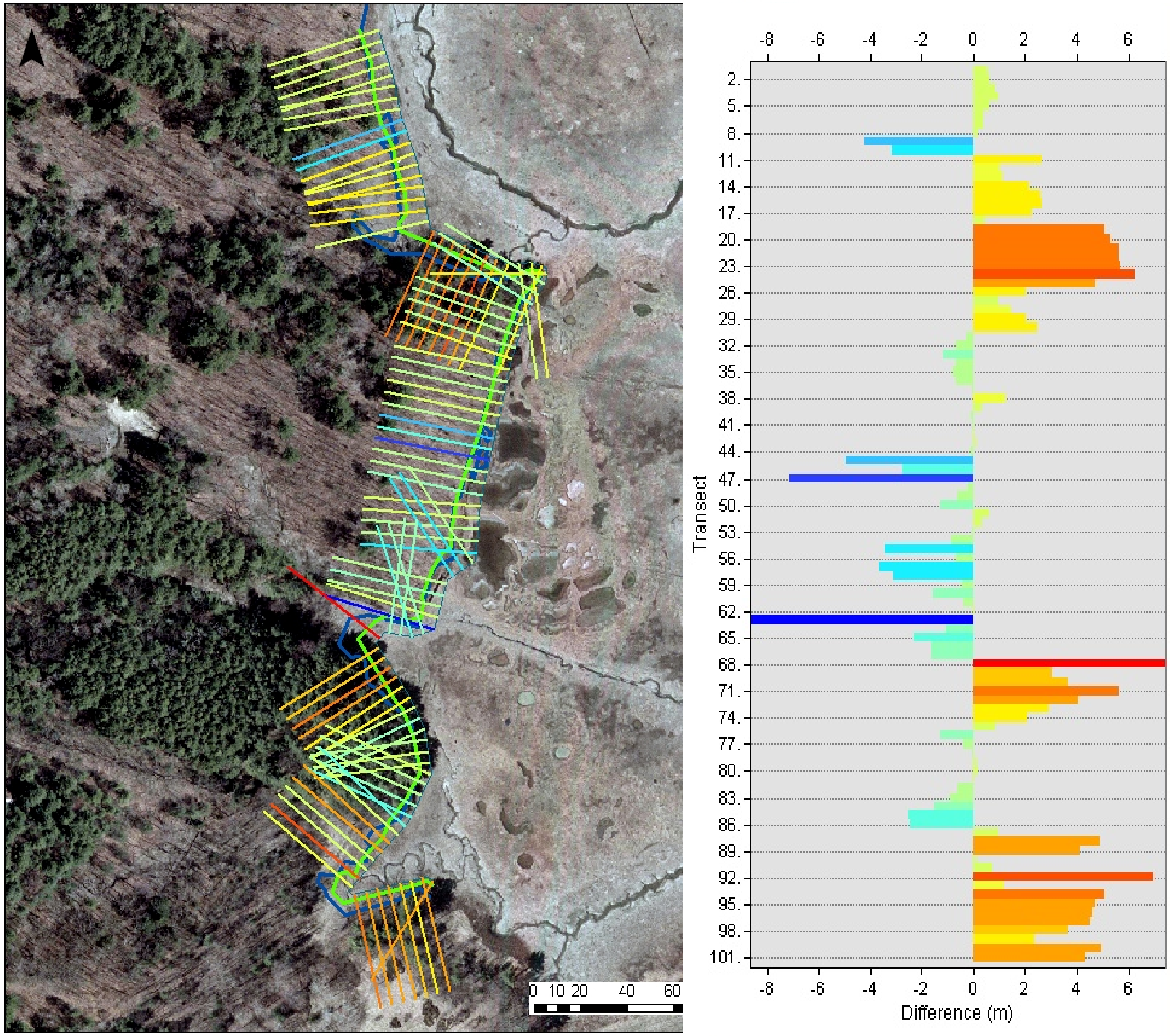


Figure 11. Comparison of HAT boundaries in the northern portion of the study area indicates that the LIDAR data has a tendency to overestimate (positive values) the inland extent of the boundary along heavily wooded areas.

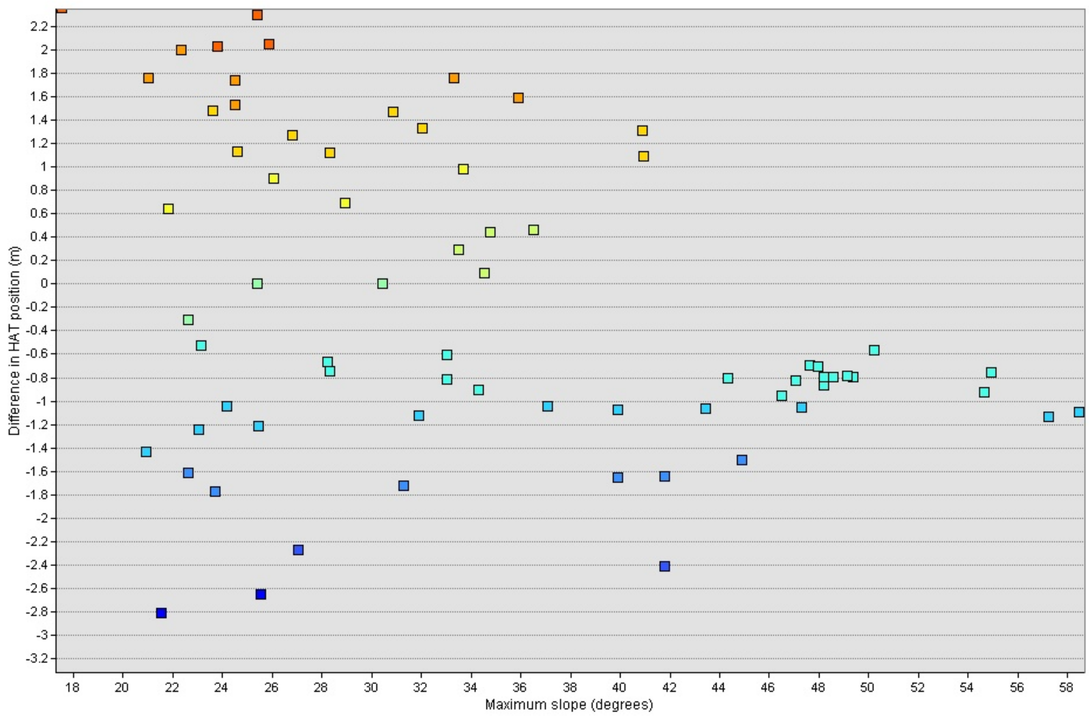
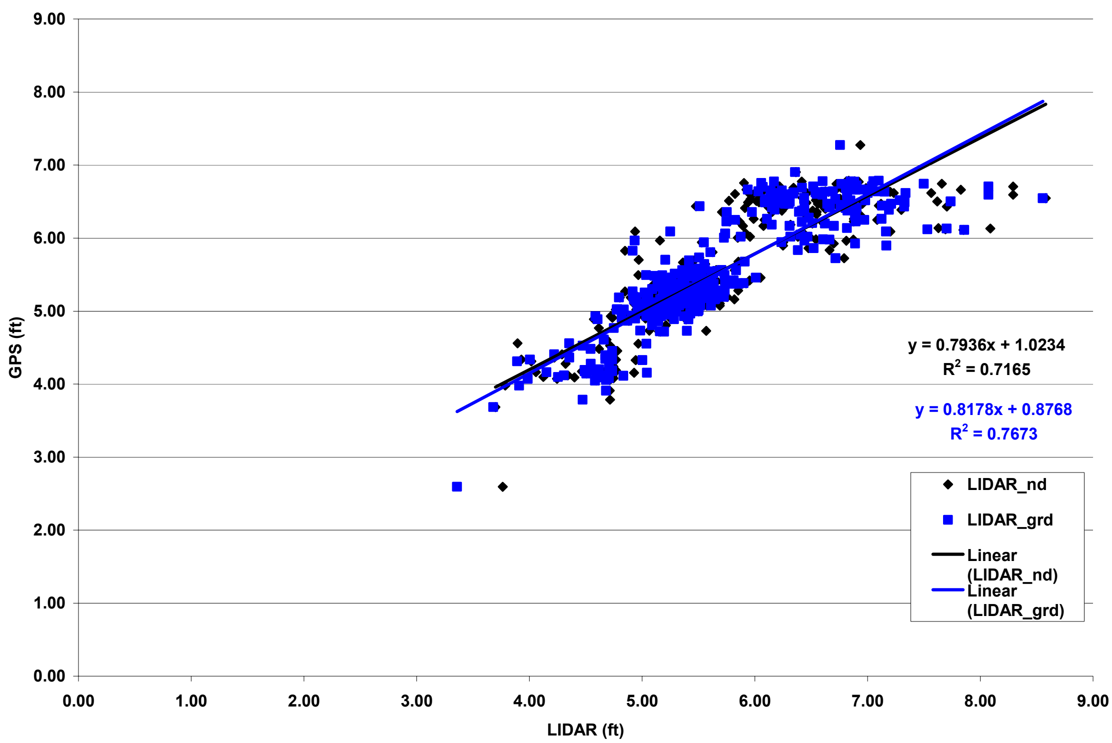


Figure 12. There is no linear relationship between the difference in the HAT position and maximum slope; however, it appears that when slopes exceed about 35-40%, the LIDAR will underestimate the boundary's inland position.

Figure 13. Although the relationship is not perfect, there is a strong linear relationship between LIDAR being able to accurately predict measured GPS values. Gridded data appears to work slightly better.



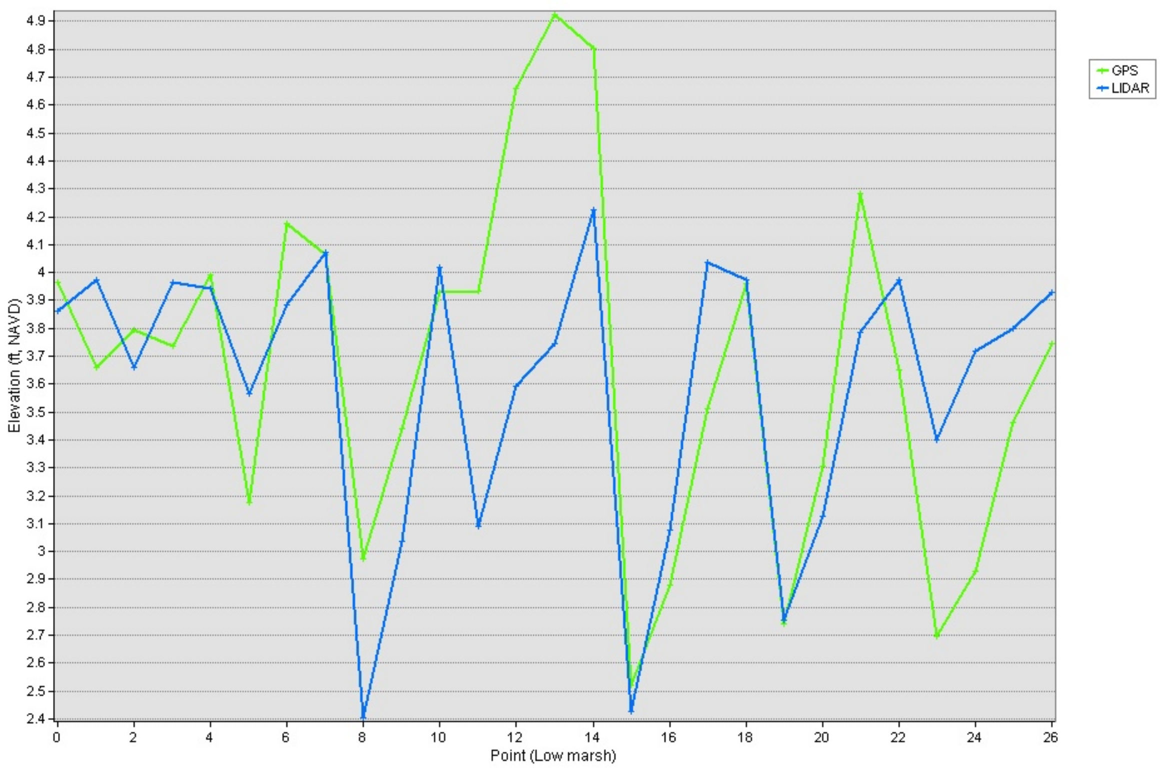
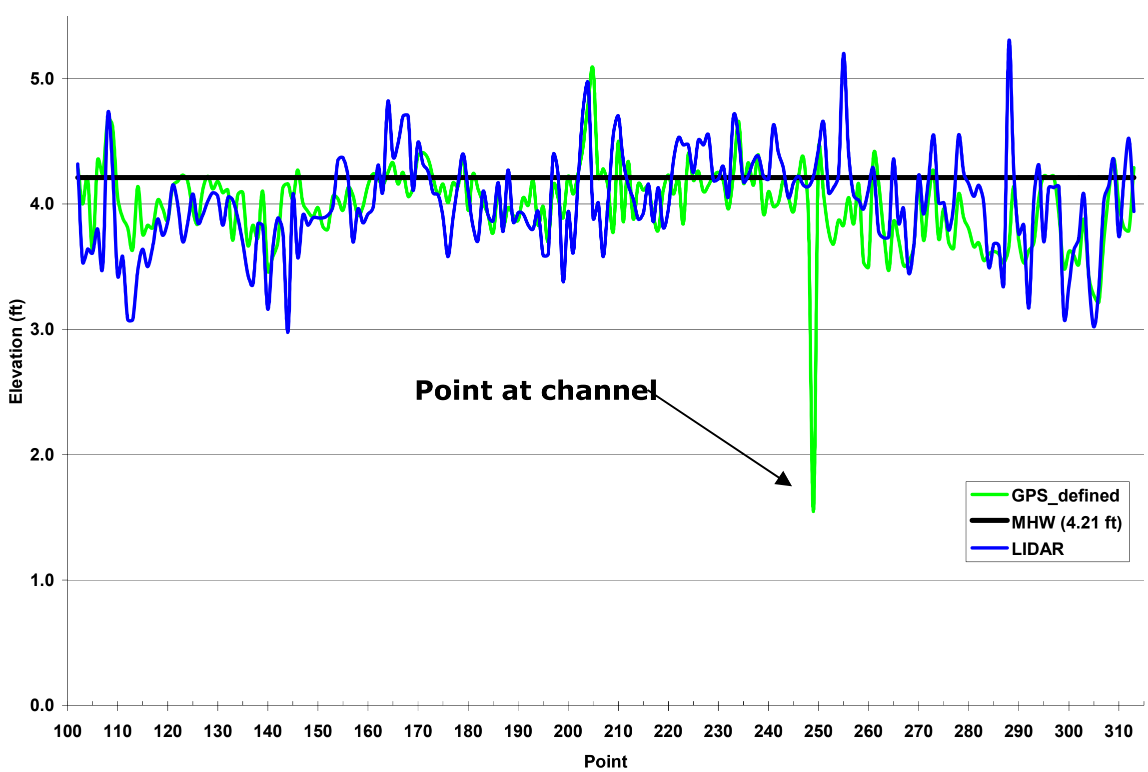


Figure 14. Relationship between LIDAR and GPS elevations within the low marsh. We are unclear as to the high value of the GPS data at this central point.

Figure 15. Relationship of LIDAR and GPS elevations along the high-low marsh (MHW proxy) boundary. The MHW line is shown in black. Note GPS elevations are higher along the left to center portion of the graph, and lower than LIDAR values to the right. The extremely low GPS point appears to be near a new channel.



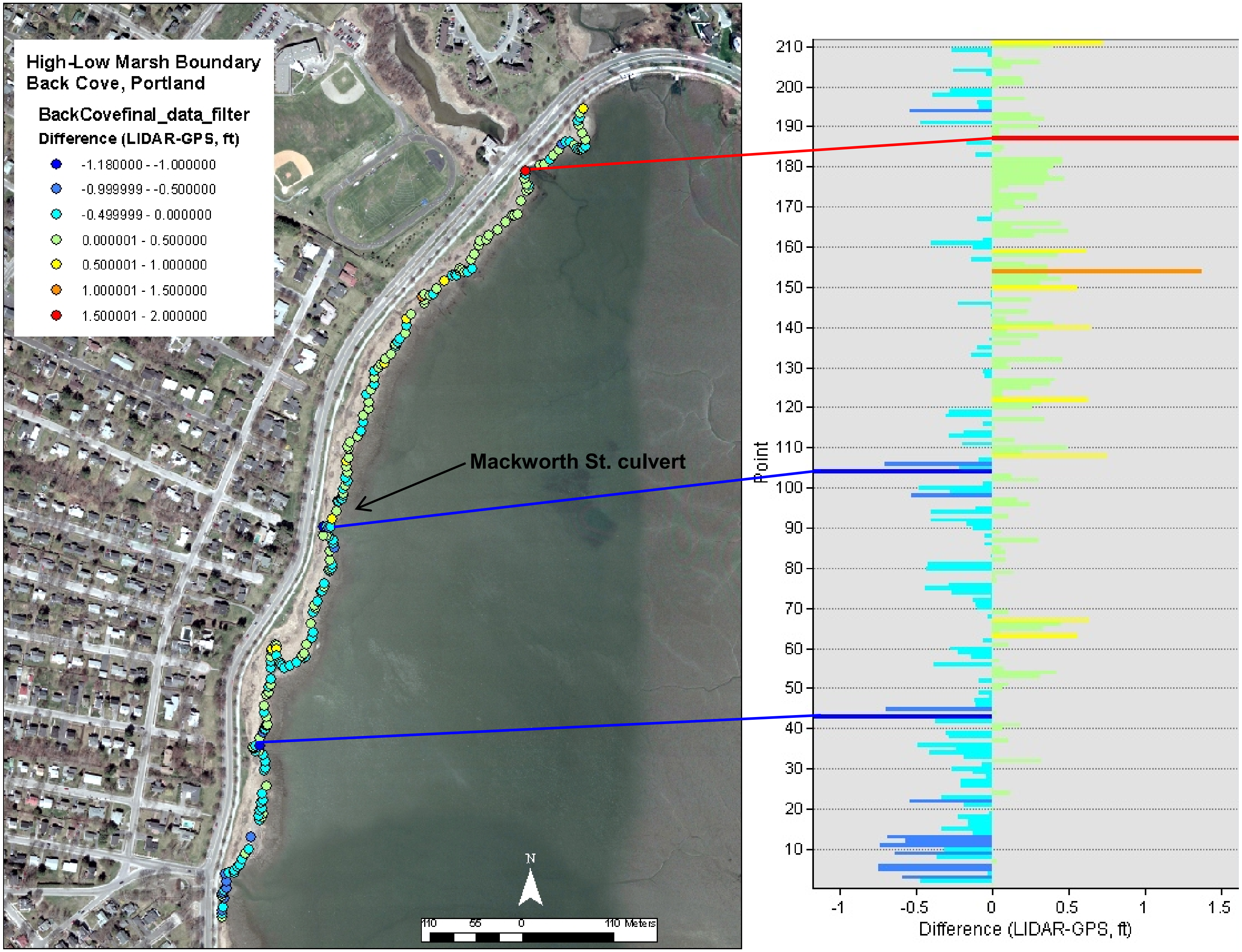


Figure 16. Longshore variation of the difference between LIDAR and GPS elevations at the high-low marsh boundary. Note nodal point near Mackworth Street culvert where signal of accretion (to south) changes to erosion (to north).

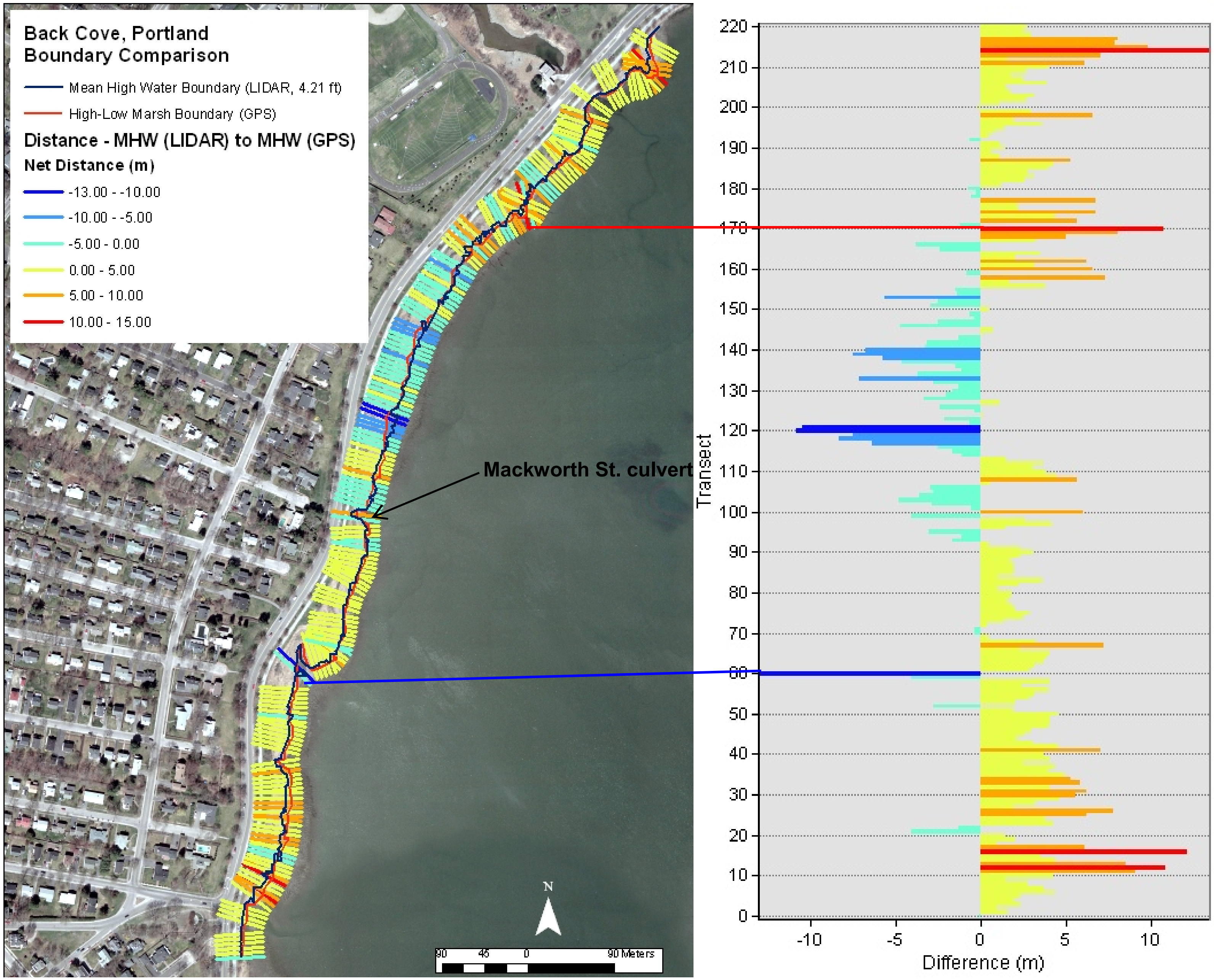


Figure 17. Spatial variation of the horizontal difference between LIDAR and GPS derived MHW (high-low marsh) boundaries. The overall difference is generally positive, indicating that the LIDAR data overpredicts the inland extent of the field defined boundary.

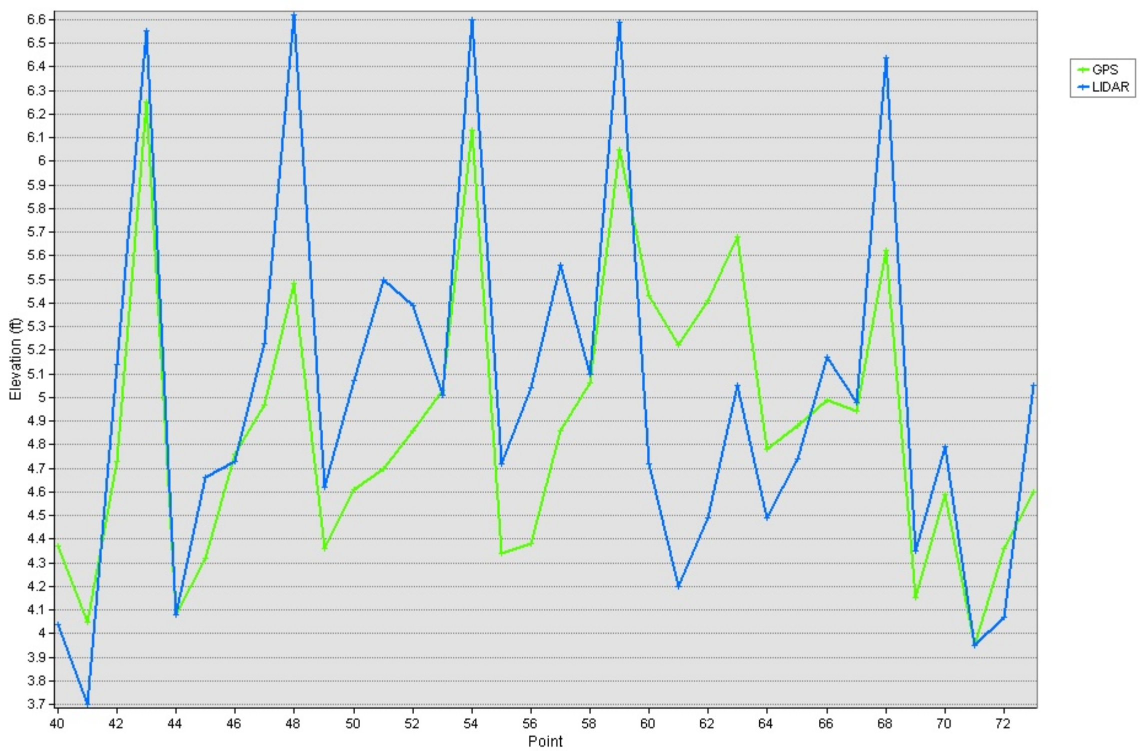
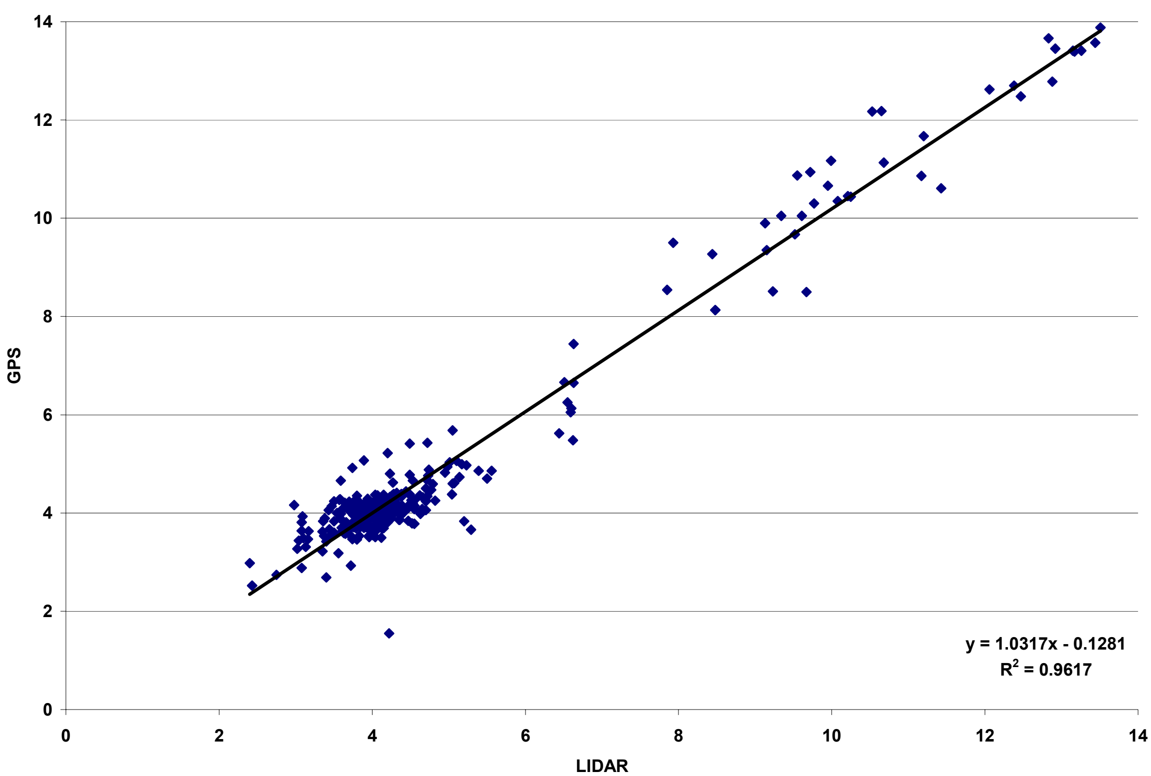


Figure 18. Relationship between GPS and LIDAR derived elevations within the high marsh area. LIDAR generally overpredicts the ground elevations.
Figure 19. There is a very good linear relationship between elevations from LIDAR and GPS (in ft) for the Back Cove study area.



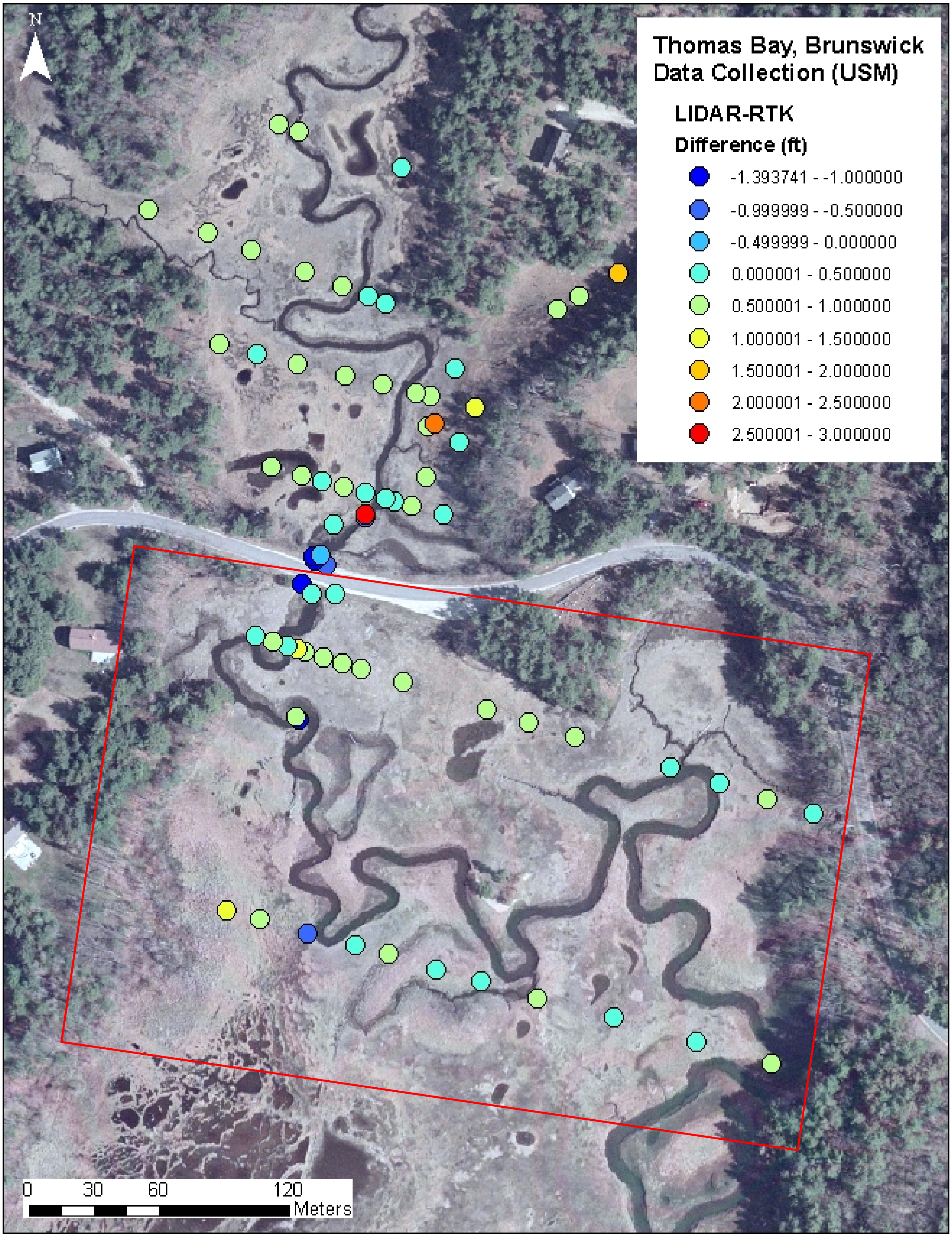


Figure 20. Distribution of LIDAR-RTK values in the southern (inside red box) and northern portions of the study area. Several high LIDAR values in the northern area slightly skew results.

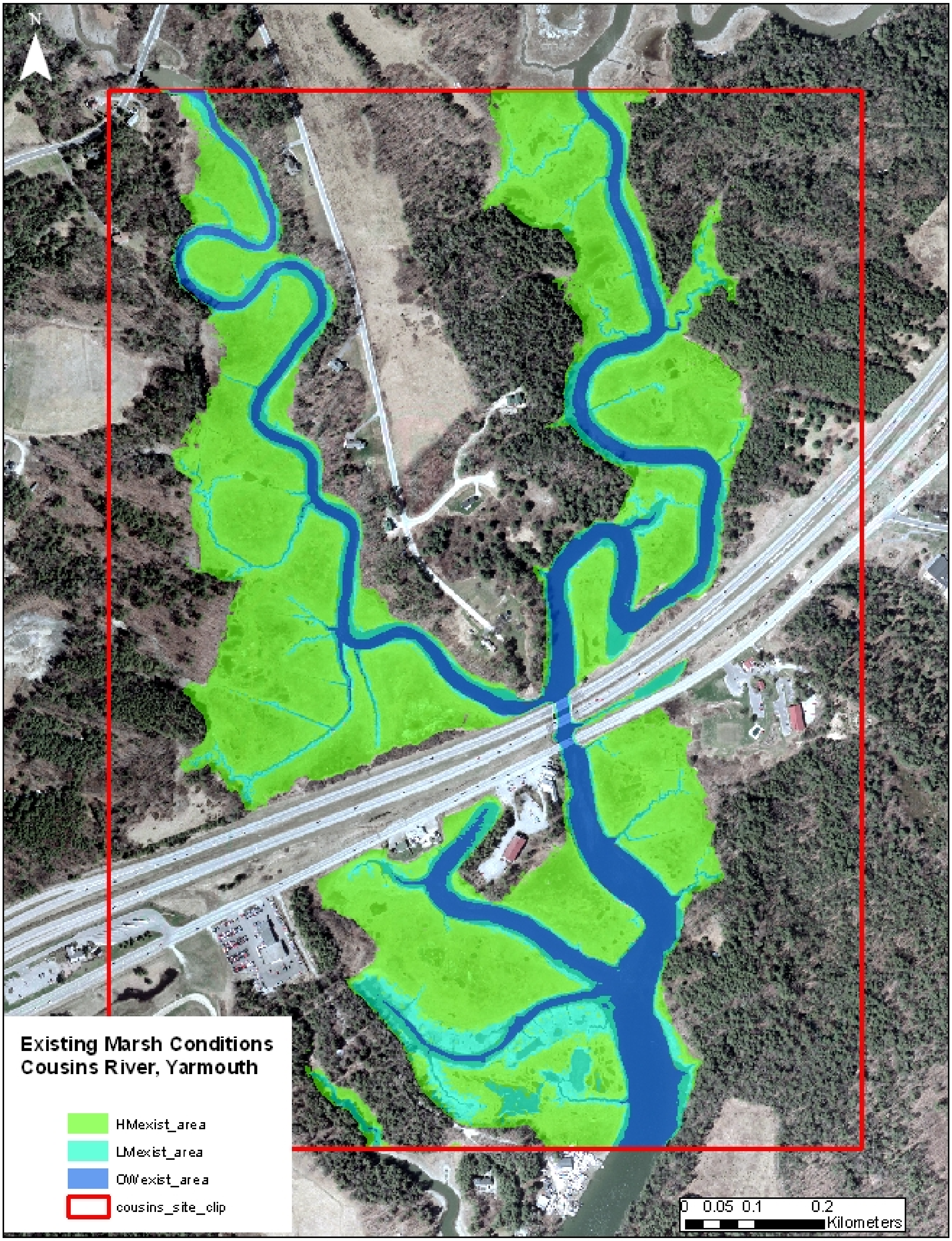


Figure 21. Simulation of existing marsh conditions at the Cousins River study area using applicable NOS tidal elevation data (NOS, 2009a). Note the dominance of high marsh, which has an area of 0.37 km^2.

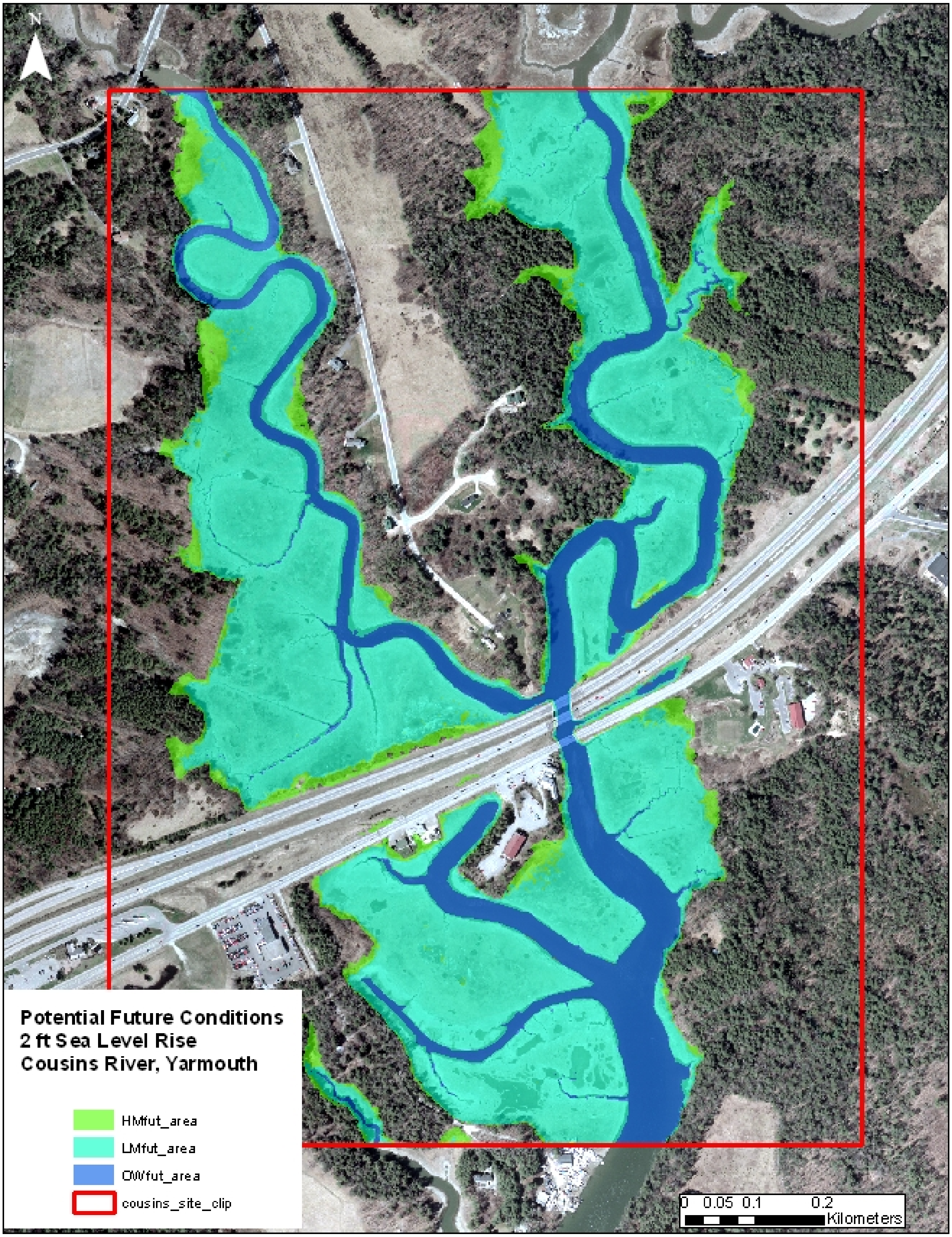


Figure 22. Simulation of potential future marsh conditions at the Cousins River after 2 feet of sea level rise. High marsh decreases by 84%, while low marsh area increases by over 325% from existing conditions.

Figure 23. Simulation of existing marsh conditions at Back Cove using NOS tide data (NOS, 2009a). Note prevalence of fringing low marsh. An area of low lying uplands at the soccer field (lower right) is actually not existing marsh.

Figure 24. Simulation of potential future marsh conditions at Back Cove after 2 feet of sea level rise. Note what little high marsh existed is pinched out by transgressing low marsh. The existing soccer field (southeast) appears to be the only area where the high marsh may have room to transgress, along with smaller finger marshes at the northern side.

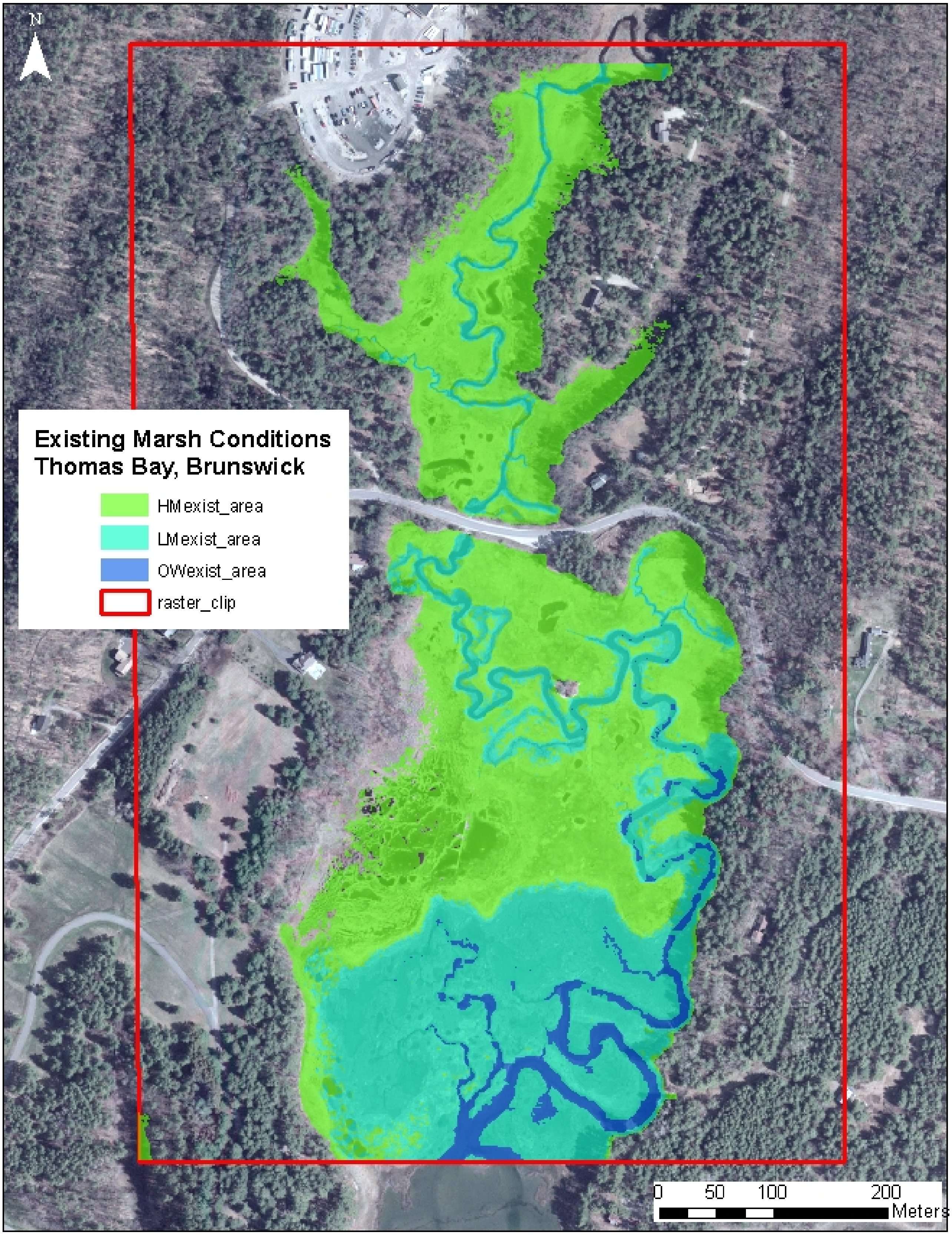


Figure 25. Simulation of existing conditions of marsh areas in Thomas Bay. Note dominant high marsh and area of extensive low marsh at south end of the site.

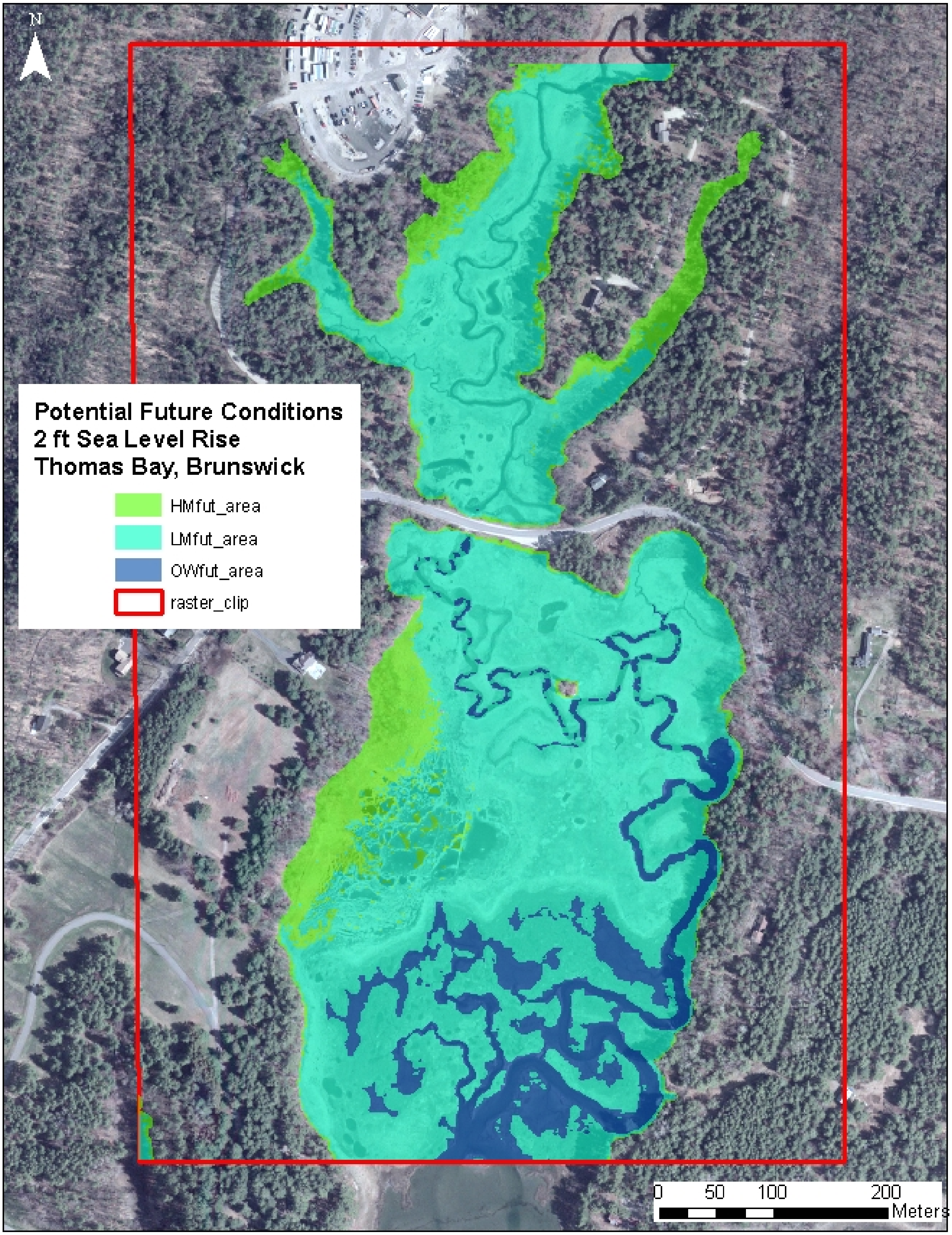


Figure 26. Simulation of potential future marsh areas in Thomas Bay. Note several small areas for high marsh transgression to occur. Low marsh becomes dominant.