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On the Use of Historical Bathymetric Data to Determine Changes in Bathymetry
An Analysis of Errors and Application to Great Bay Estuary, NH

By Martin Jakobsson[1,2], Andrew Armstrong[2], Brian Calder[2],
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Abstract

The depth measurements that are incorporated into bathymetric charts have associated errors with magnitudes depending on the survey circumstances and applied techniques. For this reason, combining and comparing depth measurements collected over many years with different techniques and standards is a difficult task which must be done with great caution. In this study we have developed an approach for comparing historical bathymetric surveys. Our methodology uses Monte Carlo modelling to account for the random error components inherited in the data due to positioning and depth measurement uncertainties.

Résumé

Les mesurages des profondeurs qui sont incorporés dans les cartes bathymétriques comportent des erreurs liées aux magnitudes en fonction des circonstances du levé et des techniques appliquées. Pour cette raison, la combinaison et la comparaison des mesurages de profondeur collectés depuis de nombreuses années à l'aide de techniques et de normes différentes est une tâche difficile qui doit être effectuée avec la plus grande prudence. Dans cette étude nous avons développé une approche pour la comparaison des levés bathymétriques historiques. Notre méthode utilise la modélisation de Monte Carlo pour rendre compte des composantes d'erreurs aléatoires dont héritent les données en raison des incertitudes liées à la détermination de la position et au mesurage des profondeurs.

Resumen

Las medidas de las profundidades que se incluyen en las cartas batimétricas han asociado errores con magnitudes que dependen de las circunstancias del levantamiento y de las técnicas aplicadas. Por este motivo, combinar y comparar las medidas de las profundidades recogidas durante muchos años utilizando diferentes técnicas y normas es una tarea difícil, que debe ser efectuada con gran precaución. En este estudio hemos desarrollado un enfoque para comparar levantamientos batimétricos históricos. Nuestra metodología utiliza la modelación de Monte-Carlo para considerar los componentes de error fortuitos heredados en los datos, debidos a las incertidumbres del posicionamiento y de la medida de las profundidades.

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Introduction

Understanding the temporal and spatial changes in the morphology of the seafloor (particularly in shallow estuarine environments) is a critical component of coastal management, with relevance for safety of navigation, habitat studies (including restoration and maintenance), contaminant distribution and a range of other processes. A seemingly straightforward approach to assessing annual, decadal or centennial changes in seafloor morphology is through the comparison of temporally separated bathymetric surveys. Although this approach seems straightforward and is frequently used, previous studies have identified a number of difficulties when comparing historical bathymetric surveys [e.g. Van der Wal and Pye, 2003]. In fact, combining and comparing seafloor measurements collected over many years with different techniques and standards

and, thus, varying associated errors, must be done with great caution [Jakobsson et al., 2002; Calder, 2005]. In addition to data quality and reference datum issues, there is also the fundamental problem of how to compare depth soundings collected many years apart at slightly different locations.

Here we present a study on the use of historic hydrographic data to estimate changes in bathymetry of the Little Bay and Great Bay, which comprise the inner portion of the Great Bay Estuary System located in the seacoast area of New Hampshire, USA (Figure 1). Two historical bathymetric data sets acquired by the US Coast and Geodetic Survey in 1913 and 1953-54 were used for our comparison. In addition, Little Bay was mapped using multibeam sonar in 2002 by the University of New Hampshire's Center for Coastal and Ocean Mapping/Joint Hydrographic Center (CCOM/JHC). The primary purpose of
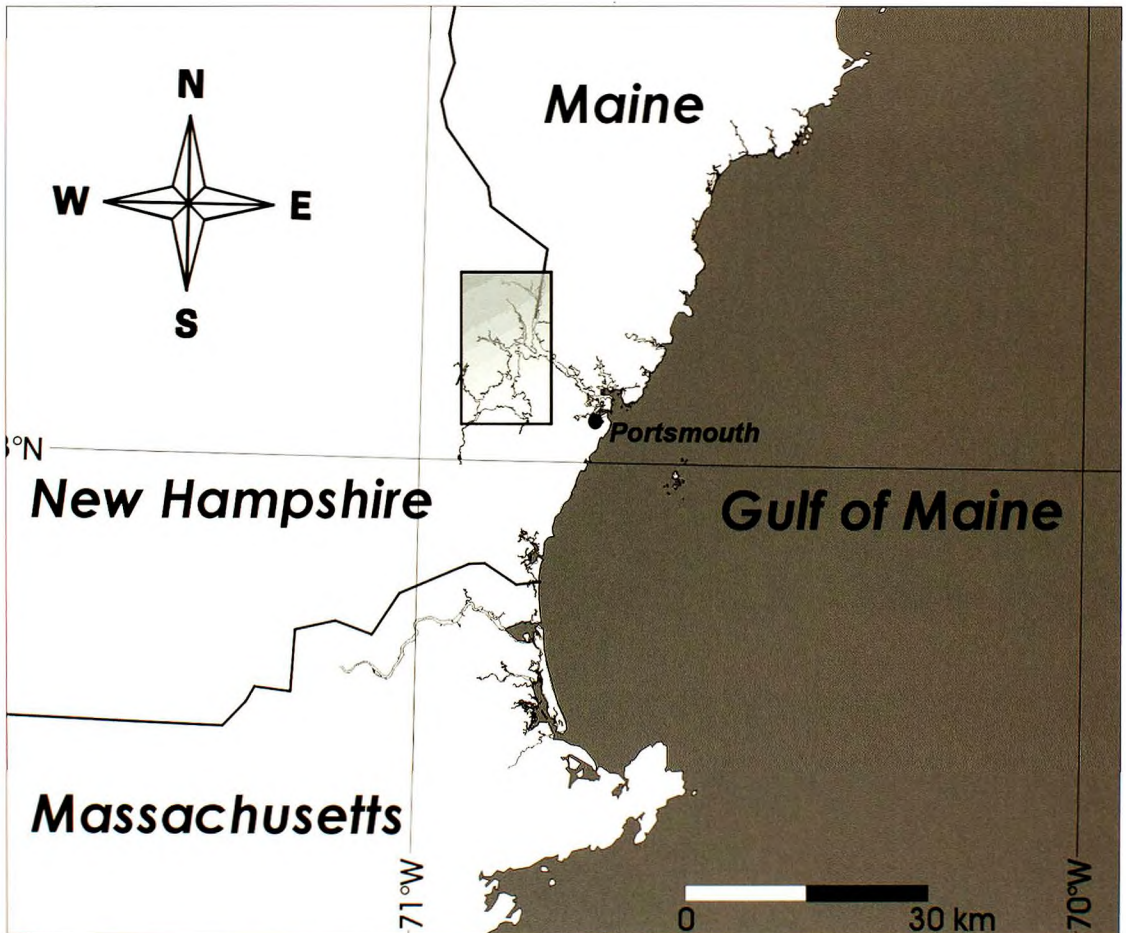

Figure 1: The Little and Great Bay study area is located in the upper portion of the Great Bay Estuary (shown in the box).

our study is to see if it is possible to quantita-tively determine significant changes over time in the bathymetry of the Little Bay and Great Bay using the available historical survey data. The multibeam survey is used only for reference. A protocol for bathymetric data comparison is developed that accounts for the probable random errors in the source data. The comparison of the data sets from 1913 and 1953-54 was accomplished through construction of Triangular Irregular Network (TIN) models using Delaunay triangulation for each data set and then the computation of point-wise differences between the respective TIN models and the original point data. To simulate the effects of random errors, Monte Carlo modelling was applied based on the approach developed by Jakobsson et al. [2002]. The recently acquired multibeam data set allowed a validation of the results from the historical hydrographic data in common areas.

Methods

Digitising

The soundings from the two data sets (1913 and 1953-54) were digitised from the U.S. Coast and Geodetic Survey's (predecessor to the National Ocean Service of the National Oceanic and Atmospheric Administration) smooth sheets. The 1913 smooth sheets (H3524 and H3525) were digitised at CCOM/JHC using a digitising tablet, and subsequently rigorously checked by importing the digitised soundings into an Access database for Intergraph's GIS system Geomedia Professional where the scanned smooth sheets were geo-registered with adjustments for scale, projection, and distortion, and used as raster backdrops. Any sounding initially digitised with the tablet that did not fall directly on its location in the checkup procedure was moved to fit the raster backdrop representing the smooth sheet using tools in Geomedia Profes-
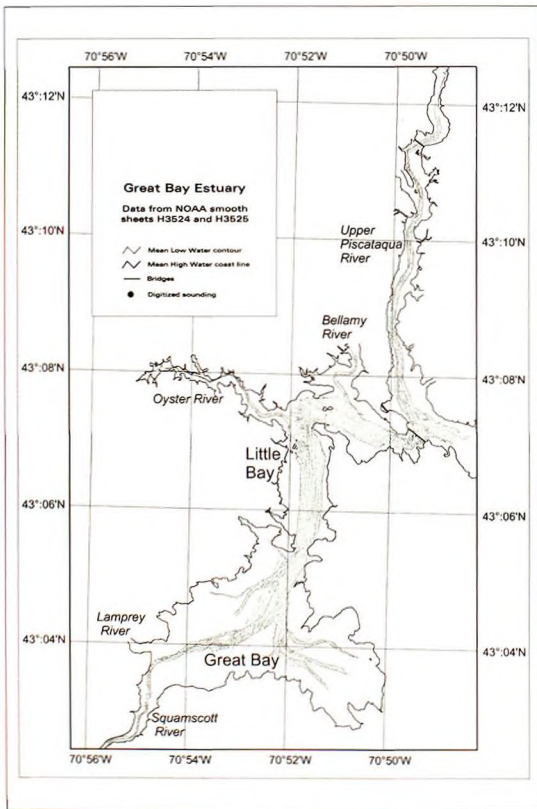

Figure 2: A) Distribution of soundings digitised from smooth sheets H3824 and H3825 containing hydrographic survey data acquired in 1913. A Mean Low Water contour was only present in the smooth sheets at very few locations hardly noticeable at the scale of this figure.
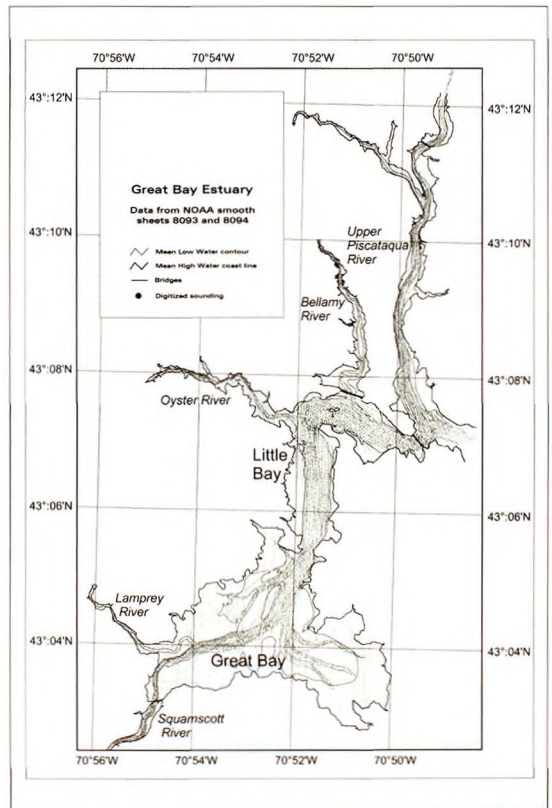

Figure 2: B) Distribution of soundings digitized by NOAA NGDC from smooth sheets H8093 and H8094 containing hydrographic survey data acquired in 1953 and 54. These sheets contained a comprehensive interpretation of a Mean Low Water contour.

sional. We estimate that the radial error of the geo-registration of the smooth sheets does not exceed 2m anywhere and, thus, the horizontal error due to the digitising process should be significantly smaller than the error for the horizontal positioning (see Error Model). The smooth sheets from 1953-54 (H8093 and H8094) were digitised by the National Geophysical Data Center (NGDC) and subjected by them to rigorous quality control procedures including verification of coordinate system, positions and soundings. These data were extracted as ASCII data files from NGDC for import to our Access database established for this pro-ject. Soundings on the smooth sheets are in feet. We converted the digitised soundings from H3524 and H3525 to metres, rounding to the nearest 0.1m. The shorelines (Mean High Water) and the 0ft (Mean Low Water) depth curves drawn on the smooth sheets were digitised using an automated head up raster digitising tool in MicroStation/ Descartes. Figure 2 shows the distribution of digitised soundings and vector shorelines.

Datum and Coordinate Transformations

The coordinates on the smooth sheets from 1913 and 1953-54 refer to North American Datum 1902 (NAD 1902) and 1927 (NAD 1927), respectively. All data that were digitised, or quality checked at CCOM/JHC, were initially adjusted within the horizontal reference of NAD 1927. The Coast and Geodetic Survey had marked a graticule referring to NAD 1927 on the smooth sheets from 1913 and, thus, the transformation from NAD 1902 to NAD 1927 was simply accomplished by geo-registering to this graticule tick. Following the digitisation and quality check, all data were transformed to NAD 1983 using the North Amer-

ican Conversion (NADCON) algorithm version 2.10 in order to overlay our results on recently acquired raster data, such as orthophotos.

The vertical datum for plotted soundings on both the 1913 and 1953-54 smooth sheets is Mean Low Water (MLW) according to accompanying Descriptive Report survey documentation. The range of interannual variation in mean sea level in the survey area is approximately 0.2m. This relatively large potential source of uncertainty in depth is eliminated, however through the establishment of tidal datums based on 19-year observation series. While it is not specifically stated in Descriptive Report, the 1953/1954 MLW datum is likely based on the 1924 – 1942 19-year tidal epoch using a tide gage formally located at Portsmouth Naval Shipyard (located at the mouth of the Piscataqua River). There were not nationally specified tidal epochs prior to 1943, so the 1913 MLW is likely referred to an earlier 19-year average from a nearby control tide station (probably Portland, Maine). Although interannual variation is removed as a source of uncertainty, mean sea level change does have an effect. Based on the recorded monthly mean sea level data at Portsmouth from 1926 through 1986, mean sea level in the study area has risen an average 1.75mm/yr, which translates to 0.07m in the 40 years between surveys. All other factors being equal, this mean sea level change would result in a corresponding 0.07m deepening of the Bays.

Triangular Irregular Network (TIN) Models and Gridding

TIN models were created from the digitised smooth sheet soundings using Intergraph's triangulation rou-
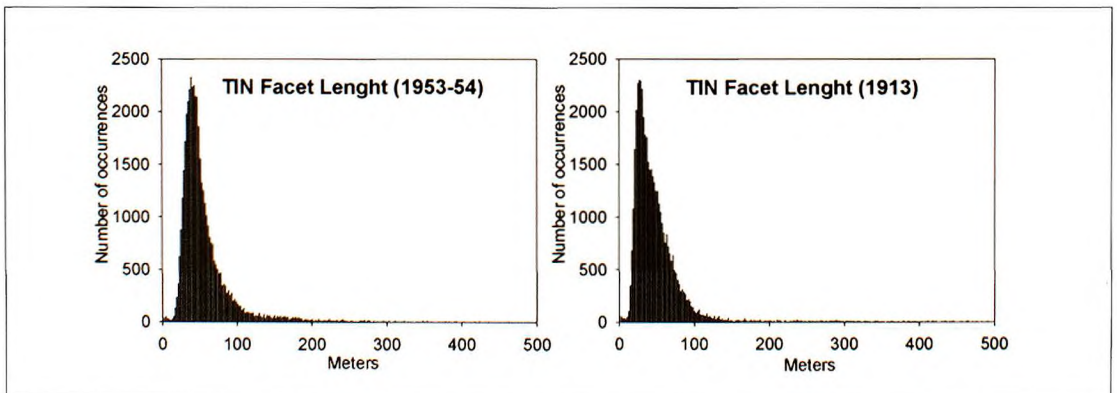

Figure 3: Histograms showing the distribution of calculated facet lengths in the TIN model generated from the data sets from 1913 and 1953-54.
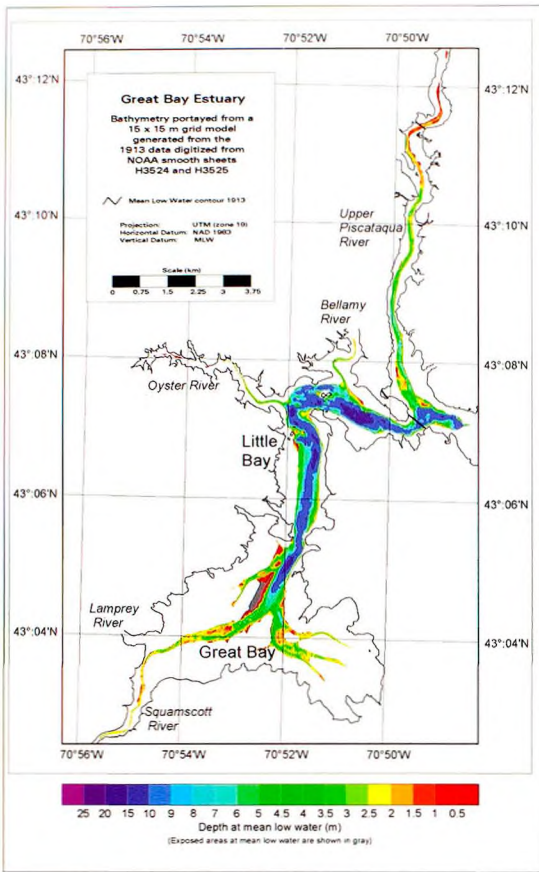
Figure 4: A) Bathymetry portrayed from a 15x15m grid model generated from the 1913 hydrographic survey data digitised of smooth sheets H3524 and H3525.
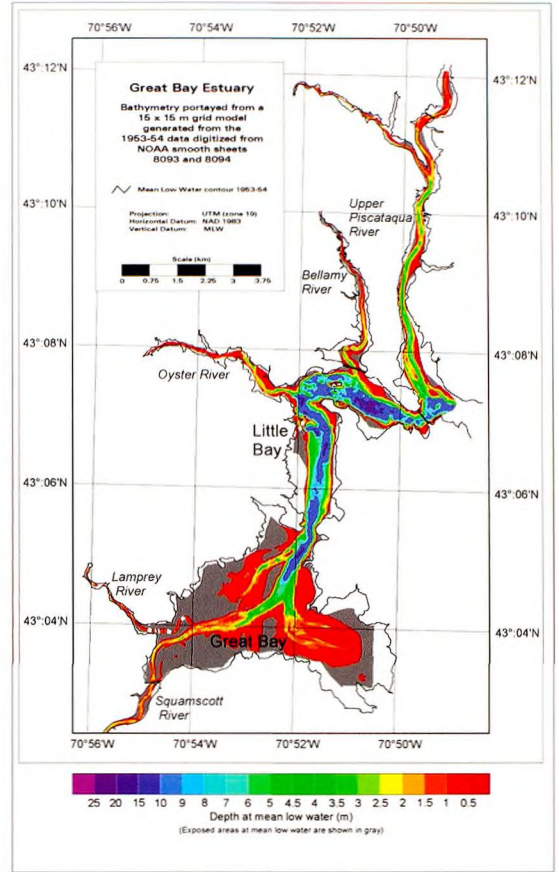
Figure 4: B) Bathymetry portrayed from a 15x15m grid model generated from the 1953-54 hydrographic survey data digitised of smooth sheets H8093 and H8094. The grey areas are mapped as mudflats, which are subareal during at the MLW level.

tine in Z/I Imaging's module MGE Terrain Analyst. This algorithm makes use of a Delaunay triangulation scheme [e.g.: McCullagh and Ross, 1980] where a set of unique optimised triangles are found from the given data set. The formed triangles are as nearly equiangular as possible and the sides of the triangles are as short as possible. This means that the greatest interpolation distance for a depth on a triangle facet is smaller than with other triangulation schemes. This is an important consideration for our analyses where one of the data sets is compared to the TIN-surface constructed from the other data set. Minimising the interpolation distance implies that our comparison algorithm (see below) compares the data points closest to each other. Initial TIN models for each data set (1913 and 1953-54) were constructed setting the longest facet of any triangle not to exceed 500m. The distributions of the computed facet lengths of these two initial TIN models are similar with distinct modes of approximately 29m in the

1913 data set and 40m in the 1953-54 data set (Figure 3). The tails of the distributions towards longer facet lengths starts at about 108 m in both data sets (Figure 3). Therefore, the maximum facet length allowed was set to 108 metres in the final TIN models used in our comparison in order to avoid long interpolation distances while still using the bulk of the data.

Finally, grid models based on the 1913 and 1953-54 historical bathymetric data were visualised using Fledermaus software. These grids were computed with 15x15m cell spacing using a bicubic interpolation algorithm in MGE Terrain Analyst. Figure 4 shows 2D maps created from the grid models illustrating the general morphology and bathymetry of Little Bay and Great Bay as represented by the 1913 and 1953-54 surveys.

Intersection between 1953-54 and 1913 Data

A quantitative comparison can legitimately be performed only within the overlapping area (intersection) of the data sets. Therefore, the intersection has to be defined according to some algorithm. This was accomplished by developing TIN models with the maximum allowable facet size defined by the distribution of the facet lengths (108m, Figure 3) and identifying the intersecting area of these models (Figure 5). This provides an analytical and reproducible approach for defining the area over which the two models can be compared (with the exception of the somewhat subjective decision of defining the maximum allowable facet length). However, this approach may exclude areas where comparison still legitimately can be carried out even with sparser data due to a flat bottom or very shallow water, such as the eastern and western extremities of Great Bay. Here, while the configuration of the bottom is adequately defined on H8903 smooth sheet, the soundings are widely spaced because of the very flat nature of the bottom. In this case a visual analysis yields clear conclusions, even though the automated analysis is impossible because of the limits on facet lengths that are appropriate for the deeper and more irregular sections of the Bays.

Monte Carlo Modelling and Comparison between 1913 and 1953-54 Data

The Monte Carlo method was initially developed as a numerical approach to compute difficult integrals that were too complex to analytically resolve [e.g. Hammersley and Handcomb, 1964]. In our study we used the modelling procedure to account for the combined three dimensional random error component that is associated with each depth measurement (inherited from the xy positioning and z (depth) measurement random errors, respectively). Our modelling procedure is based on the approach developed by Jakobson et al. [2002], which addresses the effect of random errors in bathymetric gridded compilations using the Monte Carlo method (see Appendix 1).

The comparison algorithm accounting for the random error component can be explained in the following six steps:

1) An error model for each of the data sets is assigned based on the information from the smooth sheet reports and assumptions described in the following sections.

2) One of the data sets is chosen to remain as original points.

3) The other data set is subjected to the Monte Carlo simulation of random error by perturbing the digitised data points with random vectors
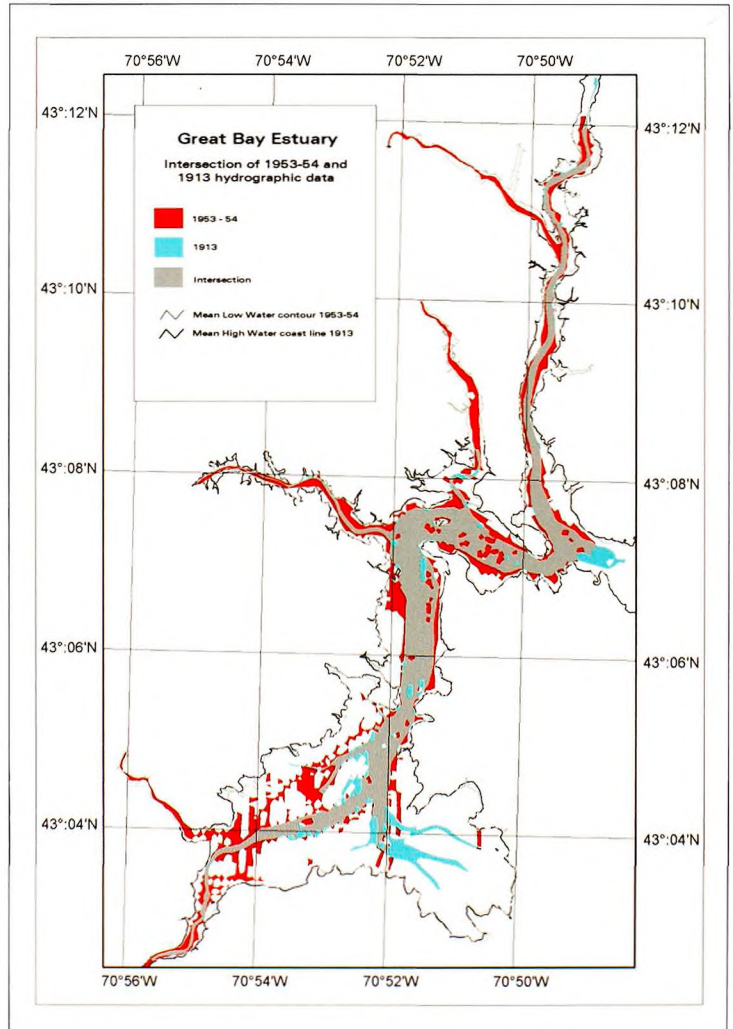

Figure 5: Defined intersecting area (grey) between the two historical data sets over where bathymetric comparison is carried out in this study.

proportional to the horizontal and vertical errors assessed for the survey (see Appendix 1).

4) For each set of perturbed data a TIN model is created using the method described above.

5) Each TIN model is compared to the original data points of the other data set by projecting the data point up or down onto the facet (Figure 6). The z-distance that the point must be projected to reach the TIN-facet is defined as the signed difference between the two data sets at that particular point.

6) We combine all signed differences from the comparisons between perturbed TIN models and original data points and compute their standard deviation at each original data point.

The main objective with this modelling procedure is that the computed standard deviation of the depth differences should show where the mean difference is significantly far from zero, i.e., where the difference observed is likely to be due to real changes, rather than measurement random errors. In our test we perturbed TIN models for the 1953-54 data and compared them to the 1913 original data points. Since we regard the two data sets having similar associated errors (see below) a second modelling experiment with perturbed TIN models for the 1913 data is not necessary.

Error Model for the 1953-54 and 1913 Data

Seafloor mapping surveys carried out by Hydrographic Offices normally conform to a standard that specifies minimum requirements for the horizontal and depth accuracies of bathymetric measurements. The International Hydrographic Office (IHO) Special Publication No. 44 on standards for hydrographic surveys is updated periodically by an IHO working group and has been published since 1968 [International Hydrographic Organization, 1968]. This publication lists recommended minimum standards for positioning and depth accuracies that depend on the type of area to be surveyed. These IHO standards were preceded by standards adopted in 1955 by the 7th Cartographic Consultation of the Pan American Institute of Geography and History. The Coast and Geodetic Survey incorporated those standards into Publication 20-2, *The Hydrographic Manual*. [Coast and Geodetic Survey, 1960]. For surveys completed prior to the adoption of these standards, it is difficult to quantify hydrographic survey accuracy. The U.S. Coast and Geodetic survey has published instructions for hydrographic work since 1878, and like other
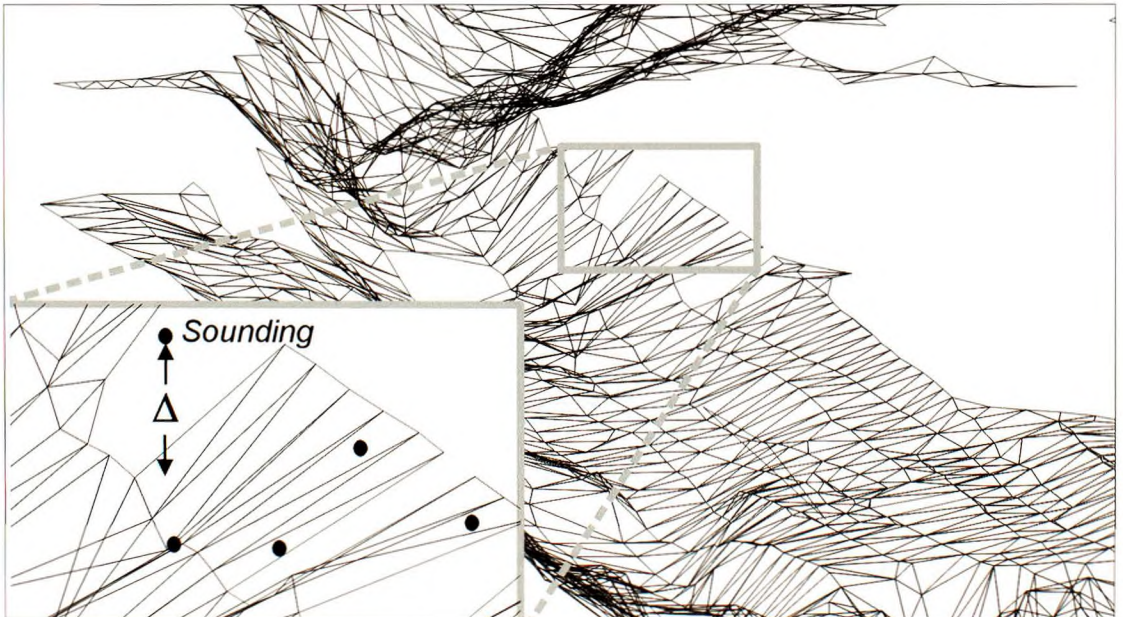

Figure 6: Illustration of the used procedure for estimating the difference between the soundings from the 1913 bathymetric data and the TIN models generated from the 1953-54 data. Each sounding from the 1913 data set is projected vertically down or up until it reaches the underlying or overlying facet of the TIN model and the vertical distance (ΔDepth) is calculated and used as a difference measure between the data sets at that particular location.

national hydrographic offices has maintained a reputation for high quality work. Because, with the exception of depth sounding, the hydrographic survey techniques used in 1913 were not significantly different from techniques used in 1953-54 and 1960, we use the 1960 *Hydrographic Manual* standards as a baseline for our error model. For each survey, we supplement this baseline with information found in the accompanying Descriptive Reports describing the positioning and depth measurement techniques used in the particular surveys.

The positioning error attributed to the Great Bay surveys arises from a combination of the accuracy of the topographic survey control stations and the accuracy of sextant resections. According to the 1960 *Hydrographic Manual*, the positioning error for a shore control station should not have exceeded 1mm at the scale of the survey. With the given survey scale of 1:10,000 this is 10m. The actual sounding positions are derived from sextant angles to the shore control stations. The maximum error for the position fixes is set at 1.5mm at the scale of the survey, giving a potential error of 15m. Noting that not every sounding is associated with a position fix (position of soundings between position fixes are dead reckoned), we interpret 'should not exceed,' and 'maximum' as Circular Error Probable (CEP) values. Using this information the accumulated overall error of the sounding positions adds up to $(10^2 + 15^2)^{1/2}= \pm18$m CEP using the standard formula for propagation of random errors expressed as standard deviations:

$$\sigma = \sqrt{\sigma_a^2 + \sigma_b^2} \qquad (1)$$

According to the 1955/1960 standards, depth measurements should have a maximum error of ±1 foot in shallow water and the error of the tide control should be no greater than ±0.5 foot. Interpreting cautiously, this gives an combined error of (1σ) ±1.1 feet (±0.34m). The depth measurements from 1913 were carried out using lead lines. This could cause significant errors in deeper water due the problem of a bulging line, however, in the shallow environment of Great and Little Bay this would not have been a problem. Therefore, it is likely that the 1913 depth measurements do not have associated errors that are larger than those of the more recent data from 1953-54. The most significant error source in both these surveys is the uncer-

tainty associated with tidal reducers. The Great and Little Bays are complicated tidal areas, and in both surveys, adjustments were made during Coast and Geodetic Survey office processing and verification. We are proceeding on the assumption that final office correctors resulted in depth soundings meeting the expected standards.

Multibeam Surveys from 2002
The multibeam data used in this study was collected as part of the Field Hydrography Course at the University of New Hampshire in summer, 2002. A Reson 9001 multibeam sonar was mounted on a bow ram on the CCOM/JHC survey vessel *Coastal Surveyor*. The sonar operates at 455kHz with 60 1.5° beams over a 90° swath width. Vessel attitude, heading and position were determined using an Applanix POS/MV v3. The raw data were logged in XTF format on a PC running Triton Isis and post-processed using Caris HIPS. Tides were measured at a gauge at the University of New Hampshire Jackson Estuarine Laboratory at Adams Point, near the southern end of Little Bay, and phase and amplitude corrections were made for areas away from the gauge. All data were corrected to represent MLLW. Sound speed casts were made approximately every two hours and applied to data close in time and space to the cast. Dynamic draft was determined using a level on shore measuring a rod on the vessel while running at different speeds.

The processed data were gridded at 1-m resolution using the weighted gridding algorithm built into Caris HIPS. The grid node is a mean of surrounding soundings, weighted by distance from the node and off-nadir angle, which correlates with measurement error.

These multibeam data did not figure in our comparison study. They were used after the fact in assessing the effectiveness of the process.

Results

Comparison between 1953-54 and 1913
The comparison between the two historical bathymetric data sets within the defined intersection (Figure 5) indicates a general shoaling from 1913 to 1953-54 (Figure 7). This comparison is calculated as the depth difference between the soundings from 1913 and a TIN model derived from the

1953-54 data as described above. The average depth difference is approximately 0.45m and the histogram plot in Figure 8 shows a symmetric distribution of depth differences around this mean. However, there are some prominent areas where the initial comparison indicates a substantial deepening from 1913 to 1953-54. One is in the western bend of the lower portion of Piscataqua River just north of the intersection with Little Bay and Great Bay between about 43°07'N and 43°08'30''N (Figure 7). The deepen-

ing here is more than 3m in the River's outer bend. Another area showing deepening is located in the middle of the river channel at about 43°07'40"N (Figure 7). As much as 4.6m deepening is indicated here. Furthermore, south of the Oyster River outlet there appears to be a large area of deepening (Figure 7).

The Monte Carlo modelling (see Appendix 1) was carried out as an attempt to quantify the influence of random errors on the comparison algorithm and thus achieve a general idea of the significance of the results and highlight areas where dubious depth changes might have been estimated. Figure 9 shows the outcome of the Monte Carlo modelling in the form of a map displaying calculated standard deviations of depth estimates at each 1913 sounding taking into account the random source data error. A large standard deviation of the depth difference implies that the random error associated with the sounding greatly influenced the comparison.

A general trend is clearly seen with higher standard deviations of the calculated depth differences following the channels (Figure 9). This is expected since the channels have sloping sides with higher gradients than the shallower sections on the flanks, making them more sensitive to random errors arising from the positioning. By querying the Monte Carlo results, and filtering out only the calculated depth differences that are larger than the estimated standard deviation, we are able to focus our interpretation especially on areas passing this criterion and reject areas where the random error causes larger uncertainties than the actual estimated depth difference. This is expressed by
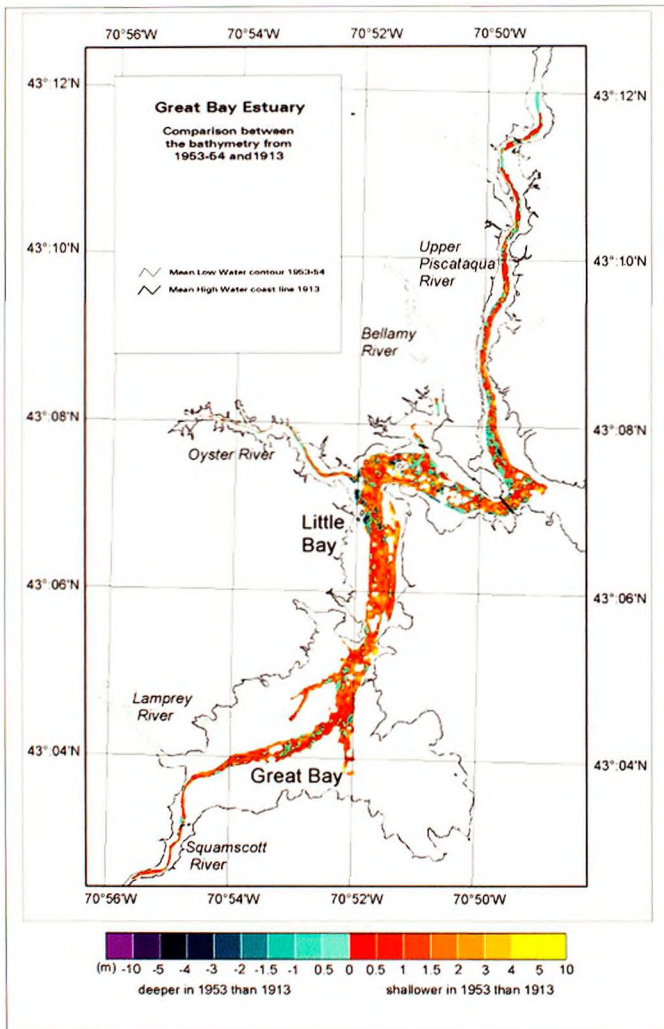
$$|\Delta Z| > \sigma(\Delta Z) \qquad (2)$$

Figure 7: Map showing the results from comparison between the 1913 soundings and a TIN model generated from the 1953-54 soundings. The comparison is made within the intersection between the two data sets as defined in Figure 7. Red-Yellow colours indicate that the bathymetry has become shallower in 1953-54 compared to 1913. The depth differences have been triangulated in order to improve the visual display.

where ΔZ is the difference between the 1913 soundings and the 1953-54 TIN model. The area that appears to have undergone a deepening in the western bend of the lower portion of Piscataqua River and the area farther out in the
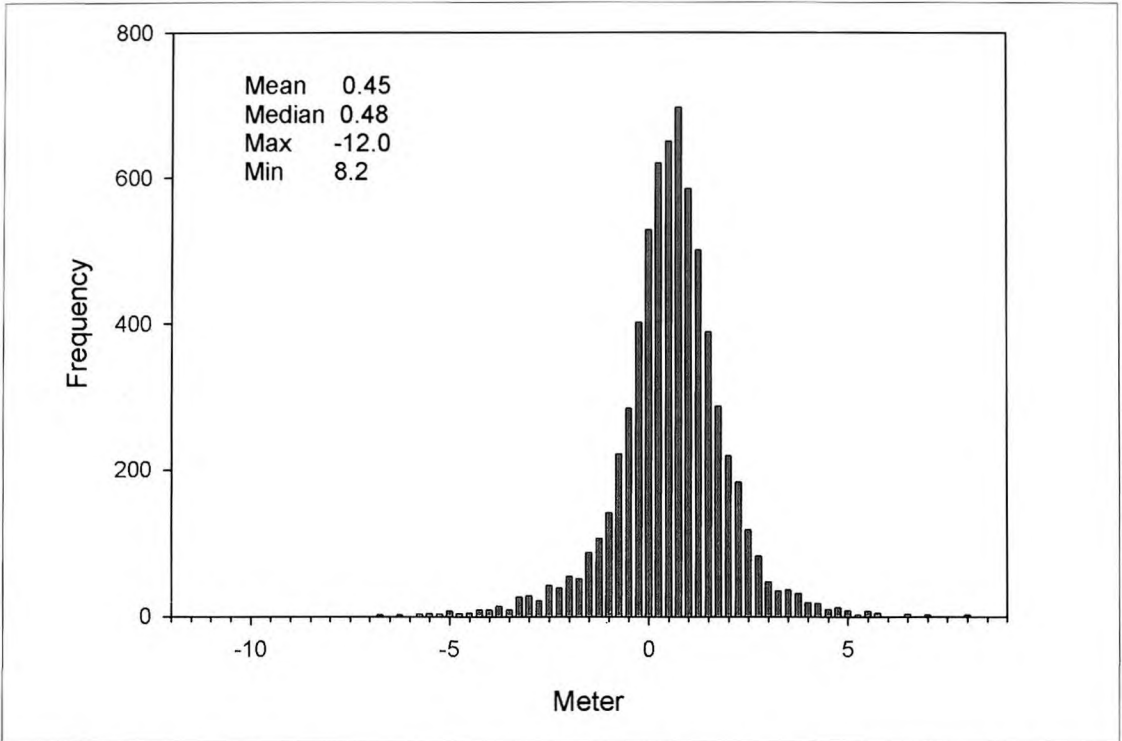
Figure 8: Histogram showing the comparison between the 1913 soundings and a TIN model generated from the 1953-54 soundings. Positive values indicates that the bathymetry has become shallower in 1953-54 compared to 1913 and, thus, an average shoaling is seen of approximately 0.45m.

channel at about 43°07'40"N (Figures 9 and 10) are associated with small standard deviations derived from the Monte Carlo modelling, passing the criterion of Equation 2 (Figure 10). Likewise, the Monte Carlo modelling generated standard deviations of calculated depth differences greater than the changes in depths in the area south of the Oyster river outlet where a deepening appears to have taken place, also passing the criterion of Equation 2 (Figure 10).

One general concern was that the results from the bathymetric data set comparison would simply reflect the horizontal distance between the soundings from 1953-54 and 1913. In other words, a larger distance between the soundings from the two historical data sets would be correlated to a larger depth difference. Comparison of the absolute value of the calculated depth differences and the accompanying horizontal distances between the 1913 and the 1953-54 hydrographic survey points indicates no trend (Figure 11). This indicates that the distances between the points had no consistent effect.

Coastline Comparison between 1953-54 and 1913
The Mean High Water shoreline from the two hydrographic surveys are both plotted in Figures 9 and 10. There is a clearly visible difference, in that the shoreline of the 1953-54 survey is located more seaward than the shoreline derived from the 1913 smooth sheets. The large differences are clearly visible in Figure 12. This apparent seaward migration of the shoreline likely results from the methodologies and definitions used in the hydrographic surveys, rather than a measurable change in shoreline position. For instance, a close inspection of an orthophoto of the Oyster River acquired by NOAA in 2001 (Figure 12) shows that the major differences primarily occur at locations where tidal salt marshes are found (at least in 2001). In addition, a photograph taken at high tide at the shoreline during in July, 2005 shows that the tidal marshes are dominated by high-standing Smooth Cordgrass (*Spartina alterniflora*) (Figure 13). This raises the question of whether the two shorelines from the historical surveys really are comparable, even if both are described in the accompanying survey metadata as representing Mean High Water.
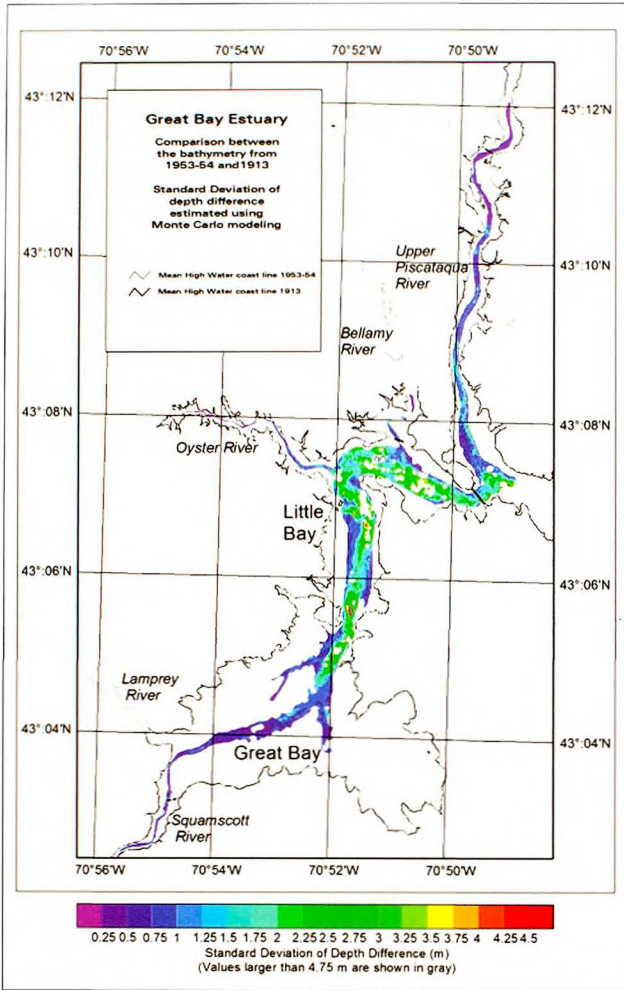
Figure 9: Standard deviation of the calculated depth differences as derived from the Monte Carlo modelling accounting for the random error component.

Discussion and Conclusions

Historical hydrographic survey data provides an important source of information for assessing morphological changes of coastal areas [e.g. Van der Wal and Pye, 2003]. However, comparing hydrographic data of historical surveys to detect changes over time requires an understanding of how the data were acquired and to what horizontal and vertical datums they are referenced. The uncertainty of depth measurements and positioning could be, in the worst case, larger than possible morphological changes, a circumstance that precludes statistically significant conclusions.

In this study we have developed an approach for comparing historical hydrographic surveys that accounts for the random errors that are inherent in the data due to uncertainties of positioning as well as the actual depth measurements. Thus, reliability of interpretations of changes in depths can be determined. However, it should also be noted that constant or systematic errors that may cause an overall bias in the depth or position measurements, such as an improperly defined vertical datum or inaccurate scale, horizontal datum, or projection on the source document, are not possible to address with our data comparison approach based on a Monte Carlo modelling.
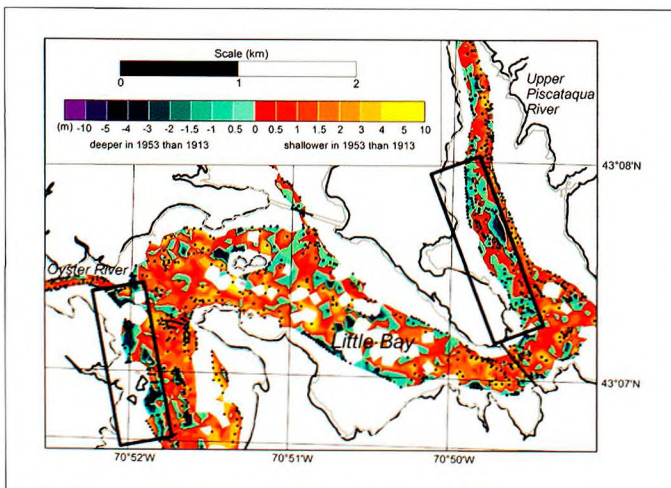

Figure 10: Detailed map showing the result from comparing the 1953-54 TIN model and the 1913 soundings. The black dots indicate the compared soundings that passed the criterion of Equation 2; the calculated depth differences are larger than the estimated standard deviation. The digitized MHW coastlines are shown in grey for 1953-54 and in black for 1913. The depth differences have been triangulated in order to improve the visual display. The two black rectangles denote the areas of deepening discussed in the text.

The general comparison of the area where the two surveys (1913 and 1953-54) overlap (Figure 5) shows an overall shoaling of approximately 0.45m (Figures 7 and 8). Is this a significant result? Does our Monte Carlo modelling help us interpret the result? From the map in Figure 9 showing the Monte Carlo computed standard deviation of calculated depth differences between the two surveys, it is hard to draw any obvious conclusion as to whether the result indicating an overall shoaling is valid or not. However, areas that show large morphological changes over time can be checked against this computed standard deviation map. For example, it is clearly seen that the lower portion of the Piscataqua River north of the inlet to Little Bay and Great Bay, as well as the area south of the Oyster River inlet, which both have calculated depth differences indicating deepening, are associated with small estimated standard deviations due to random errors (Figure 9). In addition, these two areas are both located in the "bends" of tidal channels where deepening of the channel is not unexpected.

A more detailed analysis of the apparent morphological changes in the Great Bay is provided by displaying only the calculated depth changes from 1913 to 1953-54 that are larger than the estimated depth differences standard deviations from the Monte Carlo modelling (Figure 10). In other words, only the points where the depth changes are significant according to our modelling taking into account the three dimensional random error components are dis-

played. Therefore, more confidence can be placed in morphologic changes indicated by these points. However, with only two data sets to compare, one must always keep in mind the possibility that an artificial bias could be causing the calculated depth differences. However, in our case we have defined the areas where "real" changes are likely.

The coastline comparison between the two surveys shows large changes in location when comparing the two Mean High Water shorelines. However, despite the fact that both surveys refer to the shoreline as Mean High Water, the apparent difference is more likely due to different survey approaches to establishing the shoreline. This discrepancy highlights the importance of carefully reviewing all accompanying or available metadata, i.e. the accompanying data describing survey techniques and methods etc. In addition, familiarity with the techniques and standards of hydrographic and topographic surveys are important. In our study, recent aerial and ground photographs clearly show that the difference between the two mapped shorelines is likely due to differences in mapping shorelines in areas where tidal marshes occur (Figure 13). For instance, the 1953-54 survey has clearly followed the procedures for establishing shoreline in tidal marshes described in Sea and Shore Boundaries [Shalowitz, 1964]. Here, a more practical procedure for drawing the shoreline has been followed since the marsh is a product of deposited sediment which is built up to the point when vegetation can take root. The more
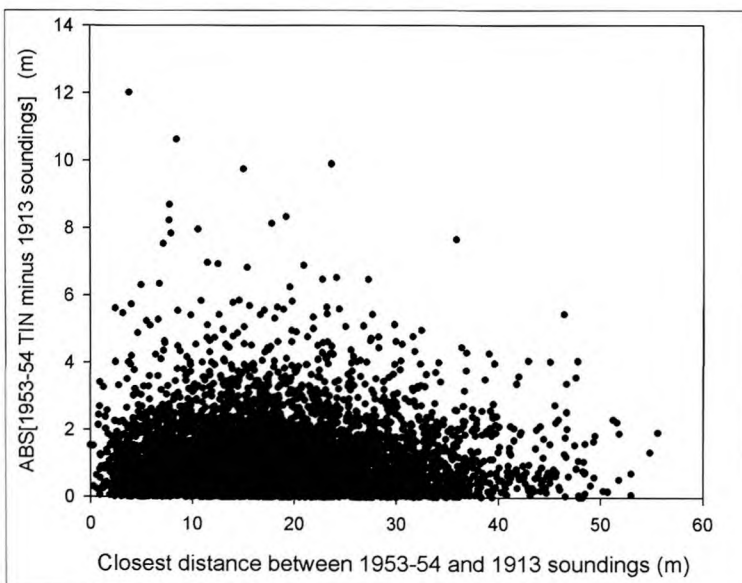

Figure 11: Calculated nearest distances between 1953-54 soundings to 1913 soundings plotted against the calculated depth difference between the 1913 soundings and 1953-54 TIN model.

modern practice for surveys in marsh areas is therefore not to establish the exact high-water line, but instead determine the outer or seaward edge of the marsh [Shalowitz, 1964]—the apparent shoreline—which the 1953-54 shoreline represents.

The areas surveyed by multibeam reveal another important factor to always consider while comparing historical sparse data sets. Surveys completed with lead line or single beam soundings rely on inference for depths between soundings or profiles. In most cases, hydrographic surveys carried out by the Coast and Geodetic Survey and similar national Hydrographic Offices locate and develop all signifi-

cant shoals in a survey area. However, and this is particularly the case in early surveys of less heavily trafficked waterways, noteworthy bathymetric features (shoals or deeps) can be missed between soundings. If one or the other of the surveys being compared locates all or part of the feature, and the other does not, then large differences in depth will be found that are neither the result of change nor the result of position or depth uncertainty. Any automated comparison such as the one we describe should be reviewed by the investigators to identify such anomalies. An example of this kind of missed feature is shown in Figure 14. In this case, neither survey located the feature completely.

Figure 12: Differences in Mean High Water coastlines from 1913 (orange) and 1953-54 (grey) surveys. The red boxes indicates areas where it is clearly visible that the 1953-54 coastline is located more seaward. A photograph taken of the area in the box marked A is shown in Figure 13.

Figure 13: Photo taken in July 2005, during high tide. The mapped locations of the coastlines from the 1913 (orange) and 1953-54 (grey) surveys are approximately plotted on the photograph. It is clearly seen that the 1953-54 coastline has been mapped at the seaward end of the muddy areas dominated by high standing Smooth Cordgrass (Spartina alterniflora) in the summer months while the 1913 coastline is mapped at the inside of these grass covered plains.
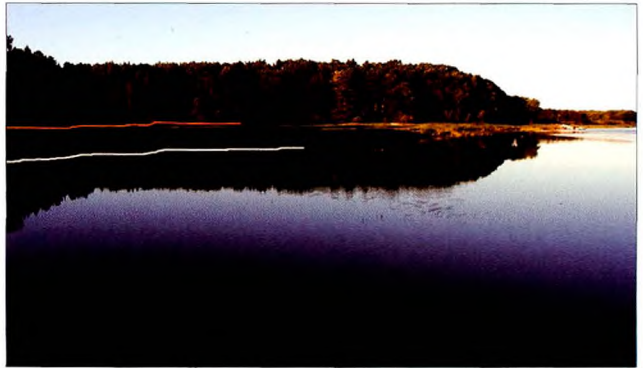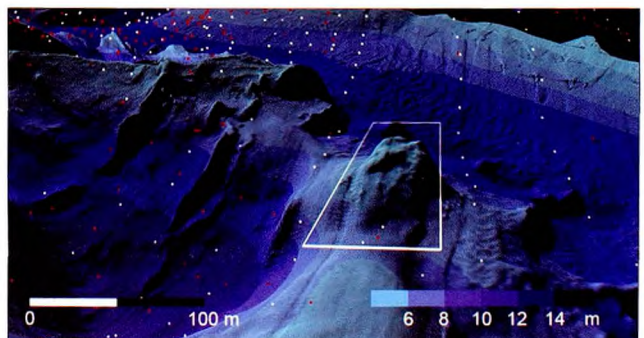

Figure 14: Multibeam data revealing the bottom of the Northern end of Little Bay with the view oriented looking towards the North. The white box is drawn around a bottom feature which is missed by both the 1913 (red dots) and 1953-54 (white dots) surveys.

Appendix 1: The Monte Carlo Method in Uncertainty Estimation

Our aim is to estimate the extent of the uncertainty that we should see at any arbitrary point in the domain of interest based on the expected uncertainty of the survey data. Such estimation allows us to determine whether the change that we see between survey epochs is greater than we might expect given the natural uncertainty of the data within either of the surveys. Our primary purpose, then, is to examine what the consequences would be if the data that we observe were to vary by their expected uncertainties as expressed through the assumed or estimated uncertainty model

$S(\theta; \beta) = \text{diag}(\sigma_x^2(\theta;\beta), \sigma_y^2(\theta;\beta), \sigma_z^2(\theta;\beta))$, where $\theta = (x,y,z)^T$, β is a vector of parameters, and $(\sigma_\eta^2(\theta;\beta)$, $\eta \in \{x,y,z\}$

is a completely general model for predicting uncertainty for any position in the problem domain. (In the particular case here, the simpler model $S(\theta;(\sigma_{xy}, k)) = \text{diag}(\sigma_{xy}^2, \sigma_{xy}^2, kz^2)$ is used).

However, there are a number of difficulties in this procedure, for example:

1. It is difficult or impossible to repeat measurements (the usual source of statistical information) since we cannot guarantee that the measurement system has not changed between measurements – there are no completely independent variables.

2. Historical measurements cannot be repeated: all we have is one sample from the population of all surveys.

3. Models used to compute or derive products from the source data can be complex. Therefore, a standard propagation of variance argument would be either very difficult to generate or very time consuming to pursue in sufficient detail to yield realistic estimates of uncertainty.

Consequently, we must pursue an alternative approach to estimating the uncertainty. Formally, the problem at hand is to determine the standard deviation that we would expect at a point on earth, $\sigma(x,y)$, given the natural variability of the input data from a single survey. This can be equivalently written as determining the variance at the point, and hence through the second central moment of the associated random variable, evaluating:

$$V(x,y) = E\left[(z(x,y) - \bar{z}(x,y))^2\right] = \int_{-\infty}^{\infty} (z(x,y) - \bar{z}(x,y))^2 \, p_z(x,y) dz(x,y)$$

This is difficult to evaluate in practice, primarily due to the difficulty in determining the probability distribution required. However, in this case we know that $z(x,y) = f(x,y;\Theta)$ where $\Theta = (\theta_1, \theta_2, ..., \theta_N)^T$ for N data points, $f(.)$ represents the method used to predict the depth, and $\theta_{i=}(x_i, y_i, z_i)$. Hence $z(x,y)$ is a random variable through the natural uncertainty of the input data, and the probability function of interest is really that of the input data. Therefore, the true expectation of interest is:

$$V(x,y) = \int_{-\infty}^{\infty} ... \int (f(x,y;\Theta) - E[f(x,y;\Theta)])^2 \, p(\Theta) d\Theta$$

in general. In practice, there are some simplifications that we might make, e.g., assuming independence so that $p(\Theta) = \prod_{i=1}^{N} p(\theta_i)$. The direct numerical evaluation would still be a formidable problem, however.

Problems of this type can be solved by the Monte Carlo method [Hammersley and Hanscomb, 1964], [Gentle, 2003], which is frequently used to evaluate integrals especially when the integrals are of high dimension, or are very complex [Brooks, 1998]. The method says, in effect, that if samples $y_i \sim p(y)$ (where '~' means 'is distributed as', or 'is a sample from' depending on context), then:

$$\frac{1}{N}\sum_i f(y_i) \approx \int_{-\infty}^{\infty} f(y)p(y)dy$$

for any function of the variables. That is, we can approximate the integral (and hence the expectation) by a sample estimate based on the data generated by drawing randomly from the appropriate distribution. Here, this means that if we simulate the mechanism by which the data would be generated and processed into depth estimates at any point, then averaging over all simulations so generated gives an estimate of the true standard deviation that we should expect, given our assumed uncertainty model $S(\theta; \beta)$ and processing model. That is, if we can generate a 'plausible' pseudo-dataset from that observed (under suitable assumptions of independence) by generating a random perturbation for each sounding:

$$\delta\theta_i \sim N(0_{3x1}, S(\theta; \beta))$$
$$\delta\Theta = (\delta\theta_1, \delta\theta_2, \dots, \delta\theta_N)^T$$
$$\tilde{\Theta} = \Theta + \delta\Theta$$

where $N(\mu, \Sigma)$ is a multivariate Normal with mean vector μ and covariance matrix Σ, then we may generate K such datasets, $\{\tilde{\Theta}_k\}$, $1 \leq k \leq K$, and summaries of the properties of the depth based on them reflect the uncertainties that would be expected given the uncertainty of the underlying data. In particular, if $T(x,y;\Theta)$ represents the value interpolated at (x,y) from a TIN generated from data points Θ, then let:

$$m_K(x,y) = \frac{1}{K}\sum_{k=1}^{K} T(x,y;\Theta_k)$$

and $$s_K^2(x,y) = \frac{1}{K-1}\sum_{k=1}^{K}\left(T(x,y;\Theta_k) - m_K(x,y)\right)^2$$

Then, $s_k(x,y)$ is an estimate of the standard deviation of depth that would be expected at (x,y) given the uncertainty model $S(\theta; \beta)$ and the TINing procedure, and can be used to test whether the observed difference between the datasets is more than might be expected by simple uncertainty of the input data in either dataset.

In practice, this process of repeated simulation of datasets can be readily implemented using suitable random number generators (see, e.g., [Gentle, 2003]), and makes a simpler, if sometimes time consuming, alternative to more formal uncertainty propagation methods. In essence, we are trading implementation efficiency for methodological simplicity.

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Dr Martin Jakobsson is an Associate Professor at Stockholm University. He worked for four years at the Center for Coastal and Ocean Mapping/ Joint Hydrographic Center, University of New Hampshire after completing a Ph.D. in 2000 at the Department of Geology and Geochemistry, Stockholm University. His thesis was titled "Mapping the Arctic Ocean: Bathymetry and Pleistocene Paleoceanography". Besides Paleocenography and seafloor processes of the Arctic Ocean Martin's research include development of robust techniques for combining historical and contemporary bathymetric data sets, tracking uncertainty in gridded bathymetric models and the use of Geographic Information Systems (GIS) for handling and analysing marine geological/geophysical data.

Captain Andrew Armstrong, NOAA (retired) is the NOAA Co-Director of the Joint Hydrographic Center at the University of New Hampshire. Along with the UNH Co-Director, he manages the research and educational programs of the Center. He is president of the Hydrographic Society of America and chairman of the FIG/IHO/ICA International Advisory Board on Standards of Competence for Hydrographers and Nautical Cartographers. Captain Armstrong has over 30 years of hydrographic experience with NOAA, including positions as Officer in Charge of hydrographic field parties, Commanding Officer of NOAA Ship Whiting, and Chief, Hydrographic Surveys Division.

Dr Brian Calder is a Research Assistant Professor at the Center for Coastal and Ocean Mapping & Joint Hydrographic Center at the University of New Hampshire. He graduated MEng and PhD in Electrical & Electronic Engineering from Heriot-Watt University in Edinburgh, Scotland in 1994 and 1997 respectively, but was subsequently seduced into sonar signal processing for reasons that are now obscure. His research interests have previously covered speech recognition, texture analysis, object detection in sidescan sonar, high-resolution sub-bottom profiling, simulation of forward-looking passive infrared images, acoustic modelling and pebble counting. Currently, they revolve around the application of statistical models to the problem of hydrographic data processing.

Prof. Larry Mayer graduated with an Honours degree in Geology from the University of Rhode Island in 1973 and received a Ph.D. from the Scripps Institution of Oceanography in Marine Geophysics in 1979. In 2000 he became the founding director of the Center for Coastal and Ocean Mapping at the University

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Dr Lloyd Huff has over 37 years in private industry and the federal government, working with acoustic instrumentation and oceanographic equipment. He received his Doctorate in Ocean Engineering in 1976 from the University of Rhode Island and was one of the lead professionals in the Office of Coast Survey (OCS) working to bring multibeam side scan sonars and multibeam bathymetric sonars into standard practice for shallow water hydrography. He was Chief of the OCS Hydrographic Technology Programs from 1988-1999. Dr Huff is working on

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Dr Larry G. Ward is a Research Associate Professor at the University of New Hampshire in the Department of Earth Sciences and Jackson Estuarine Laboratory. Dr Ward has a Ph. D. from the University of South Carolina (1978) in Marine Geology. Primary interests include estuarine, coastal, and inner shelf sedimentology and surficial processes. Dr Ward's most recent research has focused on estuarine sedimentological processes and depositional environments, coastal geomorphology and erosion, the physical characteristics of inner shelf bottom habitats, and the stratigraphy, sea level history and Holocene evolution of nearshore marine systems. Teaching interests ranges from introductory geology and oceanography courses to graduate level coastal and estuarine sedimentology and surficial processes course.