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HYDROGRAPHIC SURVEY PROGRAM ASSESSMENT

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Texas Water Development Board

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Executive Summary

To correctly manage surface water supplies for the State of Texas, it is vital that managers and state water planners have accurate estimates of reservoir volumes and understand the rate of reservoir capacity loss due to sedimentation. To address these issues, in 1991 the Texas Legislature authorized the Texas Water Development Board (TWDB) to develop a cost-recovery hydrographic surveying program. The program is charged with determining reservoir storage capacities, sedimentation levels, sedimentation rates, and available water supply projections to benefit Texas. Previous studies of the TWDB survey methodology and equipment suggest that TWDB surveys may err from 1-6% of the computed volumes, and such levels of error may limit the extent to which reservoir sedimentation rates can be determined. Surveying lakes is a labor and time intensive process and the program is continually evaluating new methodologies and technologies that have the potential to reduce the time and effort required to produce an accurate survey.

To fully address the issue of accuracy within the hydrographic survey program as well as to explore alternative methodologies that might make the survey process more efficient, TWDB performed a detailed study of Lake Lyndon Baines Johnson (Lake LBJ) in the Colorado River Basin of Central Texas. Lake LBJ was surveyed by TWDB three times between 2007 and 2009 using different survey methodologies. In addition, a diagnostic survey was conducted in the spring of 2009 to assess the variability in measurements made using different combinations of boats, equipment and survey technique used by TWDB. Additional surveys were conducted by third parties under contract to provide reference datasets for further comparison against TWDB collected data. Based on an analysis of all the collected survey data, several recommendations were made to improve the TWDB hydrographic survey program.

Volumetric surveys conducted by TWDB are very robust and can be conducted reliably with any of the equipment currently used by the TWDB. Alternative survey methodologies discussed herein provide accurate volumetric results in conjunction with the self-similar interpolation scheme (Furnans, 2006) and could be used in place of the current methodology if they reduce the overall effort required for a lake survey. Three of the boats currently used by the program can be run at higher speeds than the current standard of 6mph and still collect accurate measurements. One smaller boat should be run at the slightly slower speed of 5mph to maintain data reliability. Sediment surveys currently conducted by the TWDB are less robust than the volumetric survey. While the program uses the latest technology and processing techniques, determining the thickness of the accumulated sediment layer was found to be a much more difficult process that is highly dependent upon human judgment. Most difficulties lie in the consistent identification of the pre-impoundment surface from the echo sounder returns. This caused high variability in the sediment thickness estimates conducted by different TWDB staff and contractors. The measurement error at most individual locations is of the order of +/- 0.5 ft in most locations and is shown to be non-biased. Larger errors were found in localized regions with steep bathymetric gradients. Despite this, overall sediment volumetric estimates based on the current survey methodology are thought to be accurate to the limits of current technology. The alternate survey methodologies discussed herein are not recommended for sediment surveys for reasons described in this report. Further research is required to develop techniques or best practices to remove some of the variability in determining the pre-impoundment surface from echo sounder returns.

1. Introduction

In order to correctly manage surface water supplies for the State of Texas, it is vital that managers and state water planners have accurate estimates of reservoir volumes and capacity loss rates due to sedimentation. To address these issues, in 1991 the Texas Legislature authorized the Texas Water Development Board (TWDB) to develop a cost-recovery hydrographic surveying program. The program is charged with determining reservoir storage capacities, sedimentation levels, sedimentation rates, and available water supply projections to benefit Texas. Since its inception, staff in the hydrographic survey program have completed more than 125 lake surveys. Included in each survey report are updated elevation-area-capacity tables and bathymetric contour maps. In some reports, survey cross-sections and sedimentation results are also included. These products have been used by engineering firms and planners to determine reservoir yield and manage reservoir operation, and by TWDB, the United States Army Corps of Engineers (USACE), and the United States Geological Survey (USGS) in reporting statewide reservoir contents. The Texas Commission on Environmental Quality (TCEQ) has also used the results of TWDB hydrographic surveys in developing Texas water use permits.

1.1. Study objectives

Although TWDB staff go through every effort to assure the accuracy of their surveying and volumetric computations, each set of survey results contains some amount of uncertainty. Based on a 1997 study, Payne and Holly estimated TWDB survey accuracy ranges from 1-3% of the computed reservoir volume for any given water level (1997). Similar estimates were derived from analyses of recently completed surveys of Cedar Creek Reservoir (2007b) and Lake Kemp (TWDB, 2006), although the sources of error identified in these studies differ from those enumerated in Payne and Holly (1997). The combination of errors from both sets of sources suggest that TWDB surveys may err from 1-6% of the computed volumes, and such levels of error may limit the extent to which reservoir sedimentation rates can be determined.

To fully address the issue of accuracy in the hydrographic survey program, TWDB performed a detailed study of Lake Lyndon Baines Johnson (Lake LBJ) in the Colorado River Basin of Central Texas. The objectives of this study, aside from providing a highly accurate volumetric analysis of Lake LBJ, were to:

1) provide estimates of the uncertainties associated with TWDB's standard methods for conducting hydrographic surveys,
2) provide estimates of survey uncertainty obtained through variation of the survey/data collection methodology,
3) refine the survey methodology to reduce levels of uncertainty in the survey results, and
4) assess and improve TWDB's data processing techniques for determining reservoir volume from sounding data.

TWDB acted as the technical lead for this effort, and subcontracted several tasks out to Baylor University (Waco, TX) and with Hydrographic Consultants (Houston, TX). TWDB was responsible for the technical adequacy of all products. TWDB also consulted with representatives from the Lower Colorado River Authority (LCRA) to assure the project met their need for the Lake LBJ bathymetric survey.

This comprehensive report details all aspects of the Lake LBJ hydrographic survey program assessment project, and includes numerous recommendations for programmatic improvements.

1.2. Surveys conducted

Over the course of this project 6 separate surveys were conducted of Lake LBJ. Table 1 below describes the details of each survey.

Table 1: Summary of surveys conducted

Survey	Conducted by	Dates	Description
Multibeam	Hydrographic Consultants, Ltd.	May 21-24, 2007	Multibeam bathymetric survey for 19.3% of total lake area, shown in Figure 1
Survey1	TWDB	May 4-16, 2007 August 3, 2007 October 9, 2007	Single beam, multi-frequency bathymetric & sediment survey for entire lake
Survey2	TWDB	December 3-4, 2008 January 26-30, 2009	Single beam, multi-frequency bathymetric & sediment survey for 70.6% of lake area delineated in Figure 6.
Survey3	TWDB	March 16-18, 2009 April 20-28, 2009	Single beam, multi-frequency bathymetric & sediment survey for 70.6% of lake area delineated in Figure 6.
Baylor Sediment	Baylor University	July 9-11, 2007	Seven sediment samples described in Section 2.3.1.1 and Figure 12
Diagnostic Survey	TWDB	March 19-20, 2009 April 1-3, 2009	Single transect, single beam, multi-frequency, multi-boat, multi-transducer, multi-speed, bathymetric & sedimentation survey

The original Lake LBJ survey (Survey 1) included sedimentation analysis. This survey used TWDB's standard methodology (described in section 2.1.2) and was submitted to LCRA in report form (TWDB, 2009a). In addition, Dr. John Dunbar of Baylor University (BU) collected seven lake bottom sediment samples from Lake LBJ on July 9-11, 2007 and independently determined the accumulated sediment thicknesses (Dunbar and Estep, 2008). The locations of these sediment samples are shown Figure 12. TWDB used these sediment sample findings in interpreting post-impoundment sediment accumulation in Surveys 1, 2 and 3.

To assist in the comparison of different survey methodologies, the TWDB contracted Hydrographic Consultants, Inc. (HCI) to conduct a multibeam bathymetric survey of Lake LBJ within approximately 2 miles of Wirtz Dam on May 21-24, 2007 (HCI, 2007). This survey was used as a baseline for bathymetric comparisons in the areas it covered.

2. Effect of survey line placement and density

In April 2009, TWDB published a report named *Volumetric and Sedimentation Survey of Lake Lyndon B. Johnson* (2009a) herein referred to as the 'LBJ Report'. This report details the survey results from Survey 1 which was conducted using standard TWDB surveying procedures. These procedures call for the survey to proceed along pre-planned lines running perpendicular to the assumed location of the river channel, with the lines starting along the dam and spaced at 500 ft.

Survey planning, operationally defined here as the spacing and orientation of pre-planned survey lines, is likely to affect volumetric calculations if there are notable bathymetric changes between surveyed lines. In many cases, however, reservoir bathymetry will not be known before the survey, and survey lines must be planned based on an interpretation of the reservoir shape in map-view and the presumed location and orientation of the submerged stream channel. Previous TWDB surveys have been conducted using lines spaced at 250 ft intervals (TWDB, 2009b; TWDB, 2006), and at 500 ft intervals with selected areas of 100-ft spaced survey lines (TWDB, 2009c). Analyses of data collected on Lake Kemp indicate that greater volumes are obtained from surveys conducted with higher density line spacing, yet the volume increase is a result of the surface generation methodology used within ArcGIS (Furnans, 2006)

To assess the importance of survey line planning in computing accurate reservoir volumes, the majority of Lake LBJ was surveyed with single-beam depth sounders 3 times, each survey using lines developed according to the following criteria:

- **Survey 1 –** TWDB standard 500 ft line spacing
- **Survey 2 –** Manual line spacing and orientation optimization based on self-similar theory
- **Survey 3 –** Semi-automated line spacing and orientation optimization based on flowline theory algorithm

The survey lines in Survey 2 and Survey 3 are non-uniformly spaced and oriented and were designed in an attempt to reduce the number of survey lines (and hence man hours) needed to survey the lake while still maintaining survey accuracy. Additionally, to assess the accuracy of the TWDB standard survey methodology, several other steps were taken: 1) A partial lake, multibeam bathymetric survey was conducted by Hydrographic Consultants, Ltd. and served as the basis for comparison of volumetric data. 2) Selected survey lines were re-surveyed by Baylor University (July 9 – August 1, 2007) to compare sediment thickness data collected with different multi-frequency depth sounders. 3) Data from Survey 1 was reanalyzed by Baylor University to provide a basis to compare post processing and interpolation techniques.

2.1. Survey methodology

During TWDB surveys (i.e Survey 1, 2 and 3), data was collected at speeds not exceeding 6 mph using the ADCP boat (see Section 3.1.1 for description) and a Specialty Devices, Inc. (SDI) multi-frequency (200 kHz, 50 kHz, and 24 kHz) sub-bottom profiling depth sounder integrated with Differential Global Positioning System (DGPS) equipment. Each day prior to surveying, TWDB used a weighted tape and stadia rod to physically verify the depth recorded by the depth sounder.

2.1.1. ***Multibeam survey***

Hydrographic Consultants, Inc. (HCI) conducted a multibeam bathymetric survey of Lake LBJ on May 21-24, 2007. The multibeam depthsounder allows for obtaining a high density (5 x 5 ft) grid point coverage of the bottom bathymetry. The multibeam survey also incorporated a heave/pitch/roll sensor to properly geolocate the acoustic soundings along the reservoir bottom. The extent of the multibeam data collection is shown in Figure 1 below.

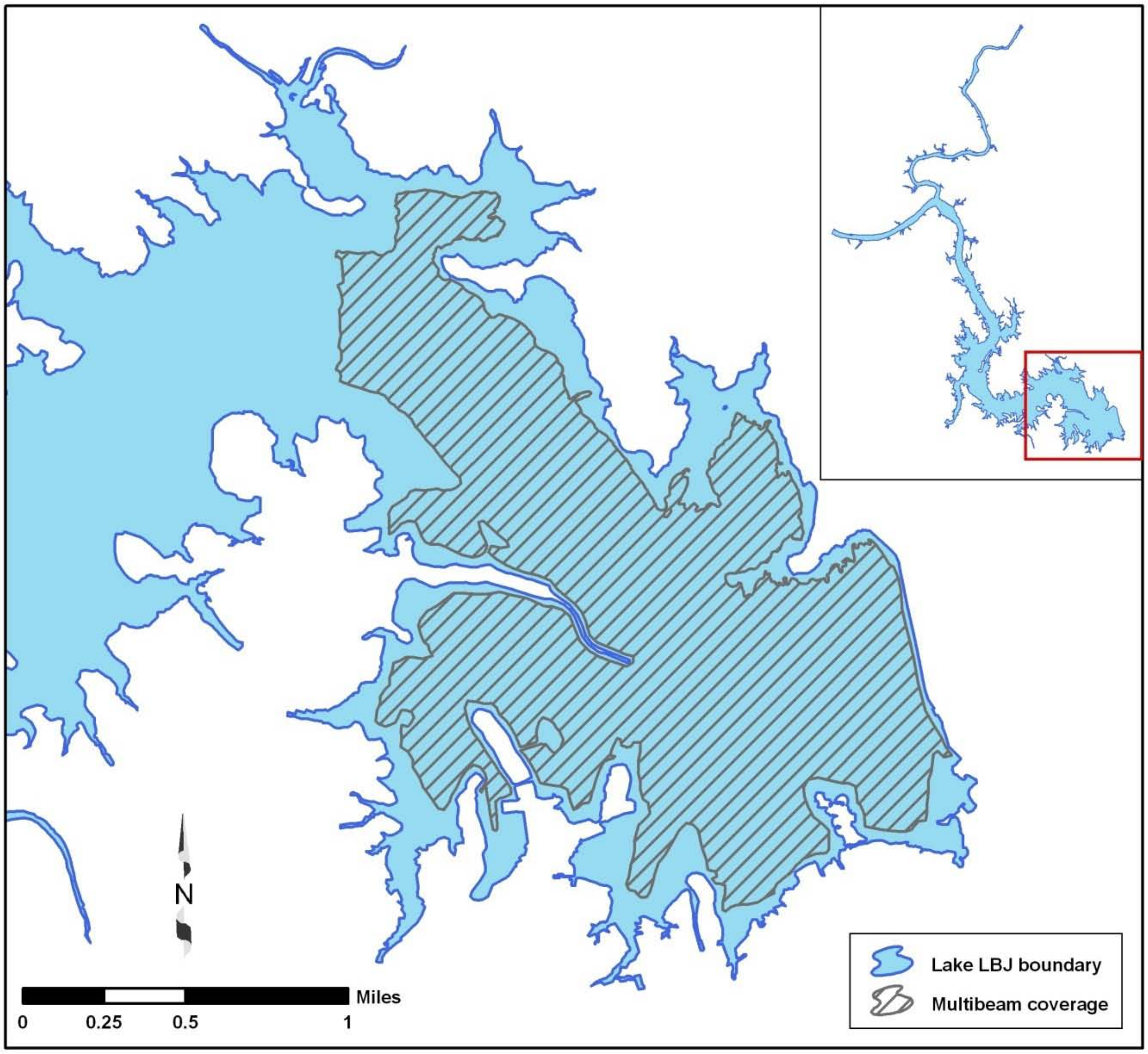


Figure 1: Multibeam survey coverage

2.1.2. ***Survey 1 – TWDB standard survey***

The TWDB standard bathymetric survey planning method consists of data collection lines spaced 500-ft apart and oriented perpendicular to the assumed location of the submerged river channel. Radial lines are utilized when the shape of the lake and presumed shape of the submerged river channel curve. Survey 1 data collection occurred on May 4, 7-10, and 14-16 of 2007 with additional data collected on August 3 and October 9, 2007. During data collection, the water surface elevation of the lake ranged between 824.57 and 824.98 feet above mean sea level (NGVD 29). It should be noted that the majority of Survey 1 data collection occurred ***before*** the flooding of the Highland Lakes system in the Summer of 2007, whereas the additional Survey 1 data collection occurred ***after*** the flooding. Figure 2 below shows the location of data collected ***after*** the 2007 flooding.

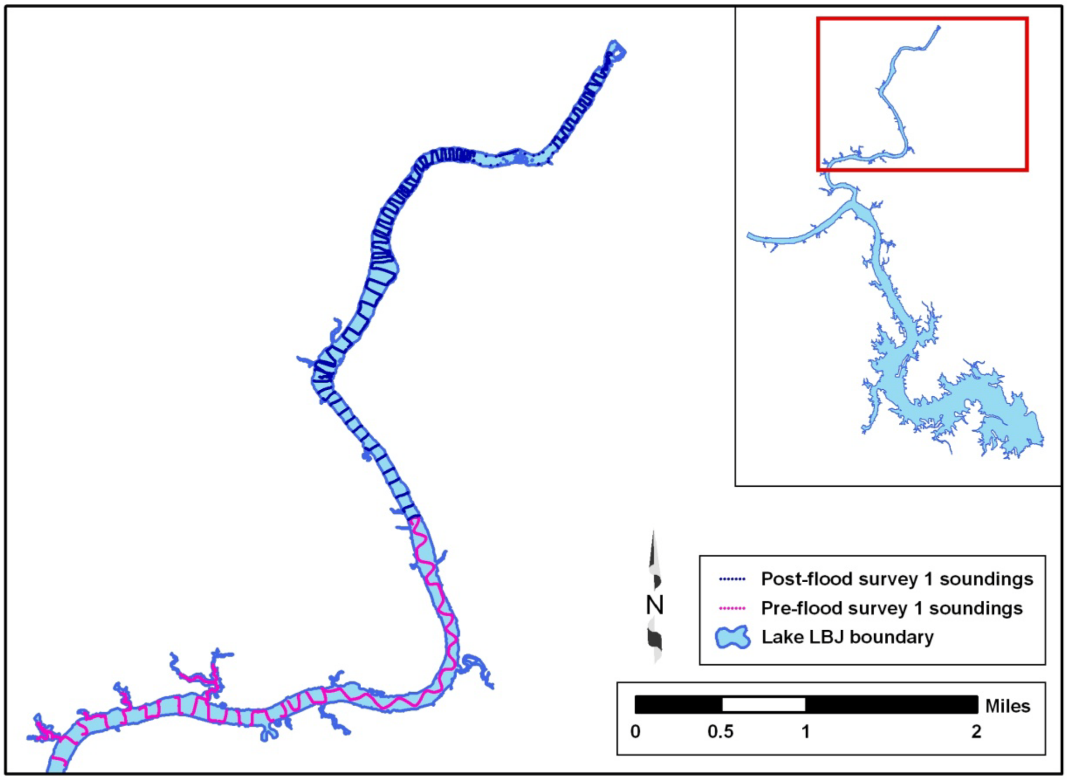


Figure 2: Survey data collected following July 2007 flooding

During the Survey 1 data collection, team members collected approximately 149,000 data points over cross-sections totaling nearly 146 miles in length (Figure 3). Information concerning data processing techniques, self-similar interpolation and line extrapolation can be found in the LBJ Report. Survey line placement for all three TWDB surveys (Surveys 1, 2, and 3) are shown in Figure 3 below.

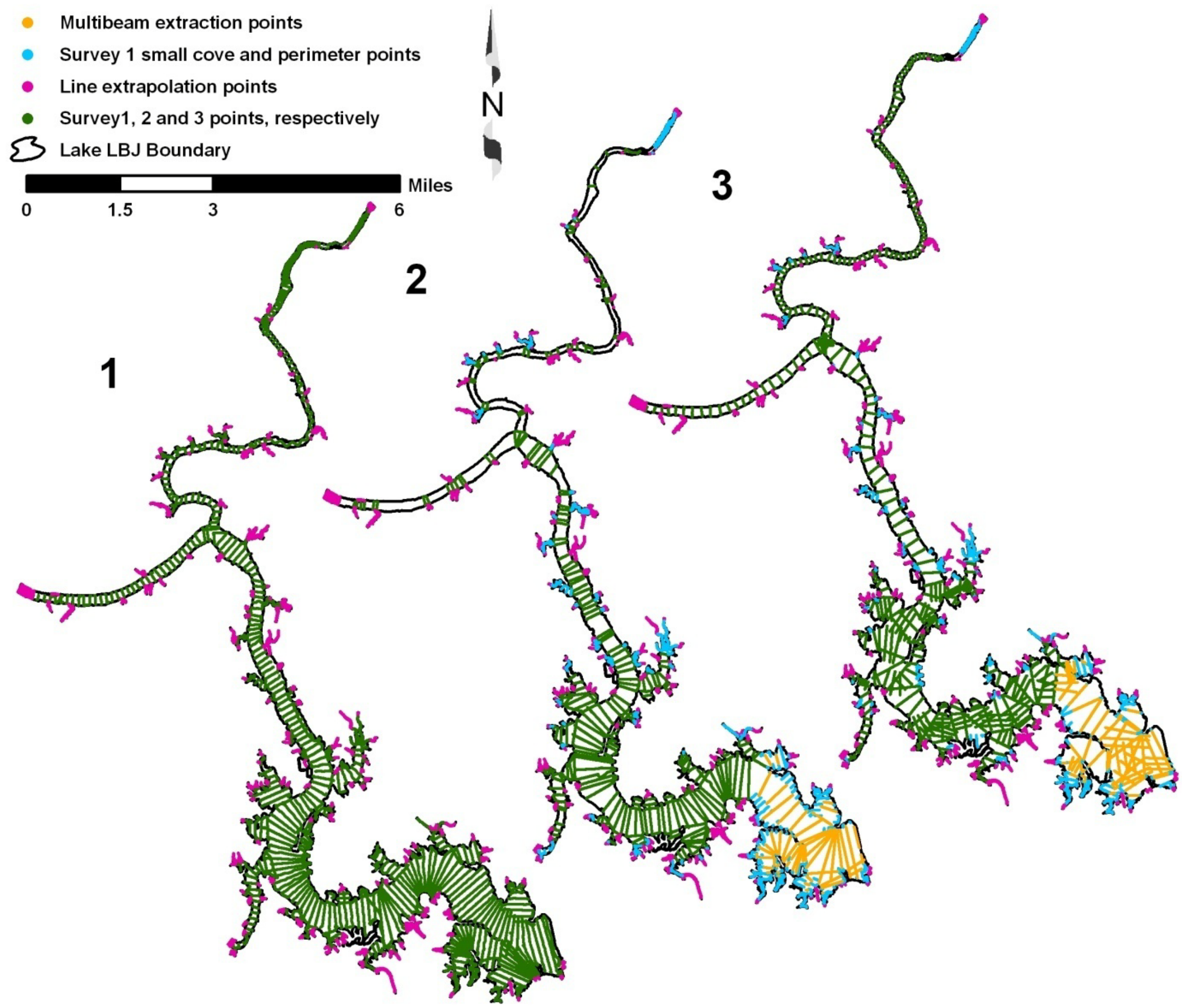


Figure 3: Survey line spacing comparison and data compilation for volume comparisons

The standard TWDB 500 ft line spacing provides a uniform coverage for the lake and attempts to capture transects perpendicular to the assumed relic stream channels. In an effort to save time and resources, Surveys 2 and 3 did not provide complete coverage of Lake LBJ. Further details concerning concerning data used in Surveys 2 and 3 are discussed in Section 2.5.

2.1.3. *Survey 2 – Self-similar line method (SSLM)*

Survey 2 data collection occurred on December 3-4, 2008, January 26, 2009, and January 29-30, 2009. Survey 2 lines were manually placed in optimal locations in an attempt to maintain the volumetric survey integrity while minimizing survey transects. Optimal locations were typically located at abrupt changes in the general lake shape, or at the interfaces between the main reservoir body and adjacent coves. In areas of reservoir shape change, a greater density of survey lines would be expected in order to properly represent the true (unknown) bathymetry in a Triangulated Irregular Network (TIN) model. In contrast, in areas where the reservoir shape is fairly uniform (i.e. channelized, riverine sections), a lower density of survey lines might be sufficient to represent the bathymetry.

Survey points for Survey 2 are shown in Figure 3. To save time, TWDB did not survey the lines located within the area of the multibeam data collection near Wirtz Dam. Bathymetric data within the multibeam survey area was extracted from the multibeam TIN model along all planned Survey 2 lines. The extracted bathymetric data points were spaced at 5-foot intervals. Data in areas near the Wirtz Dam and outside the multibeam survey area were supplemented with Survey 1 data. Small cove data was supplemented from Survey 1 data and line extrapolations remained constant for all three surveys. During the Survey 2 data collection, team members collected approximately 49,532 data points. Raw data files were processed in the same manner as Survey 1.

2.1.4. ***Survey 3 – Semi-automated flowline algorithm method***

For Survey 3, survey lines were automatically generated by considering the reservoir shape in plan view. By analyzing the reservoir shape (derived from aerial photos), it is possible to estimate the flowlines, which join together forming a flow network, and thus indicate how water traveled through the previously unsubmerged reservoir watershed. Survey lines located at strategic locations along this flow network will produce cross-section data which may yield an accurate reservoir bathymetry.

TWDB developed the flowline algorithm to determine required survey line locations in order to best represent the expected bathymetry of each flow region. Currently, the flowline algorithm exists as a suite of MATLAB scripts. The user must manually delineate flow regions and flowlines before implementing the flowline algorithm. Figure 4 below illuminates the flow regions and flowlines chosen for Lake LBJ. The basic operating procedure of the scripts is as follows:

1. Read in flowlines and flow regions
2. Locate survey lines within each flow region
3. Locate survey lines near the confluence of multiple flow regions
4. Output survey lines in format suitable for use in Hypack Max

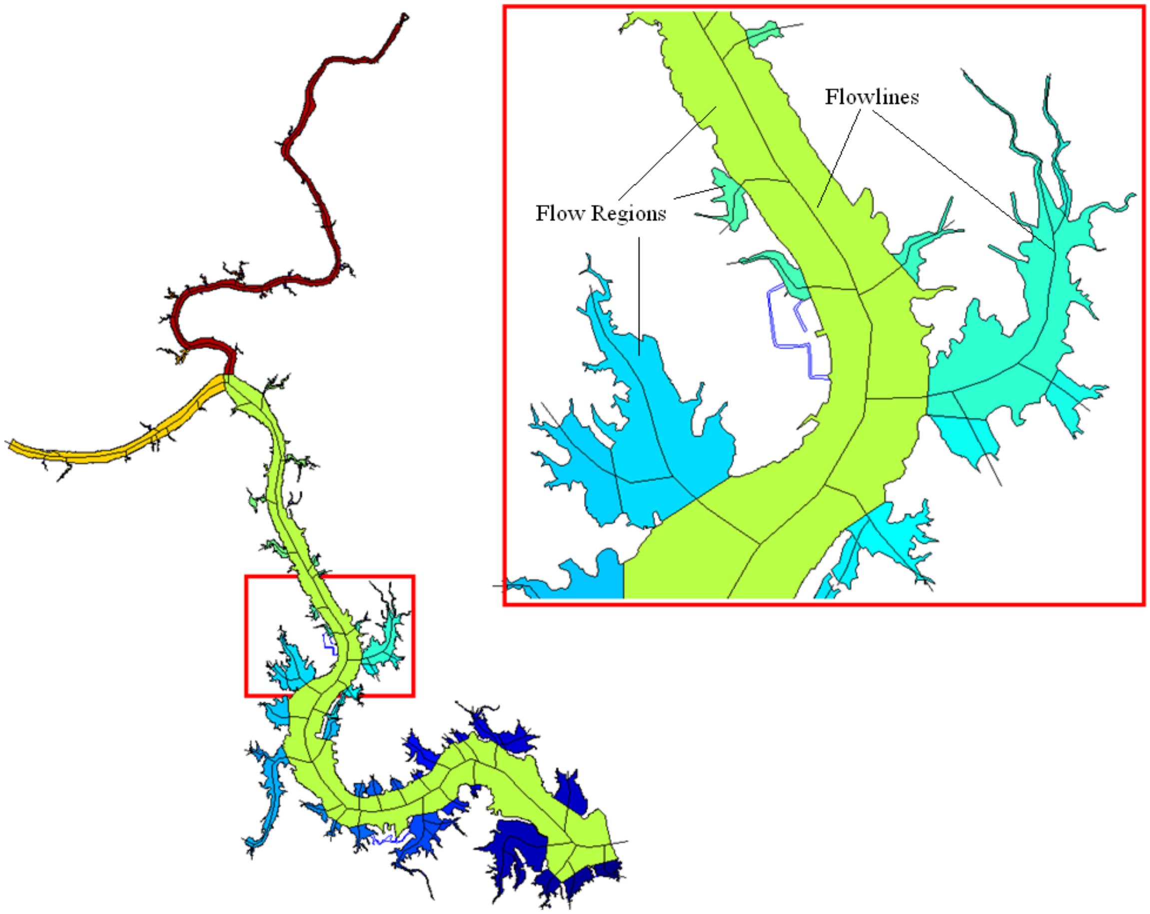


Figure 4: Lake LBJ flowline and flow region definitions. Polygons of differing color indicate distinct flow regions which contribute flow to the respective flowline.

Within each flow region, survey lines are located nearly perpendicular to flowlines and crossing of survey lines within the region is not permitted. Survey lines are located at intervals determined by the local flow region width, with the user specifying the minimum and maximum spacing between adjacent survey lines. Distances between survey lines are measured along the flowline, which may not be continuously straight.

At the confluence of flow regions, survey lines or “confluence lines” are located within the more downstream flow region, and are perpendicular to the flowline from the upstream flow region (Figure 5). The length and number of confluence lines are user specified parameters. The former is a fraction of the width of the upstream flow region at the region terminus. For the example shown in Figure 5, the confluence line length is 1.5 times the width of the upstream flow region, and three confluence lines are used. Confluence lines may cross previously determined survey lines. An example of flow regions, flowlines and confluence lines are shown below in Figure 5.

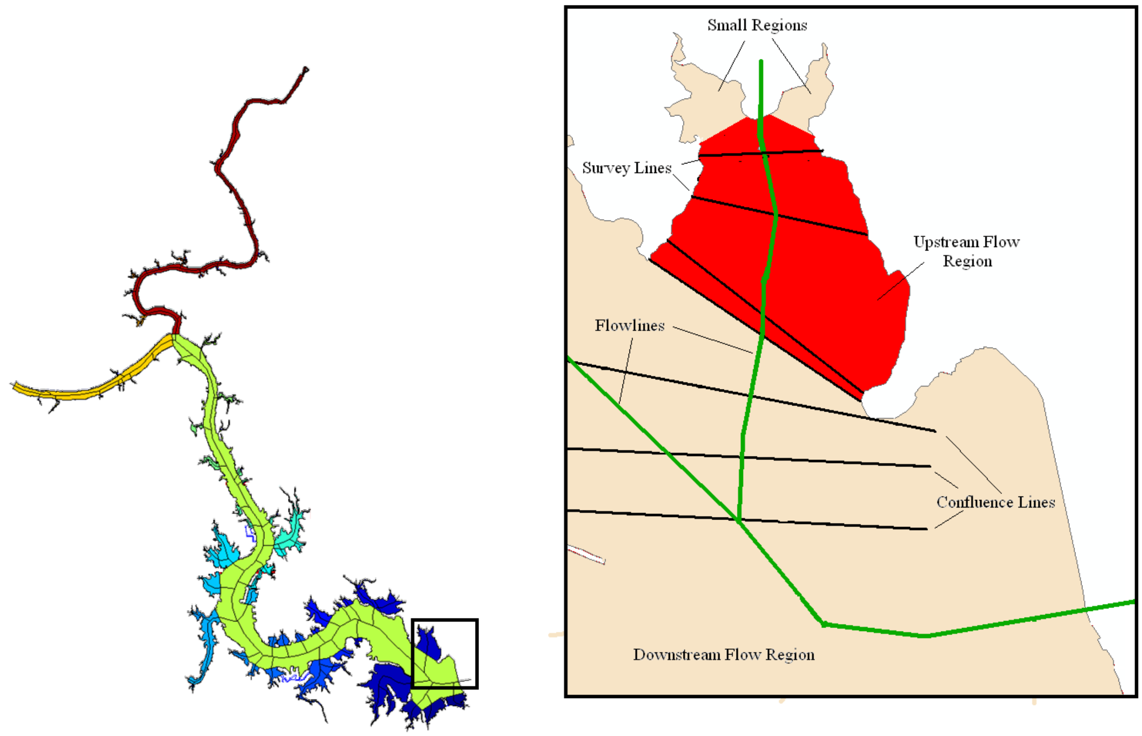


Figure 5: Flowline algorithm implementation at confluences. Confluence lines are located in the downstream flow region, oriented perpendicular to the upstream flow region's flowline. For clarity purposes, only survey and confluence lines for the displayed "Upstream Flow Region" are shown.

For flow regions deemed too small for use in defining survey lines with the flowline algorithm, survey data is to be collected only at the discretion of the technician doing the collection. Such "small regions" as shown in Figure 5 are identified as having an area less than the user-specified fraction of the entire lake area. For this analysis, survey lines were only defined for flow regions greater than 0.15% of the area of Lake LBJ. The delineation of Lake LBJ produced 85 flow regions, however only 35 regions were greater than the minimum 0.15% threshold.

The survey line file for the Lake LBJ Survey 3 data collection was created automatically within MATLAB, and was imported directly into Hypack Max for use during data collection. To save time, TWDB did not survey the lines located within the area of the multibeam data collection near Wirtz Dam. Bathymetric data in this area was extracted from the multibeam TIN model along all planned Survey 3 lines within the area of the multibeam data collection. The extracted bathymetric data points were spaced at 5-foot intervals. Data in areas near the Wirtz Dam and outside the multibeam survey area were supplemented with Survey 1 data. Small cove data was supplemented from Survey 1 data and line extrapolations remained constant for all three surveys.

Survey 3 data collection occurred on March 16-18, 2009, April 20-22, 2009 and April 28, 2009. It should be noted that the all Survey 3 data collection occurred ***after*** the flooding of the Highland Lakes system in the Summer of 2007, therefore some differences in bathymetry resulting from the Survey 3 data compared to that from the Survey 1 data may be due to sediment deposition/scour during the flooding. During the Survey 3 data collection, team members collected approximately 49,008 data points.

2.1.5. ***Triangulated Irregular Network (TIN) model creation***

After processing the data, applying self-similar interpolations and line extractions, the 3D Analyst extension of ArcGIS was used to create two TIN models for each survey. The self-similar interpolation and line extraction techniques are described in detail in the LBJ Report (TWDB, 2009a). The first TIN models for each survey depict the current bathymetric surface. The names of these TIN models for Surveys 1, 2 and 3 are ***surface 1***, ***surface 2*** and ***surface 3***, respectively. The second TIN model created for each survey illustrates accumulated sediment thickness. The names of these TIN models for Surveys 1, 2 and 3 are ***thickness 1***, ***thickness 2*** and ***thickness 3***, respectively. Figure 3 shows the various data used to create the TIN models for each survey. The 3D Analyst Extension of ArcGIS, which uses Delaunay's criteria for triangulation to place a triangle between three non-uniformly spaced points, including boundary vertices (ESRI, 1995).

To save time and data collection efforts, Survey 1 bathymetric data for small coves and line extrapolation data were used in the ***surface 2*** and ***surface 3*** TIN models. The repetition of data nullifies volumetric TIN comparison in these areas. The sediment thickness TIN model does not include any lake area within approximately 2 miles of Wirtz Dam due to the absence of Survey 2 and Survey 3 multi-frequency data in this area. Survey 1 sediment thickness data for small coves was used in the ***thickness 2*** and ***thickness 3*** TIN models. This repetition of data nullifies sediment thickness TIN comparison in these areas. Figure 6 below illustrates the extent of the sediment thickness TIN models.

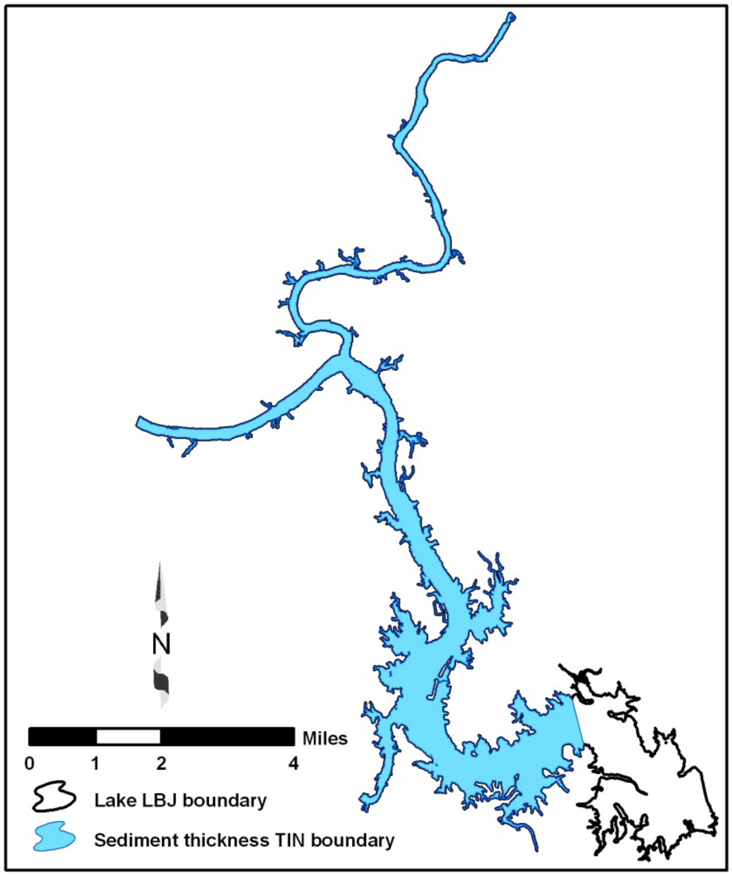


Figure 6: Extent of coverage for sediment thickness TIN models. Volumetric TIN models cover the entire lake.

2.2. Bathymetric survey analysis

Determination of the reservoir volume from a hydrographic survey involves compiling the bathymetric data from all the individual soundings and generating a TIN model of the lake from those soundings. The quality of the volume estimate depends on the quality of the individual soundings, the ability of the survey line spacing to pick up major bathymetric features and the interpolation scheme used to estimate bathymetric values in between survey lines.

2.2.1. ***Comparison of individual soundings***

To assess the precision of the bathymetric determinations between surveys, individual soundings from each survey was compared to close by soundings from the other surveys.

2.2.1.1. *Survey 1 vs multibeam*

As a first step in assessing the similarities between the three volumetric TIN models and the multibeam TIN model derived through this survey planning analysis, Survey 1 sounding data were compared against the multibeam data. Both datasets were collected before the 2007 flooding, and therefore both datasets should be representative of the same true Lake LBJ bathymetric surface. As the Survey 1 soundings were not collected at the same locations as the multibeam soundings, bathymetric elevations from the TIN model created from multibeam data were extracted at the locations of the Survey 1 sounding points. This allowed for the comparison of elevations at identical spatial locations. For this analysis, comparisons were made only for Survey 1 sounding points with a minimum of four multibeam sounding points located within a 10 ft by 10 ft box centered on the Survey 1 point location and at least 1 multibeam data point located within each 5 ft by 5 ft quadrant of the 10 ft by 10 ft test box. As shown in Figure 7, elevation comparisons were made for 27,717 Survey 1 sounding points.

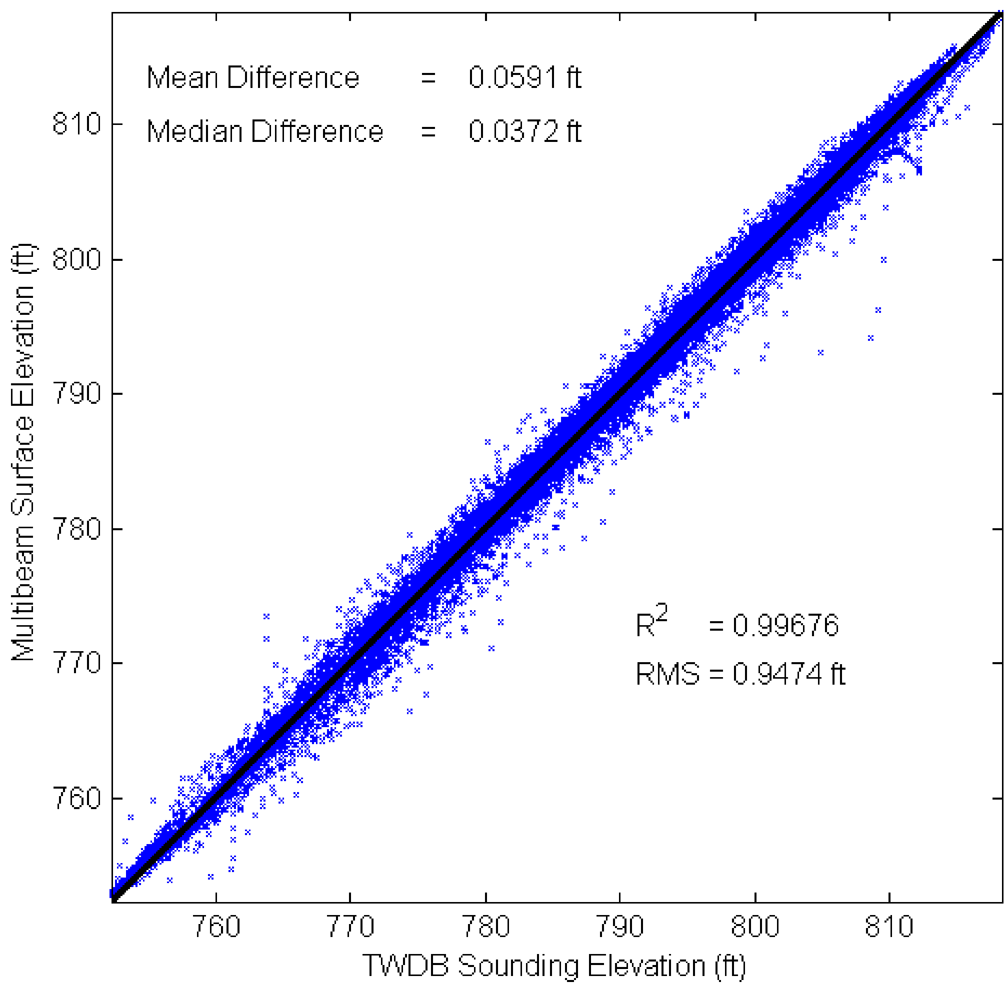


Figure 7: Sounding data comparison of Survey 1 vs multibeam

As shown in Figure 7, the agreement between the Survey 1 soundings and multibeam data is high, with an R^2 value nearly equal to 1 (perfect correlation). The RMS value of 0.9474 ft reflects the influence that larger elevation differences have on this parameter, as 56% of all soundings have absolute elevation differences of less than 0.5 ft and 72% have absolute elevation differences of less than 0.75 ft. Differences between datasets may be due to wave action at the time of the Survey 1 data collection, as heave/pitch/roll sensors and gyroscopes were not used during TWDB surveys (but were used during multibeam data collection). Larger errors are most likely associated with positional errors between the surveys.

2.2.1.2. Survey 1, 2 and 3

To assess the precision of the bathymetric measurements between surveys 1, 2 and 3, the TWDB identified areas of survey line intersection; more specifically individual sounding points from the three different surveys (within 1 or 5 ft) were compared. Figure 8 shows locations in the lake where survey points on intersecting lines were within 5 ft of each other. Intersecting points within 1 ft of each other showed similar trends to those within 5 ft but with a much smaller sample size and the results are not presented here.

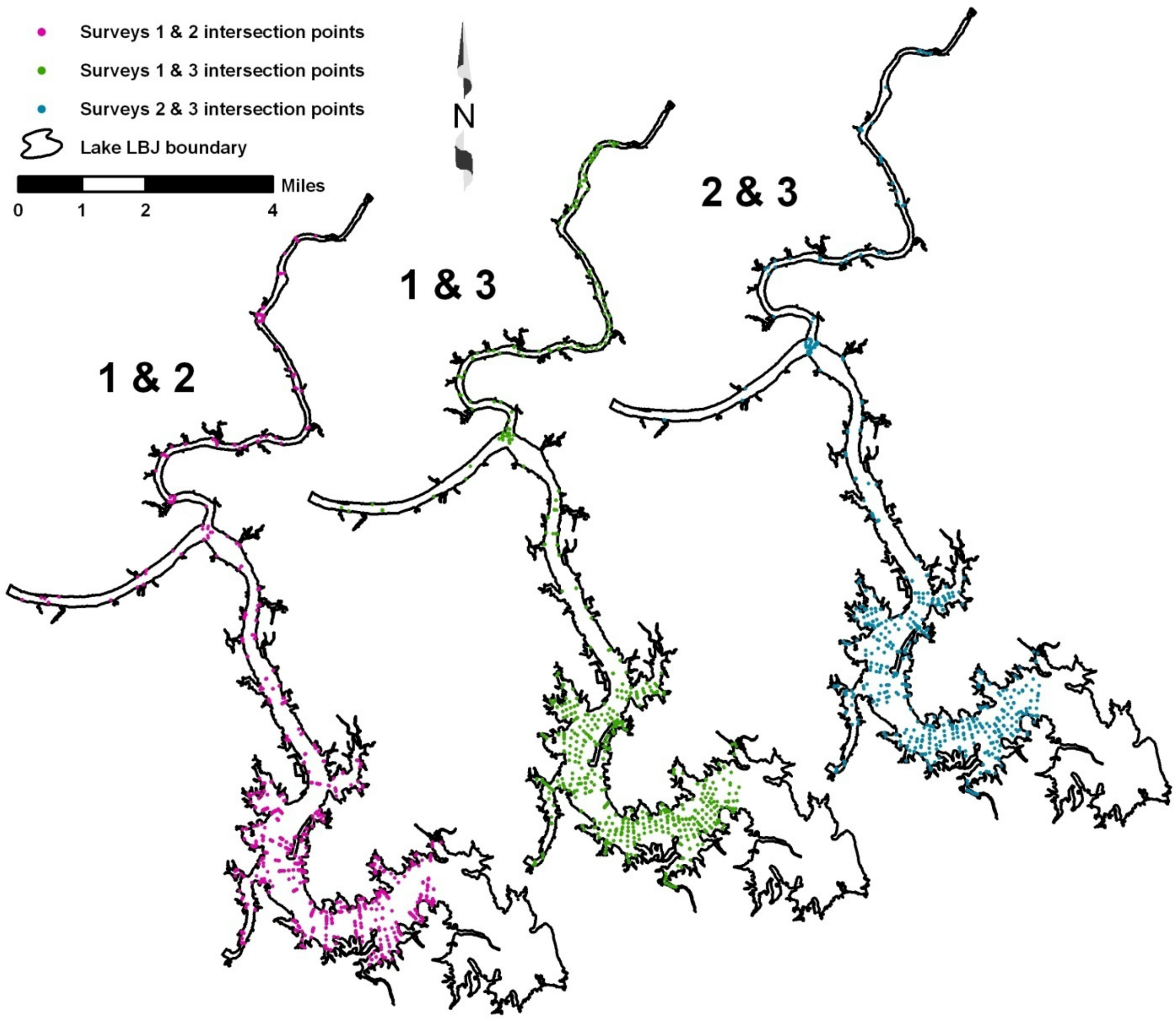


Figure 8: Intersection points between surveys (within 5 ft)

In Figure 8, the intersection points for Surveys 1 and 2 are more abundant near the edges of the lake, whereas the intersection points for Surveys 1 and 3 or Surveys 2 and 3 are more evenly spread across the width of the lake. Otherwise, the spatial distribution of intersecting points is relatively similar between comparisons. Close up examples of intersecting sounding points, within 1 ft and 5 ft radii, are presented in Figure 9.

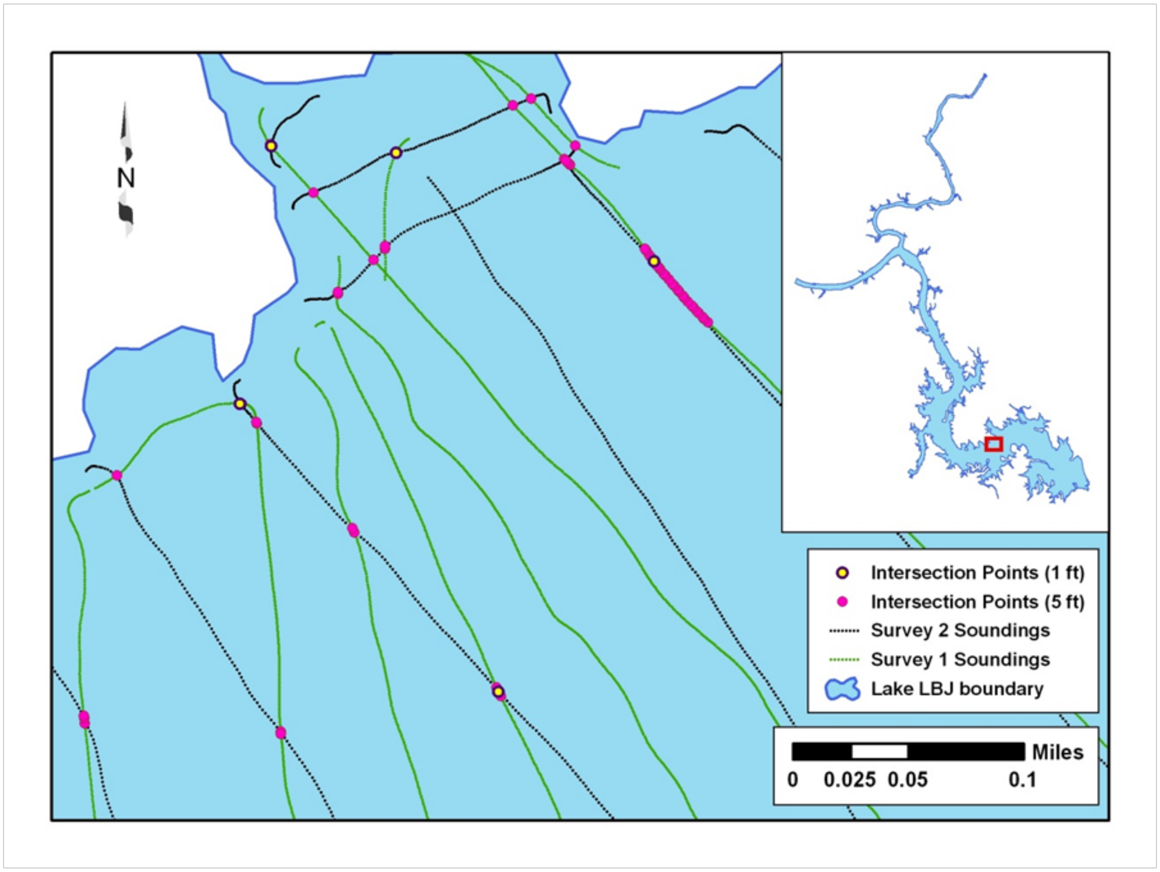


Figure 9: Survey 1 and 2 intersection points within 1 and 5 ft.

The various types of intersections are shown in Figure 9. In some areas of the lake, transects parallel one another, creating large strings of intersection points. Otherwise, intersections create one, two or three 5 ft intersection points. The 1 ft intersection points are not common and not always accompanied by additional surrounding 5 ft intersection points. However, the 1 ft intersection points are by default included in the 5 ft intersection point dataset. Figure 10 compares depth measurements for intersecting points within a 5 ft radius.

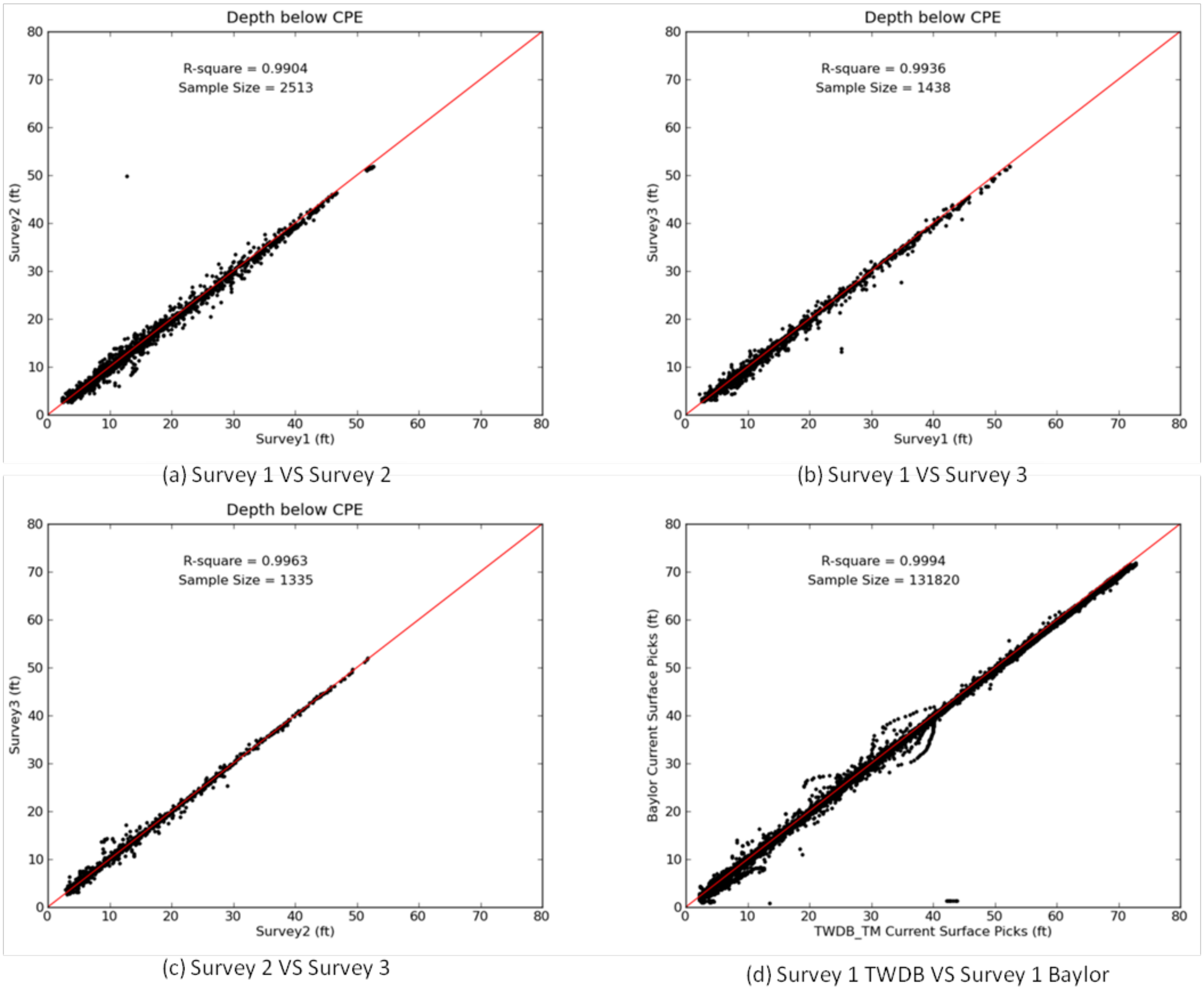


Figure 10: Comparison of depths for intersection points within 5 ft.

The 5ft radius intersection results are presented in Figure 10. The agreement between the surveys is high; the lowest R-squared value is .9904. An R-squared value of 1 represents perfect correlation. In addition, Survey 1 data was reanalyzed by Baylor University and compared to Survey 1 data analyzed by the TWDB. Figure 10d compares the TWDB determination of current surface versus the Baylor University determination. The resulting R-square value is 0.9994 with a sample size of 131,820 points. Hence, measurement of bathymetric depth at any particular location is highly repeatable and both the survey technique and the data post processing techniques are very robust.

2.2.2. ***Volumetric comparison of multibeam survey and Survey 1***

To assess the accuracy of the survey methodology and interpolation, the Survey 1 TIN models, with and without self-similar interpolation, were compared to the multibeam TIN model. The multibeam dataset was considered the baseline due to its high resolution and incorporation of a heave/pitch/roll sensor. Due to the limited area coverage of multibeam data, the comparison was performed only within the area where the multibeam data and Survey 1 data overlapped (the area near Wirtz Dam where the multibeam data was collected) as seen in Figure 1. The multibeam survey area measures 1,195 acres and is 19.3 percent of Lake LBJ's total surface area at the conservation pool elevation (CPE) of 825.0 ft NGVD29. The NGVD29 datum is used throughout the report.

Table 2: **Comparison of multibeam TIN with Survey 1 TINs with and without interpolation**

Survey	Interpolation	Volume at CPE (Acre-ft)	Volume difference	
			Acre-ft	Percent
Multibeam	No	47,527	< >	< >
1	No	46,898	-629	-1.32
1	Yes	47,633	106	0.22

Table 2 provides further evidence of the accuracy of Survey 1 seen in Figure 10. Without TWDB interpolation of the survey points, the TIN model is accurate within 1.32% of the lake volume calculated using the multibeam TIN model. An increase in accuracy is achieved using interpolation; however the estimation changed from an underestimation to a slight overestimation of volume.

The multibeam survey area is located within the 2-mile area extending upstream from the Wirtz Dam, the deepest area of the lake. However, the multibeam survey did not extend to the boundary of the lake in shallow areas because a "limitation of the multi-beam method is that, because the acoustic beams travel at non-vertical angles, the method requires water depth of at least 1/6 the track-line spacing" (Dunbar and Estep, 2009). Additionally, the multibeam survey was not extended to the shallow boundaries of the lake to avoid damage to the expensive multibeam equipment.

2.2.3. ***Volumetric comparison of Surveys 1, 2 and 3***

The majority of Survey 1 data collection occurred ***before*** the flooding of the highland lakes system in the summer of 2007, whereas Surveys 2 and 3 data collection efforts commenced ***after*** the flooding. Therefore some differences in bathymetry resulting from the Survey 2 and 3 data compared to that from the Survey 1 data may be due to sediment deposition/scour during the flooding. Comparison between Survey 2 and 3, however, will be void of influence from the flooding.

Table 3 provides volumetric comparison between TIN models created with and without interpolation in an effort to analyze the effects of interpolation between various survey planning strategies.

Table 3: Comparison of volume change through interpolation

	Volume at CPE (acre-ft)		Volume difference[a]	
Survey	**No interpolation**	**With SS[b] interpolation**	**Acre-ft**	**Percent**
1	125,795	133,025	7,230	5.75
2	115,911	132,561	16,650	14.36
3	119,732	132,728	12,996	10.85

[a] Percent volume differences calculated based on non-interpolated volumes
[b] Self-similar interpolation conducted by TWDB

Table 3 shows the least amount of change in volume for Lake LBJ using the standard TWDB survey planning strategy of 500 ft spacing applied in Survey 1. All three survey strategies show increase in volume estimates after interpolation, and increased precision relative to the current volume estimation (Survey 1). Table 4 below shows the differences in volume relative to Survey 1, before and after self-similar interpolation is performed.

Table 4: Comparison of volume between surveys before and after interpolation

			Volume difference[a]	
Survey	**Interpolation**	**Volume at CPE (acre-ft)**	**Acre-ft**	**Percent**
1	Yes	133,025	< >	< >
2	Yes	132,561	-464	-0.349
3	Yes	132,728	-297	-0.223
1	No	125,795	< >	< >
2	No	115,911	-9,884	-7.86
3	No	119,732	-6,063	-4.82

[a] Volume differences calculated based on Survey 1 before and after interpolation, respectively

Table 4 illuminates the increase of precision achieved with interpolation. Self-similar interpolation helps overcome the shortcoming of Delauney triangulation interpolation applied in ArcGIS whereby it fails to fully connect the bathymetric cross sections particularly near lake boundaries. Further explanation of the self-similar technique is provided in the LBJ Report (TWDB, 2009a).

2.3. Sediment survey analysis

Estimating sediment volume from a hydrographic survey is more involved than obtaining a volume estimate. Before presenting the results for comparisons between the three surveys, we discuss the existing methodology and techniques used in determining sediment thickness profile along individual survey lines. Individual sediment thickness profiles are the basis for the generation of the TIN model that is then used to estimate sediment volume for the entire lake. Errors in these individual profiles will propagate into the final sediment volume estimate through the self-similar interpolation. The equipment used in the multibeam survey does not return any sediment information. Therefore, the following analysis is limited to the three TWDB surveys within the area of the lake described in Section 2.1.5, Figure 6. In addition, Survey 1 data analyzed by TWDB staff is compared to the same dataset analyzed by Baylor University staff.

2.3.1. Determination of pre-impoundment surface

The sediment thickness profile along a survey line is determined by subtracting the current surface profile from the pre-impoundment surface profile. The current surface profile is determined in a fairly automatic manner by the SDI DepthPic software based on the return from the 200 kHz echo sounder during data collection. Minor edits are made during data review to remove spurious data and small oscillations caused by wave action. As seen from the results in the bathymetric survey analysis section (Section 2.2), these results are fairly robust and repeatable in multiple surveys. Determining the pre-impoundment surface requires manual ‘picks’ of the pre-impoundment surface at each sounding along the profile by visual inspection of the 50 kHz and/or 24 kHz echo sounder returns within the DepthPic software. Figure 11 shows the DepthPic software display of a representative 50 kHz echo sounder return with the current surface depicted in red and the pre-impoundment surface displayed in yellow.

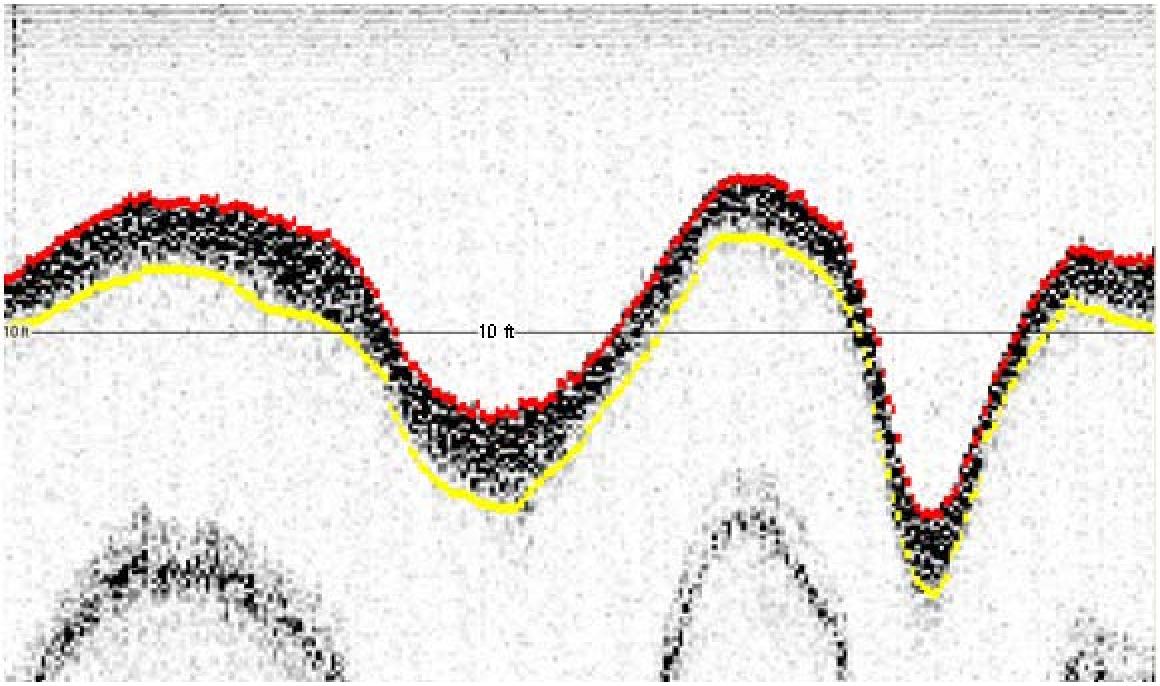


Figure 11: Survey 1 transect including current (red) and pre-impoundment (yellow) surface picks on 50 kHz frequency returns

Determining the pre-impoundment surface is not an exact process; TWDB currently uses a two step procedure to reduce the subjectivity in this determination. This involves taking representative sediment samples at multiple locations in the lake then using them to guide the picking process. These steps are described in the next two sections.

2.3.1.1. Sediment coring analysis

Analysis of accumulated sediment begins by collecting representative spatially distributed sediment samples throughout the lake. Sediment sampling was performed under contract by Dr. John Dunbar of Baylor University in 2007 as part of the original volumetric and sediment survey (Survey 1) (TWDB, 2009a). Figure 12 shows the location of the seven sediment samples collected during the original Lake LBJ survey. The locations of these samples were determined through preliminary examination of the profile data.

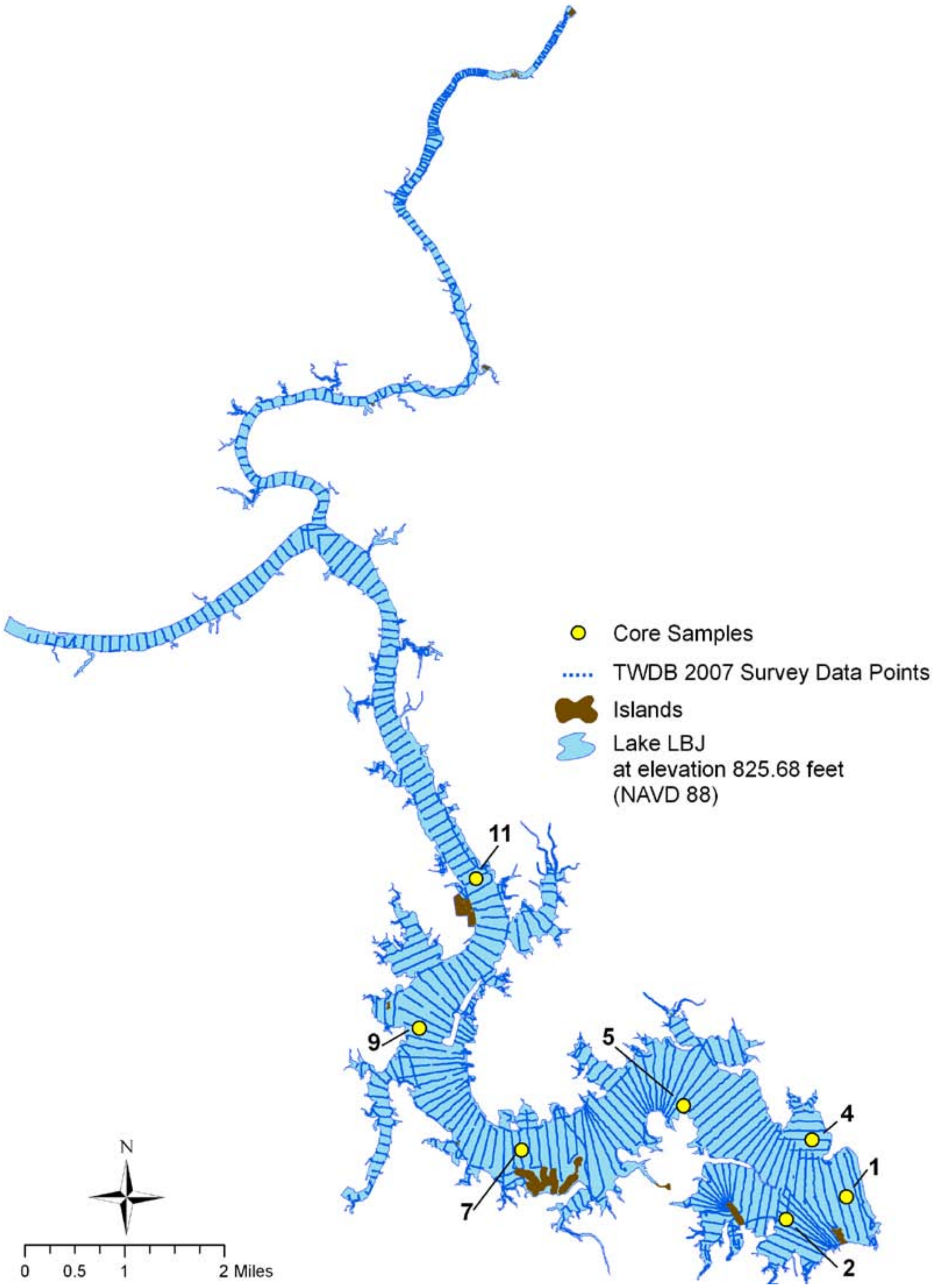


Figure 12: Sediment (core) sample location map with Survey 1 data points

Sediment samples are analyzed and the pre-impoundment layer is identified based on various characteristics of the sediment sample, including soil texture, structure, and color; the presence of organic material; and in this analysis by Dr. Dunbar, levels of various elements. Further explanation of the sediment sample analysis is in Appendix D of the LBJ Report (TWDB, 2009a). After identifying the pre-impoundment surface based on the sediment characteristics, the sediment samples are compared to the soundings obtained from the survey at approximately the same location. Figures 13 and 14 show each sediment sample against the backdrop of the transect signal return (50 kHz) where the sediment sample was taken. The 50 kHz signal was chosen (rather than the 24 kHz signal) for the comparisons using the procedures outlined later in section 2.3.1. On each figure, the yellow bar represents accumulated sediment found within the sediment sample and the green bar represents soil present before impoundment. Therefore, the interface of the yellow and the green bars is the pre-impoundment surface.

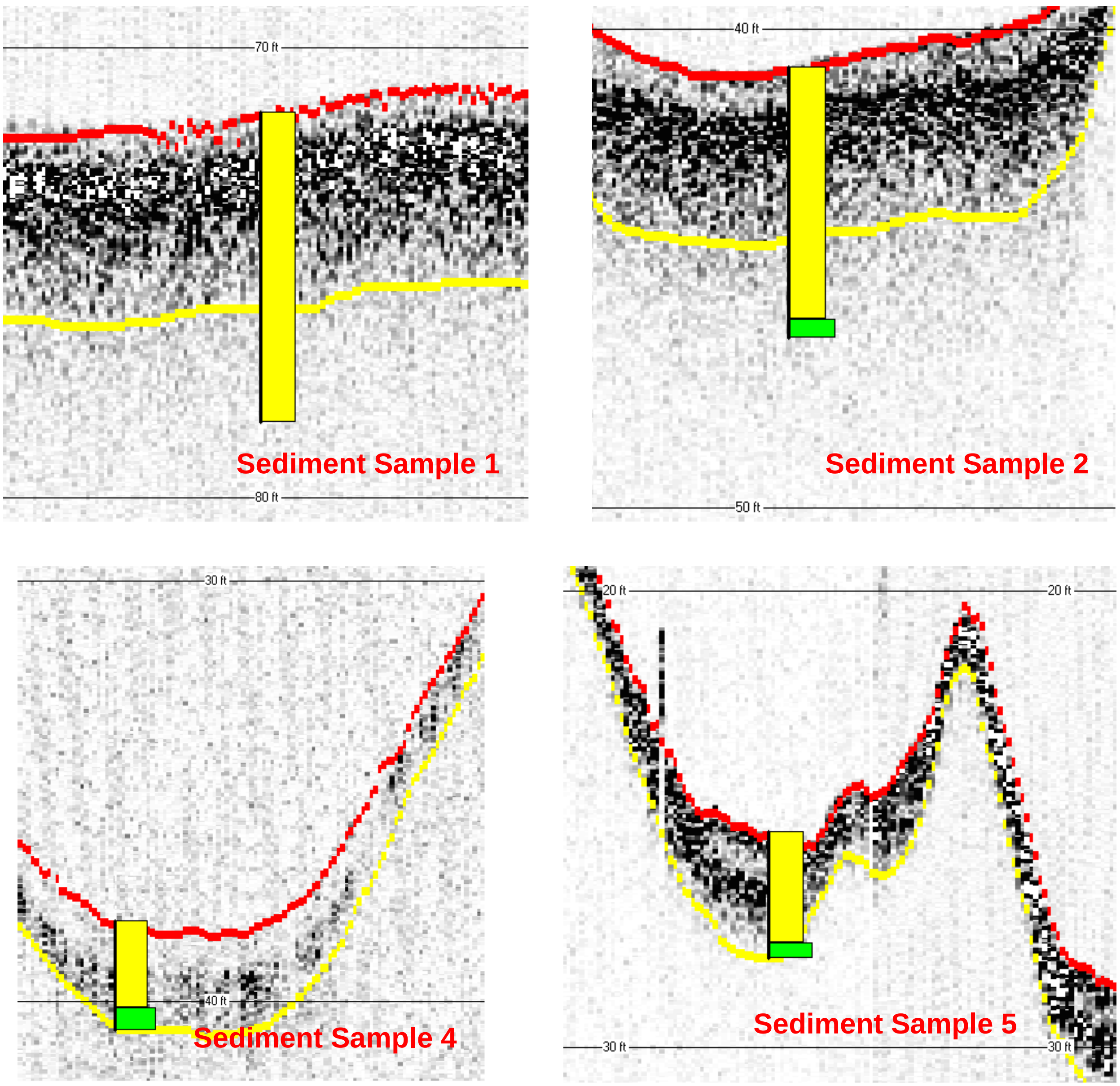


Figure 13: Sediment samples 1, 2, 4, and 5 superimposed on 50 kHz sounding returns

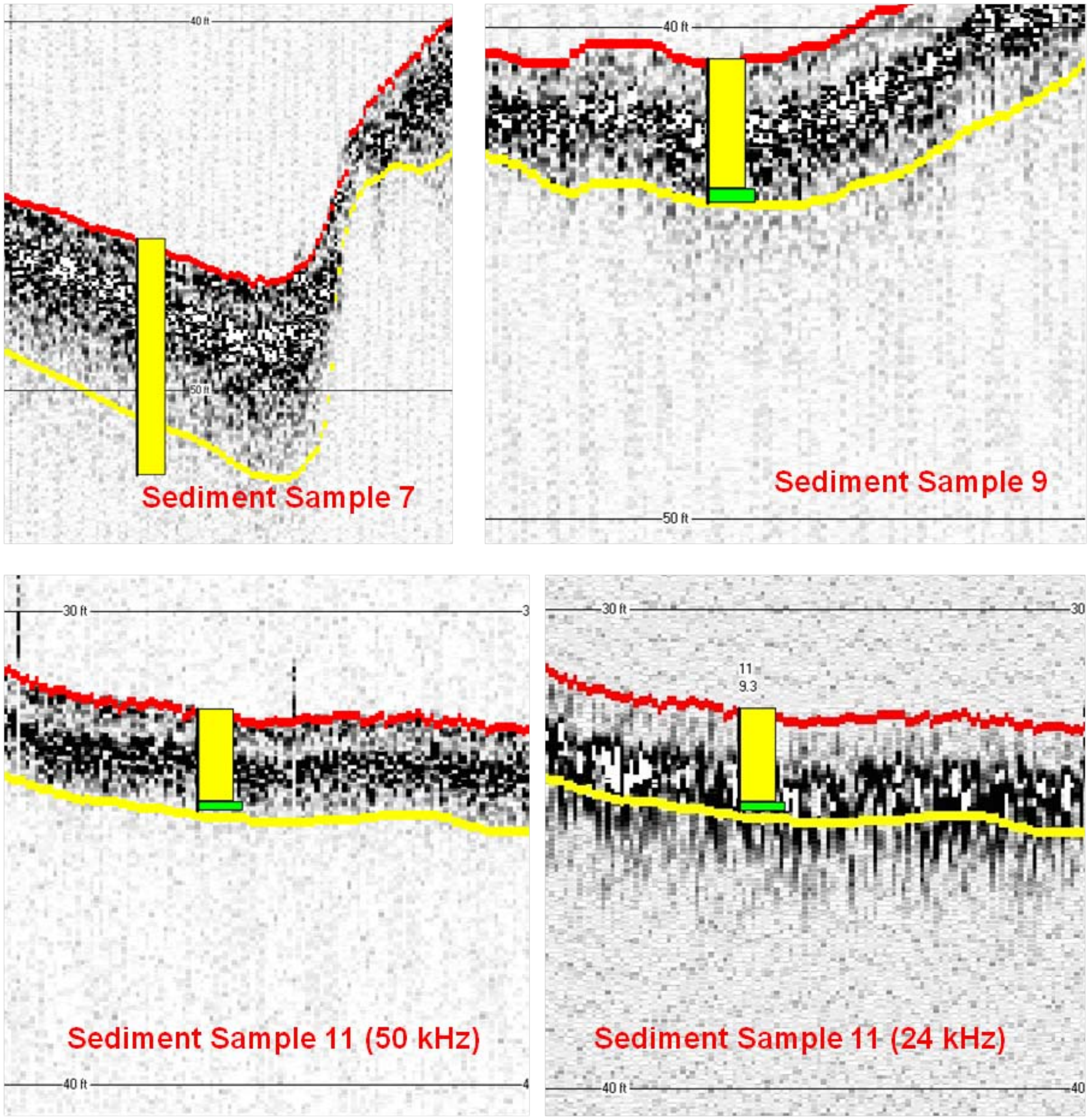


Figure 14: Sediment samples 7, 9, and 11 superimposed on 50 kHz sounding returns and sediment sample 11 superimposed on 24kHz sounding returns

Figures 13 and 14 above illuminate the discrepancies found when comparing sediment samples with the sounding data. For samples 1 and 7 the pre-impoundment layer could not be identified and/or was not reached. Also, in sediment samples 1, 2, and 7, the sediment sampling penetrated further than the return signals indicate a pre-impoundment layer should exist. Sediment sample 4 shows a less pronounced signal return, potentially due to a variation in the SDI settings used. The 50 kHz signal returns and the identified pre-impoundment layer correlate well in sediment samples 4, 5, 9 and 11. The Baylor University *Hydrographic Survey Program Assessment* report states that there can be differences in which signal frequency (i.e. 24 kHz or 50 kHz) corresponds best with the base of sediment and that this is likely to be due to differences between power and gain settings used on the SDI unit (Dunbar and Estep, 2009). These differences can be seen in the 24 kHz and 50 kHz returns for sediment sample 11 in figure 14.

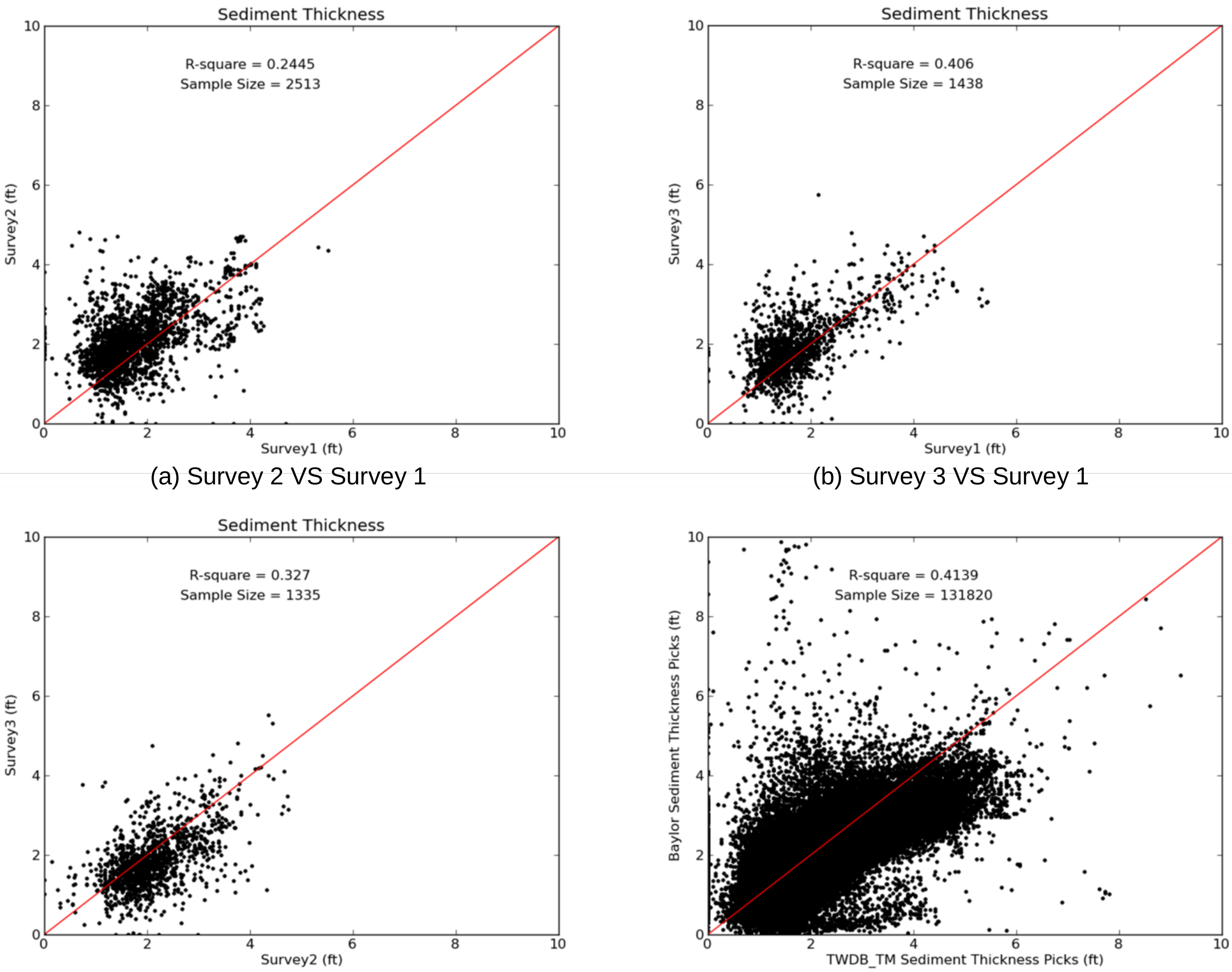
2.3.1.2. Pre-impoundment layer delineation

Delineation of the pre-impoundment layer is a manual process. The surface is picked using mouse clicks along the transect profile based on visual interpretation of pixel shade within the DepthPic software.

Based on the sediment coring analysis discussed previously, the signal returns (i.e pixel shade in the DepthPic software) corresponding to the pre-impoundment surface in sediment samples 4, 5, 9 and 11 were used as representative examples to guide the manual picking of the pre-impoundment layer for all the individual survey lines in Surveys 1, 2, 3 and for the diagnostic transects described later in section 3. Additionally, for this study, a single TWDB staff member conducted the pre-impoundment delineation for all the survey lines in an attempt to avoid compounding human discrepancy.

2.3.2. *Comparison of individual soundings*

To assess the similarities of the sediment thickness determinations between surveys, a similar analysis to that done in section 2.2.1.2 is presented here. The sediment thickness at sounding points from the different surveys within a radius of 1 and 5 ft of each other were compared. The locations used are the same as in the earlier analysis and can be seen in Figure 9. The scatter-plot results of those comparisons are presented below in Figure 15. The 1ft results followed the same trend as the 5ft results and are not presented here. In addition, Figure 15d, compares the TWDB determined sediment thickness with the BU determined sediment thickness and is a direct indication of the variability in the determination of pre-impoundment surface.



(a) Survey 2 VS Survey 1

(b) Survey 3 VS Survey 1

(c) Survey 3 VS Survey 2

(d) Baylor Survey 1 VS TWDB Survey 1

Figure 15: Sediment thickness comparison for intersection points

Sediment thickness is determined by subtracting the current surface (or bathymetric depth) from the pre-impoundment surface. Our earlier analysis comparing the current surface measurements showed a very high correlation ($R^2 > 0.99$) between surveys, hence the differences between the sediment thickness values between the surveys is almost exclusively due to errors in the pre-impoundment surface delineation. As shown in Figure 15, there is a large variation in results between the surveys and the correlations are very low. In Figures 15a, b and c it could be argued that some of the variation may be caused by changes in boat orientation or the 2007 flood etc, but Figure 15d shows that the primary source of variability is the post processing of the depth sounder data used to determine the pre-impoundment surface.

Figures 16 through 18 are representative examples of pre-impoundment delineation comparisons between surveys for soundings within 1 ft. The green arrows in these figures demonstrate intersection points (within 1 ft radius) from different surveys where the distance between the red and yellow lines (i.e. sediment thickness) should be equal. Note that these transects are oriented differently and only the location indicated (by the green arrows) should be expected to match. While some error can be attributed to the human judgment involved in picking the pre-impoundment surface, these figures also demonstrate differences in the depth sounder return signals that are contributing significantly to the variability. The current hypothesis is that these differences are caused by differences in power/gain settings used during each profile. Unfortunately, not enough information is available to verify this hypothesis.

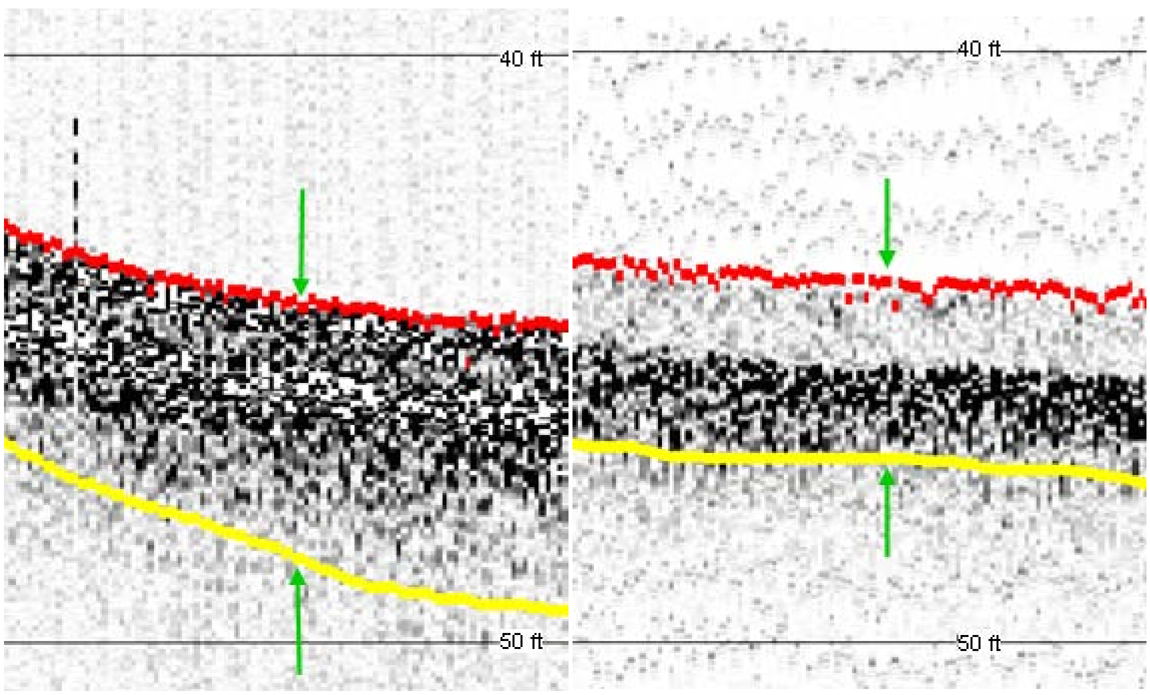


Figure 16: Example sediment thickness comparison of points (indicated by green arrows) within 1 ft from Survey 1 (left) and Survey 3 (right)

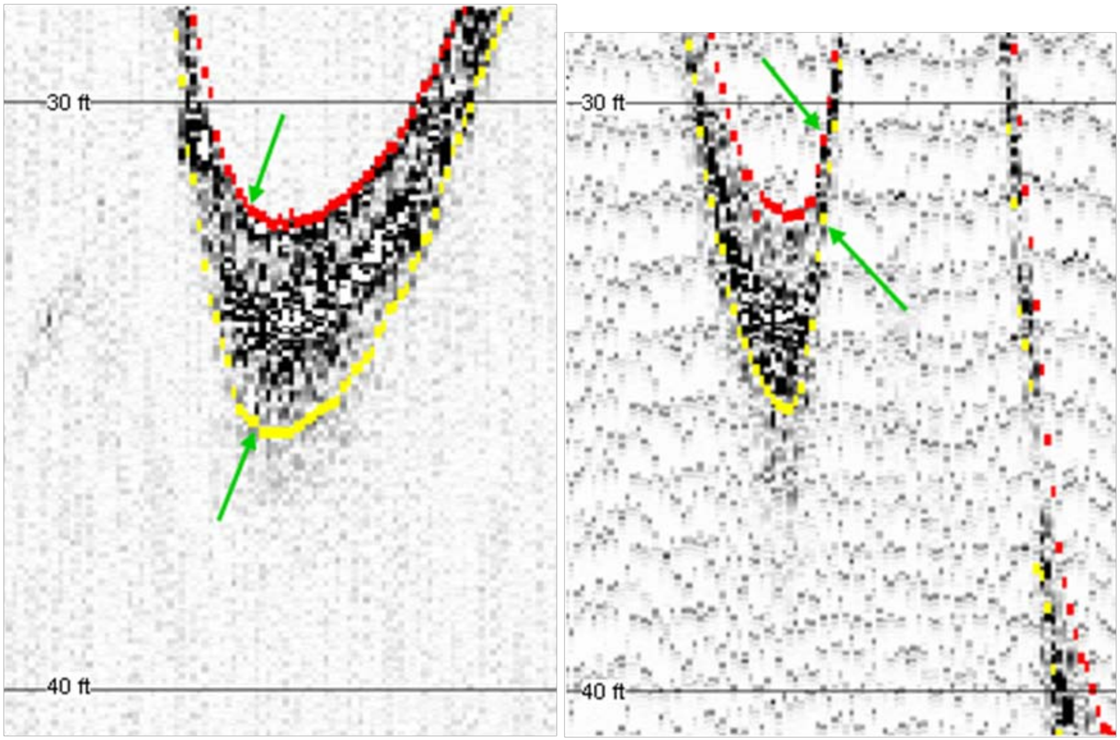


Figure 17: Example sediment thickness comparison of points (indicated by green arrows) within 1 ft from Survey 1 (left) and Survey 2 (right)

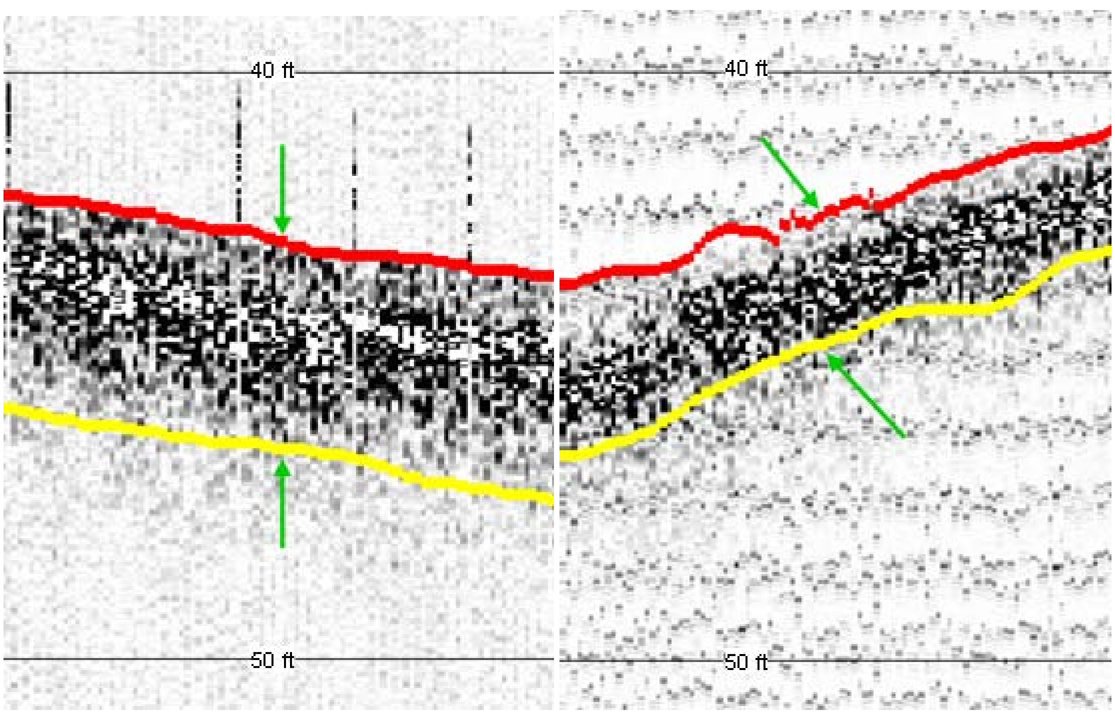


Figure 18: Example sediment thickness comparison of points within 1 ft (indicated by green arrows) from Survey 1 (left) and Survey 2 (right)

It is important to note the visual distinctions between the two soundings. On the left, no light grey space exists above the dark areas as seen on the right. This difference exists between Survey 1 and

Survey 3, as seen in Figure 16, as well as between Survey 1 and Survey 2, as shown below in Figures 17 and 18. This difference is likely due to power and gain setting differences during surveying. Unfortunately power and gain settings are not recorded with Hypack 3.3 version of the software, whereas these settings are recorded with the later 4.3 version. All Survey 1 sounding data recorded prior to the 2007 flood event used Hypack version 3.3 and analysis of the potential for various settings to create the discrepancies shown in Figures 16 through 18 is not possible.

One final note is that from visual inspection the scatter plots in Figure 15 seem to indicate that the error in determining the pre-impoundment surface (and hence sediment thickness) does not seem to be have a large bias, i.e the variability is generally equally distributed above and below the red 1:1 line. This may mean that while the sediment thickness at individual sounding locations may be inaccurate, overall sediment volume estimates may still be reasonable.

2.3.3. ***Sediment volume comparisons between Survey 1, 2 and 3***

In light of the discussion in the previous section, differences in sediment volume caused by variations in choice of survey line placement are difficult to isolate. The results presented in this section should be considered with the understanding that there is a compounded error present in the sediment volume estimates that includes both errors in determination of the pre-impoundment surface as well as errors cause by survey line placement strategies. With that caveat in place, Table 5 and 6 are comparisons of sediment thickness volumes between the surveys and the effects of the self-similar interpolation technique.

Table 5: Comparison of sediment volume with and without interpolation

Survey	Volume at CPE (acre-ft)		Volume difference	
	No interpolation	With SS[b] interpolation	Acre-ft	Percent
1	6,685	6,904	219	3.28
2	6,357	8,226	1,869	29.40
3	6,318	7,433	1,115	17.65

Table 6: Comparison of sediment thickness volume

Survey	Interpolation	Volume of sediment (acre-ft)	Average sediment thickness (ft)	Volume difference[a]	
				Acre-ft	Percent
1	Yes	6,904	1.560	< >	< >
2	Yes	8,226	1.858	1,320	19.12
3	Yes	7,433	1.679	529	7.66
1	No	6,685	1.442	< >	< >
2	No	6,357	1.436	-328	-4.90
3	No	6,318	1.427	-367	-5.49

[a] Volume differences calculated based on Survey 1 before and after interpolation

Surprisingly, before interpolation overall sediment volumes from the three surveys agree within about 5.5% even with the high variability in determining the sediment thickness at individual locations. This may be due to the non-biased nature of the error as discussed earlier or random cancellation of the differences between the surveys. The sediment distribution across the lake varied from survey to survey as can be seen in Figures 19 and 20 for a selected section of the lake. Application of the self-similar interpolation however increases the volume of the sediment drastically in Surveys 2 and 3, increasing the variation between surveys to almost 20%.

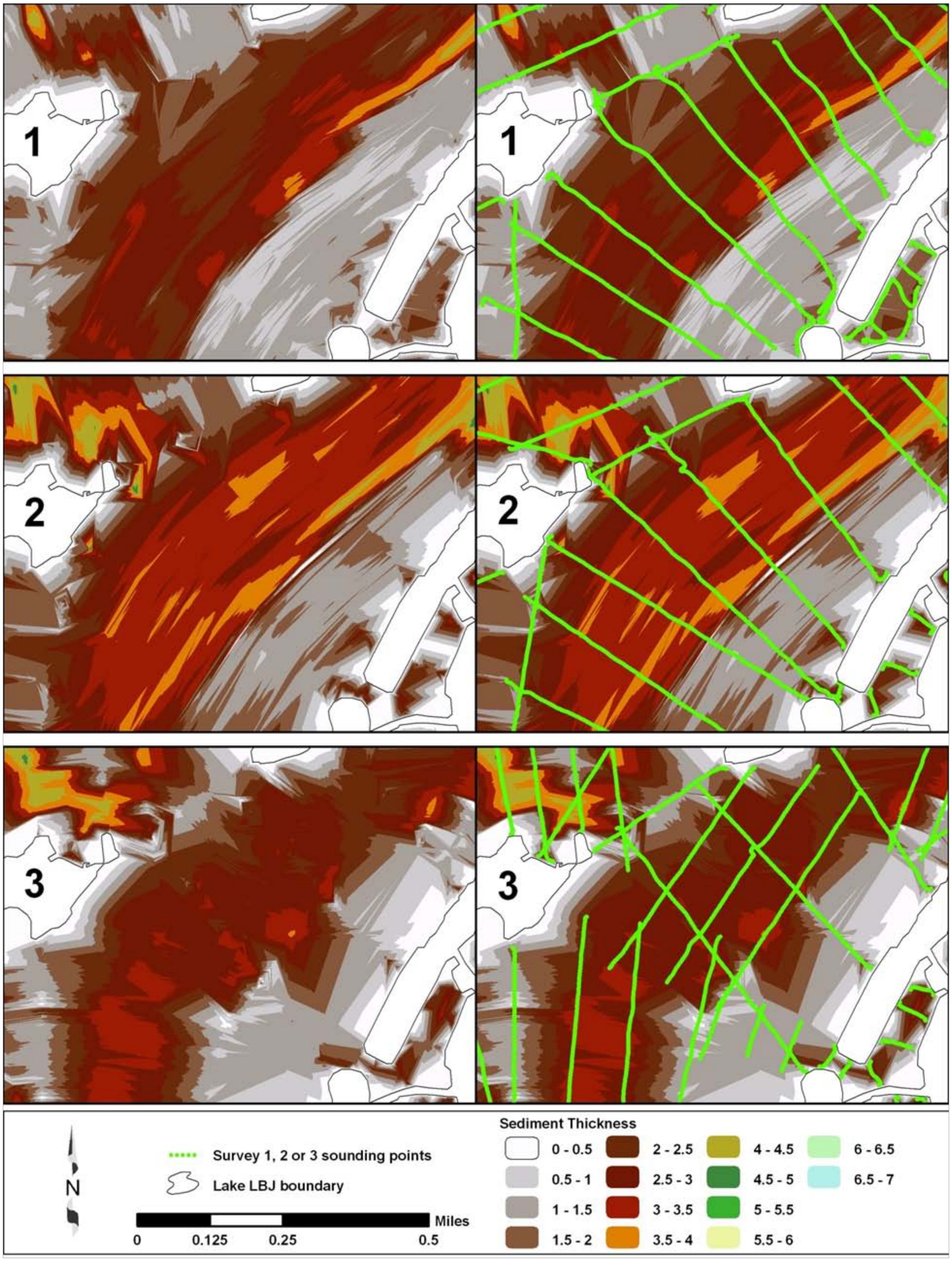


Figure 19: Surveys 1, 2 and 3 TIN models before interpolation showing survey soundings

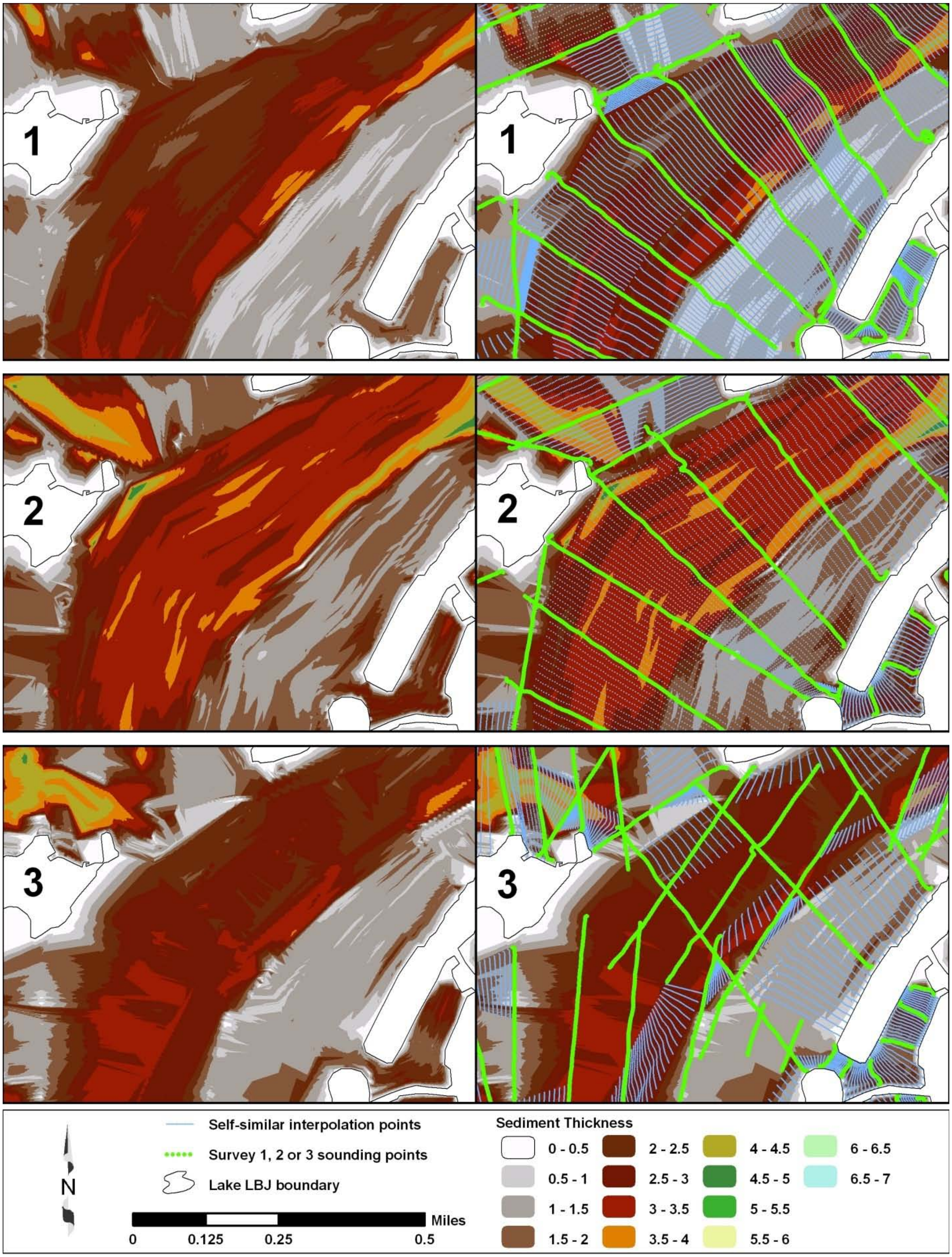


Figure 20: Surveys 1, 2, and 3 TIN models after interpolation showing survey soundings and interpolations

Figures 19 and 20 are used to demonstrate possible sources of error. In Figure 19, with no interpolation, Survey 1 and Survey 2 have similar survey line distributions for this region. Despite this, the sediment thickness distributions are significantly different, indicating variability in either current and/or pre-impoundment picks and resulting in inconsistent sediment thickness volumes. It is possible that some of this difference is due to the flood of 2007, but similar comparisons (not presented here) at other locations in the lake, as well as the earlier discussion on the high correlation of current surface measurements (and volume estimates) between the three surveys and the results from the diagnostic analysis presented later in this report in section 3, make this unlikely.

Looking at the results from Survey 3 in Figures 19 and 20, for non-parallel survey lines the application of self-similar interpolation becomes increasingly difficult. The self-similar approach was initially designed to improve interpolations between parallel survey lines between which the profile shape is expected to remain similar. Surveys 2 and 3 have varying densities of survey lines and use survey line placement strategies where orientation may not be parallel. In these situations, the choices of how self-similar interpolation should be applied and between which survey lines and in what orientation, becomes increasingly complicated. This can be seen in Figure 20 through the pale blue lines that represent the self-similar interpolation points used in this region for Survey 3. In the case of sediment volume calculations, these applications of self-similar may significantly affect sediment volume calculations, as seen in the 2-15% increase in sediment volume difference in Table 4 above. Later in this report in section 3.3, we show that significant errors in sediment thickness can occur near steep changes in bathymetry. Hence, for a typical survey line across the lake the errors may be localized to those areas of steep change; however in Surveys 2 and 3, the orientation of the survey lines and the self-similar interpolation direction choices may have expanded the error from the steep bathymetry to other parts of the lake. The self-similar direction choices were made based on the volumetric analysis and it is possible that different choices based on inspection of sediment data would have provided better results. It is also possible that these differences are more due to the difficulty in determining the pre-impoundment surface than the survey line placement technique.

3. Effect of survey equipment and technique

To assess how variations in surveying equipment and techniques may affect the collected depths and resulting reservoir volumes, diagnostic survey data were collected using a variety of TWDB survey equipment. Currently TWDB uses either a Knudsen Dual Frequency Echosounder or a Specialty

Devices Inc. Multi-Frequency Sub-bottom Profiler. In both cases, the 200 KHz primary frequency is used to determine the current surface. The secondary lower frequencies can be used to estimate sediment thickness by determining the per-impoundment surface. In practice, TWDB does not use the lower Knudsen frequency and only uses the SDI echosounder for sedimentation surveys. TWDB has several boats that are used for surveying depending on the lake conditions, all of which can be set up with either depth sounder. Data collection occurred in the area of Lake LBJ where multibeam data was previously collected, thus allowing the use of the multibeam dataset as a baseline for comparison for current surface determination. The multibeam data was collected before the 2007 flooding event. All diagnostic survey data was collected from March-April, 2009 after the flooding event of 2007.

The diagnostic survey was designed to study the effect of the following parameters on determination of the current and pre-impoundment surfaces at a single pre-planned survey line across the lake:

- Boat model
- Boat speed
- Direction of travel along the transect
- Depth sounding equipment

For each boat/sounder combination, TWDB attempted data collection in both a North-South (N-S) and a South-North (S-N) direction at speeds close to 2 mph, 4 mph, 6 mph, 8 mph, 10 mph and 15 mph. Actual speeds varied based on survey conditions and boat capabilities.

Varying the boats was expected to quantify any changes in survey results due to boat characteristics. Varying the boat speed was expected to aide in assessing the maximum permissible surveying speeds suitable for collecting valid bathymetric data, recognizing that the orientation of the transducer is likely to change as the pitch of the boat changes at different speeds of travel. Varying the direction of data collection was expected to provide insight into the effect of transducer orientation relative to the bathymetry. TWDB does not currently use a heave/pitch/roll sensor which would correct for variations in the survey boat attitude.

3.1. Diagnostic survey methodology

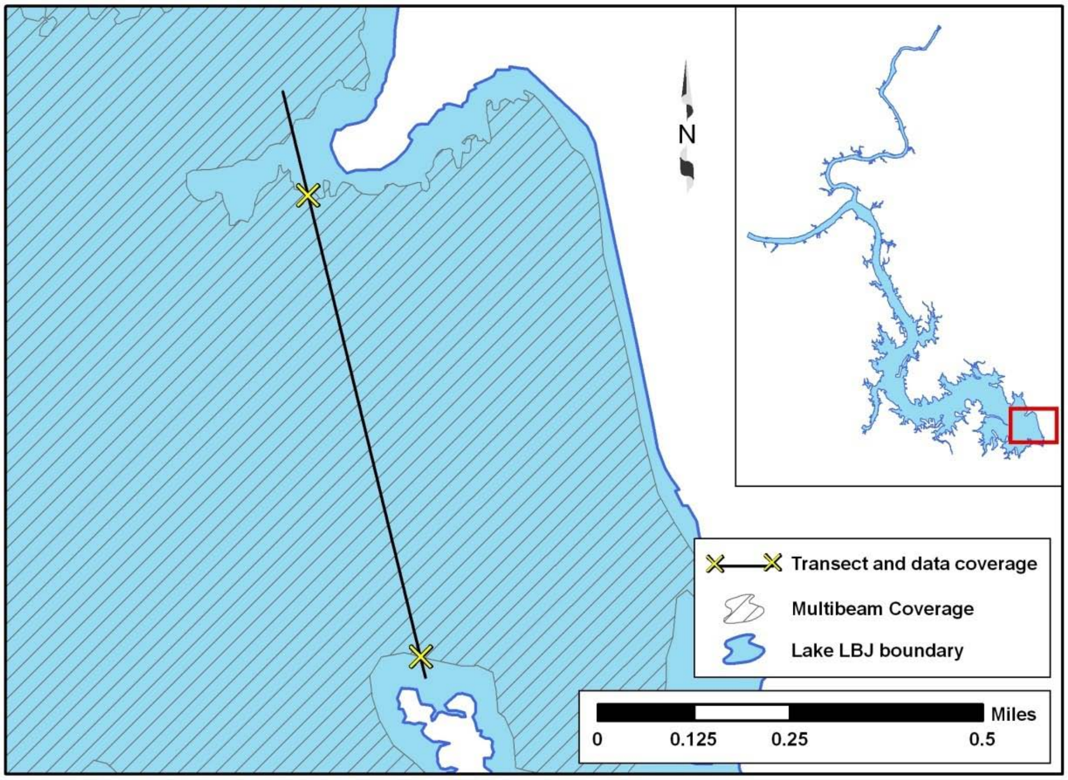


Figure 21: Location map of preplanned survey line on Lake LBJ used for the diagnostic survey.

A total of 76 transects were made along the preplanned survey line shown in Figure 21. Table 7 shows the parameters that were varied during these transects. In addition, current surface data was extracted from the multibeam survey along the preplanned survey line for use as a baseline dataset. Due to gaps in multibeam coverage, the analysis was restricted to the portion of the preplanned survey line that overlapped the multibeam coverage area, i.e, between the portion contained between the two yellow X's in Figure 21.

Table 7: Parameters varied during the diagnostic survey

Parameter	Options
Boat model	Hydro, Core, ADCP, Tunnel
Boat speed	2mph – 16mph
Direction of travel	South to North (S-N), North to South (N-S)
Depth sounder	SDI, Knudsen

Since the boat paths and sounding locations do not coincide exactly between transects, the current surface and pre-impoundment surface data from each transect was projected onto the survey line defined in Figure 21 and linearly interpolated to a 1ft spacing. Comparisons between transects were conducted between these projected and interpolated datasets. In addition, while field notes indicated the speed for each transect, in practice the ability of the boat to attain that speed varied due to boat characteristics, wind, etc. and varied along the length of the transect. In the analysis presented in this section, the boat speeds indicated are average speeds for the each transect calculated from timestamps in the sounding data.

3.1.1. *Description of boats*

The TWDB currently uses 4 boats as part of its hydrographic survey program. These boats (shown in Figure 22) have different handling characteristics, drafts, speed capabilities, and depth sounder mounts.

Figure 22: Hydrosurvey boats from left to right: Hydro, Core, ADCP and Tunnel

The Hydro boat (far left) is a 23 ft dual outboard engine, triple v-hull craft with a fully enclosed cabin and starboard (right) mounted helm. The depth sounder mounts to the starboard side of the bow (front right). The core boat (second from left) is a 25 ft single outboard engine v-hull craft with a partially enclosed, center mounted cabin and a starboard mounted helm. The depth sounder mounts to the starboard side of the bow, forward of the cabin. The core boat is a modified commercial fishing vessel specially redesigned for hydrographic survey and lake sediment coring. The ADCP boat (third from left) is a 17ft single outboard engine, modified v-hull craft with a partially enclosed cabin and center helm/cabin. Depth sounder equipment is mounted in the center of the boat, rear of the helm, in a well designed specifically for hydrographic surveying. The tunnel boat (far right) is a 14 ft single outboard engine, flat bottom, starboard mounted helm, john-boat style craft. Depth sounder equipment is mounted on the starboard side of the boat, forward of the helm. The stationary draft is measured daily after mounting the depth sounder as part of the pre-survey routine.

Due to the starboard helm mount on all boats, two TWDB staff members were present in each boat during surveying to balance the boats evenly.

3.1.2. ***Depth sounders***

3.1.2.1. Specialty Devices, Inc. (SDI)

The SDI depth sounder is the primary device used for volumetric and sediment surveys conducted by the TWDB. This depth sounder transmits and receives three frequencies (200, 50 and 24 kHz). With multiple frequencies, the device collects data pertaining to sub-bottom profiles. With regards to lakes, the TWDB collects sub-bottom profile information to determine the pre-impoundment surface. Post processing of data is done through the Depthpic software.

3.1.2.2. Knudsen Engineering, LLC

The Knudsen depth sounder is used for current bathymetry analysis only. This depth sounder transmits and receives two frequencies (200 and 50 kHz). Post processing of data is accomplished manually through the Hypack software or automatically through the HydroEdit software.

3.1.2.3. Multibeam

The multibeam depth sounder allows for obtaining a high density (5 x 5 ft) grid point coverage of the bottom bathymetry. Unlike the single-beam echo sounder that provides one sounding directly beneath the transducer, multibeam surveying acquires depths across the entire range of the swath, with each beam in the swath producing an actual depth sounding. For this data collection, HCI used a Reson 8101 Multi Beam Echo Sounder to collect multibeam data. Because the 8101 measures depths along a swath perpendicular to the vessel, a gyro compass and dynamic motion sensor must be used to measure the vessel's attitude in real time as well as a GPS receiver to measure position. Detailed descriptions of the multibeam unit and related equipment are provided in the HCI report (2007). Figure 23 below shows the difference between multibeam and single beam surveying.

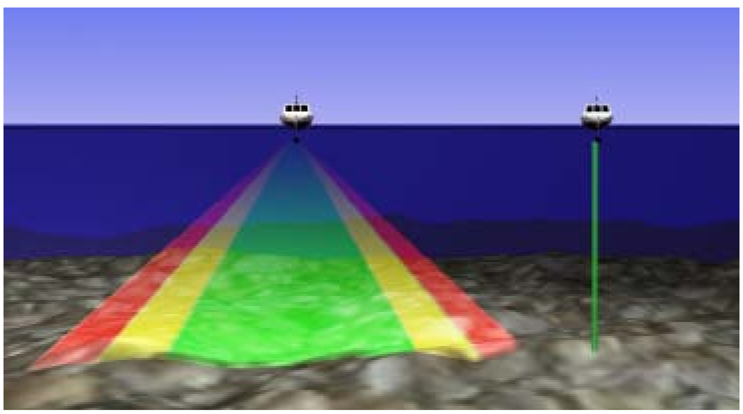


Figure 23: Multibeam versus single beam survey coverage

3.2. Current surface analysis results

To analyze the TWDB diagnosis data profiles, the baseline profile shown in Figure 24 was extracted using soundings from the multibeam survey.

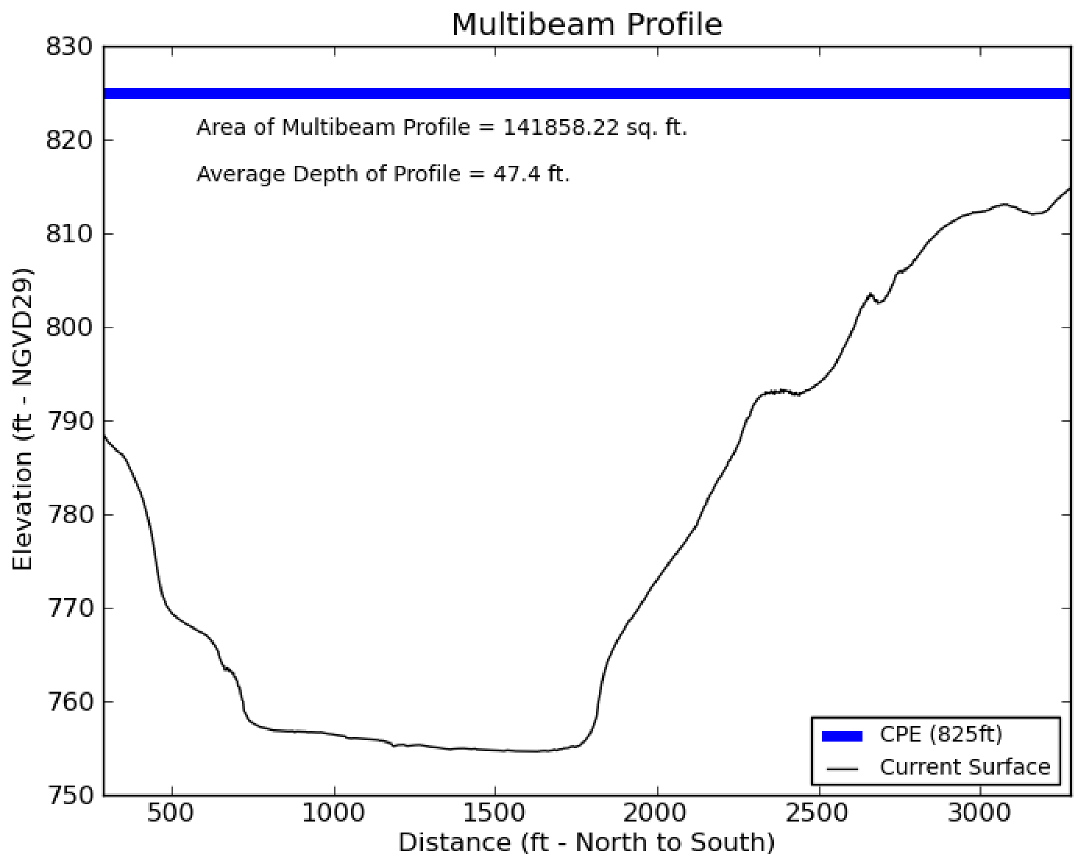


Figure 24: Multibeam profile of the diagnostic survey transect

Each diagnostic transect profile is plotted against the extracted multibeam baseline profile. The cross sectional area of this profile is approximately 141,900 sq. ft. and its average depth is 47.4 ft. A conservation pool elevation (CPE) of 825.0 ft was used to convert the depth readings to elevations.

Figure 25 below exhibits an example of the individual diagnostic transect profiles found in Appendix B. The plots show the baseline multibeam profile (black), depth sounder data used to create each profile (teal), and soundings that were thrown out as spurious (red).

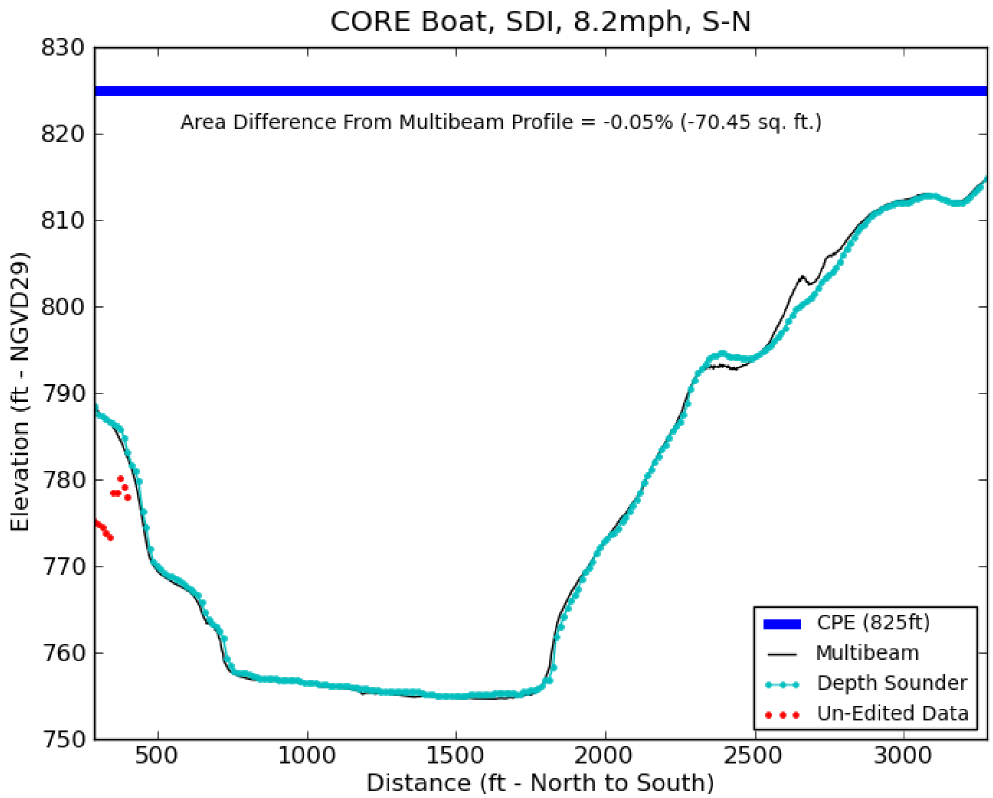


Figure 25: Example of transect profile plot. Core boat using SDI travelling S to N at 8.2 mph

All transects, except for one, were used in the final analysis. The transect obtained using the Hydro Boat, Knudsen Depth Sounder, travelling South to North at 9.1 mph (shown in Figure 26) was deemed unusable due to a lack of usable data and large portions of missing data.

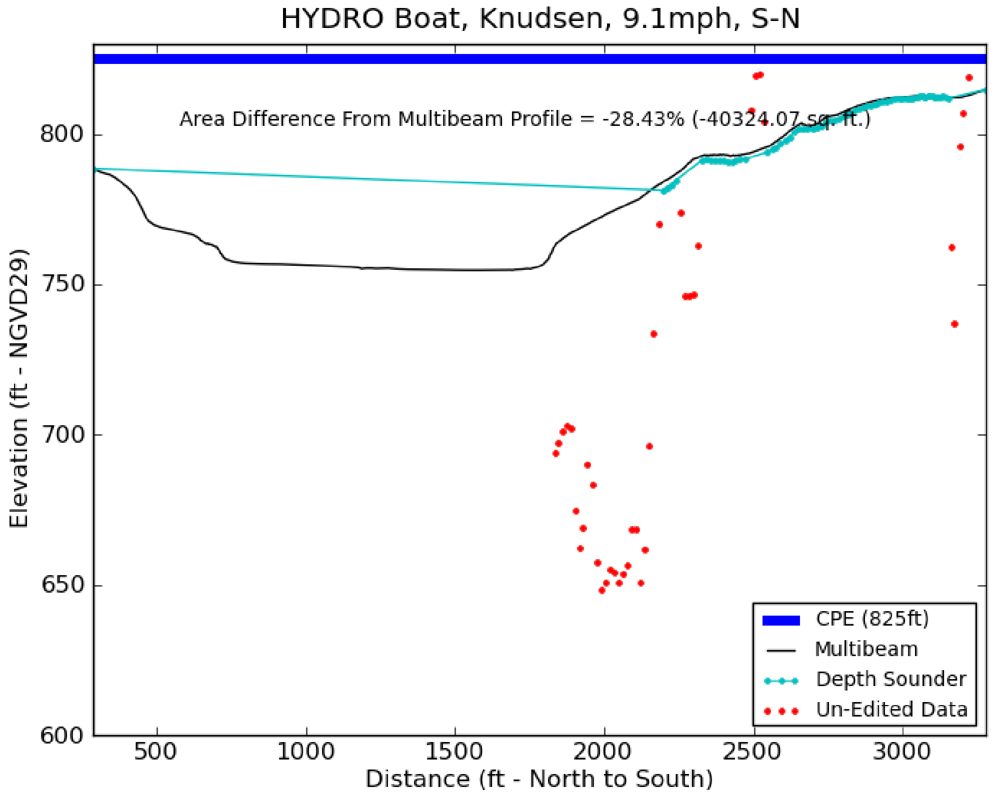


Figure 26: Unused transect for Hydro boat using Knudsen travelling S to N at 9.1 mph

3.2.1. *Summary of results*

Here we present some overall conclusions about the effects of boat type, sounding equipment used, travel direction and boat speed on the determination of the current surface and hence the cross sectional area of the profile along the survey line. Detailed results are presented by boat type in the subsequent sub sections.

Figure 27 summarizes the effect of boat speed on the estimated cross-sectional area and average depth of the transect profile. In particular, it can be seen from these figures that at speeds less than approximately 8mph the overall error in determining the cross sectional area of the profile is less than 2% and the average depth of the profile is within 1ft of that of the baseline multibeam survey. Above approximately 8 mph, the current surface depth estimations generally increase, potentially due to the increased boat angle from increased speed. Table 8 shows the speeds below which consistent measurements were able to be taken for each boat.

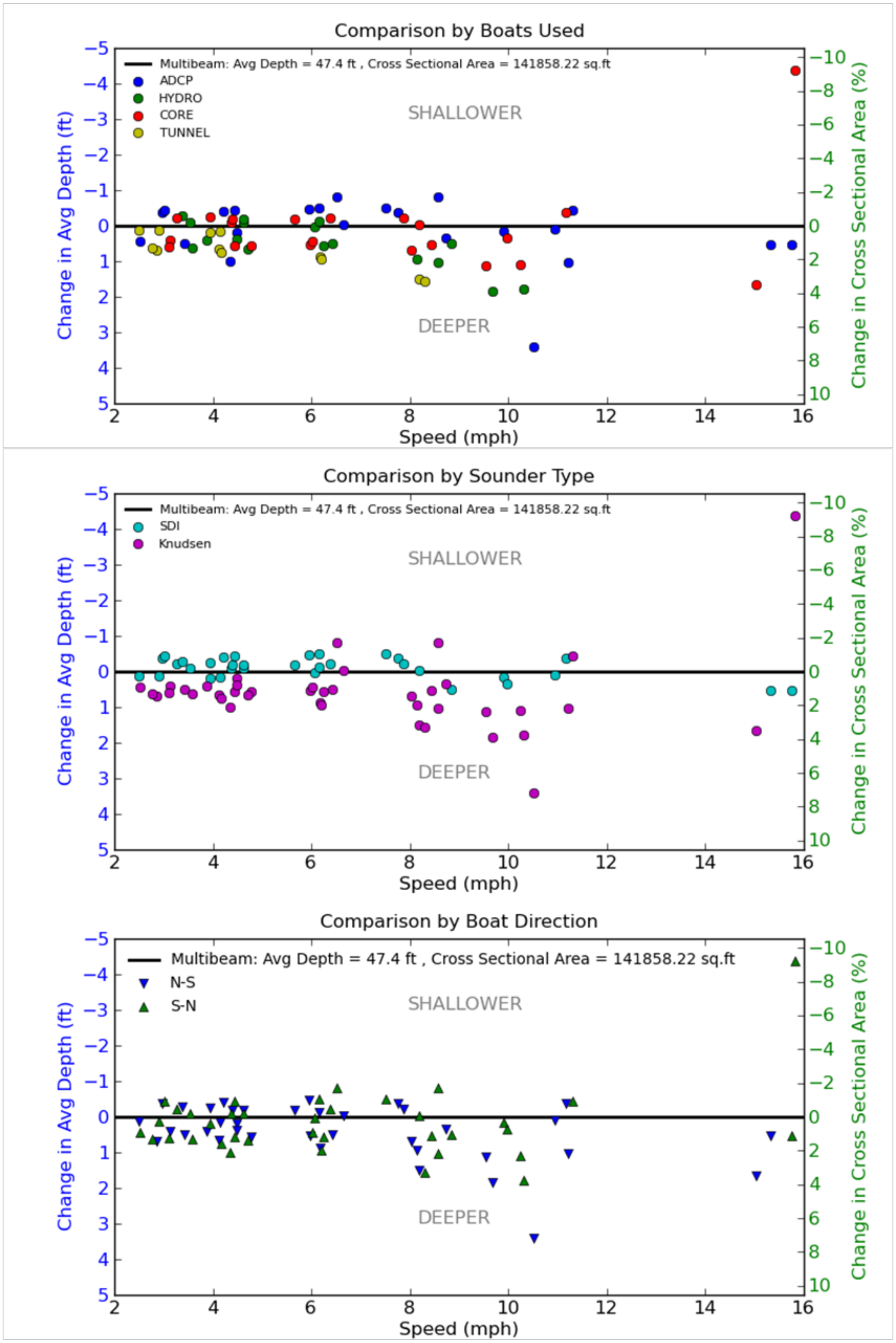


Figure 27: Comparison of diagnostic survey profiles at different boat speed with profile extracted from multibeam survey.

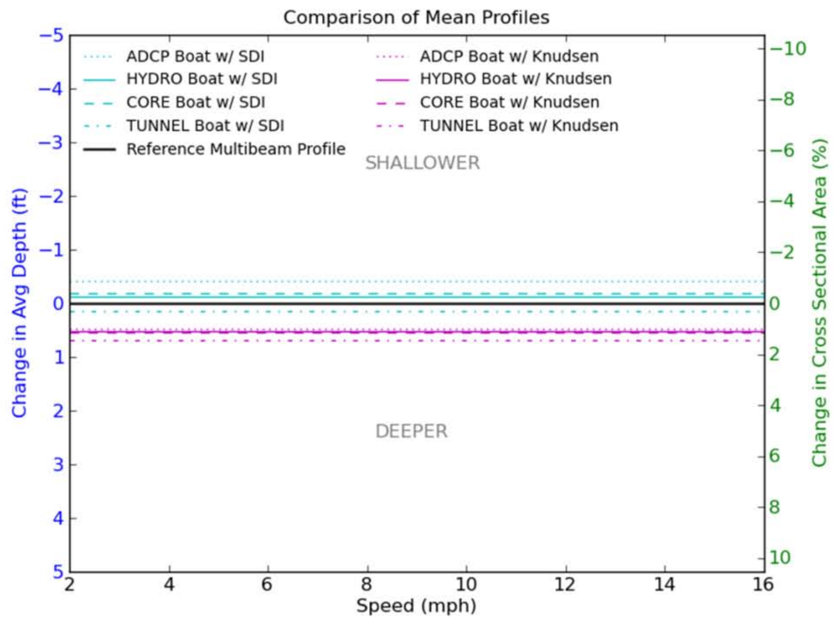
Table 8: Boat speeds below which consistent measurements were taken

Boat	Speed
Hydro	7 mph
Core	9 mph
ADCP	9 mph (SDI), 4 mph (Knudsen)
Tunnel	6 mph

3.2.1.1. Effect of boat and sounding equipment

The clearest trend visible in Figure 27 is the differences between measurements taken by the SDI and the Knudsen depth sounders (Figure 27b). This trend dominates the data and makes the other trends difficult to see at this level. Figure 28 shows the same information as biases in average depth and cross sectional areas between boats and depth sounders. The averages for each boat/sounder combination were calculated using profiles taken at speeds less than those shown in Table 8. This figure shows that while the greatest bias is related to the sounder used, there are biases between the boats as well.

The SDI equipment measurements generally agreed better with the baseline multibeam survey, though depth readings were consistently slightly shallow and output more consistent measurements at different speeds. The Knudsen equipment consistently measured deeper than the baseline multibeam survey and output increasing variation at higher speeds. The only exceptions to this are some of the higher speeds ADCP/Knudsen profiles which seem to measure shallower than the baseline multibeam. As we discuss later, much of the ADCP/Knudsen data above boat speeds of 4mph was spurious and required heavy editing to be usable.



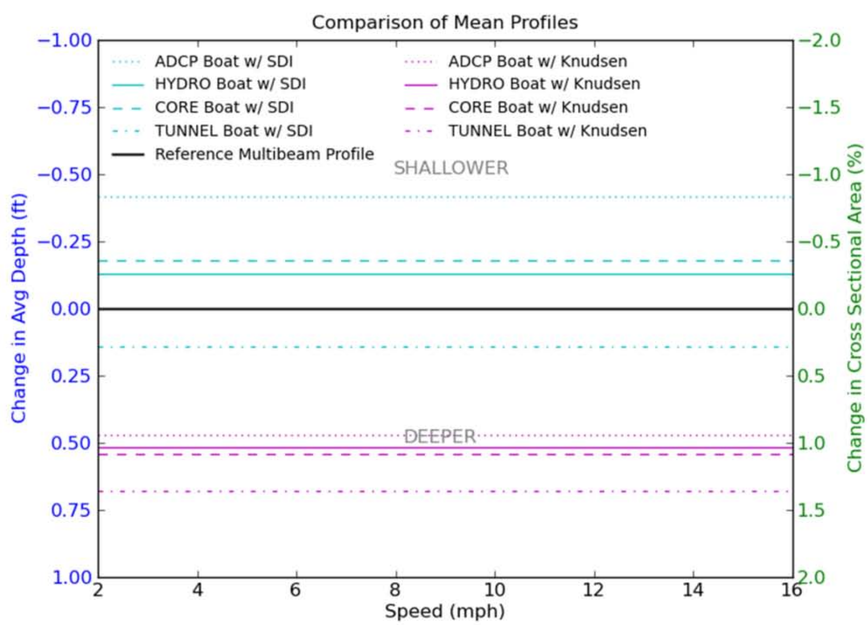


Figure 28: Survey biases by boat and depth sounder examined with average difference in depth and between depth sounders

A distinct bias is evident between depth sounders. Possible explanations include weight discrepancies between depth sounders and differences in settings such as power, gain, etc. or differences in post processing of the data. Both depth sounders perform well in pre-survey depth verification measurements, returning depths within 0.1 ft of stadia rod measurements at a fixed location. These depth verification measurements are taken while the boat is stationary. The Knudsen depth sounder is considerably lighter than the SDI depth sounder and this may cause differences in the attitude (pitch) of the boat when in motion or change the boat draft. It is not clear that the settings for the SDI and Knudsen depth sounders were equivalent during diagnostic surveying. The post processing methods and removal of spurious data are also not equivalent between the systems and may contribute to the bias.

After discussion with the manufacturer of the SDI equipment it is thought that a large portion of the bias is due to a special algorithm the SDI software uses to partially correct for transducer angle. A simplified explanation of this algorithm is that rather than using the strongest return signal from the cone of sound waves generated by echo sounder it uses the first return. This has the effect of partially mitigating the effect of transducer angle in the absence of a correction factor from a heave/pitch/roll sensor. This also explains why the SDI equipment measurements generally agreed better with the baseline multibeam survey which did incorporate a heave/pitch/roll correction.

A clear difference also exists between boats. The ADCP boat returns the deepest depth measurements; the tunnel boat returns the shallowest depth measurements; and the Core and Hydro boats return similar depth readings between the two extremes. Probable sources of depth reading differences may be attributed to differences in physical boat characteristics. Exactly how individual boat characteristics affect depth readings is also currently unknown. Most likely, causes of these biases between boats may be due to differences in transducer angle when the boats are at rest as opposed to when in motion, and discrepancies in stationary draft versus the draft while in motion. Another possibility may be depth sounder mounting arrangements for each boat. As noted in section 3.1.1, The ADCP boat is unique because the depth sounder is mounted near the center of the boat, whereas the other boats employ variations of forward mounts off the starboard (right) side. Incorporating heave/pitch/roll sensors may correct some of the discrepancies due to boat characteristics.

It is notable that measurements from the SDI system have a higher ‘spread’ (i.e variation in average depth measured between boats) than the Knudsen system. If the variation between boats were solely caused by physical boat characteristics this spread would be expected to be similar for both depth sounders.

3.2.1.2. Effect of directionality of transect

Direction of travel along the diagnostic transect had little effect on the determination of the profile cross sectional areas. It does however have an effect on the determination of the current surface. Transects taken at similar speeds on the same boat using the same sounding equipment had virtually identical cross sectional areas (Figure 30). This can be seen more clearly in the following sections where the results are presented by boat used (Figure 31 through 33 and 35). Individual sounding measurements are affected by the directionality and the profile shape shifts slightly when the direction of travel is changed (See Figure 30).

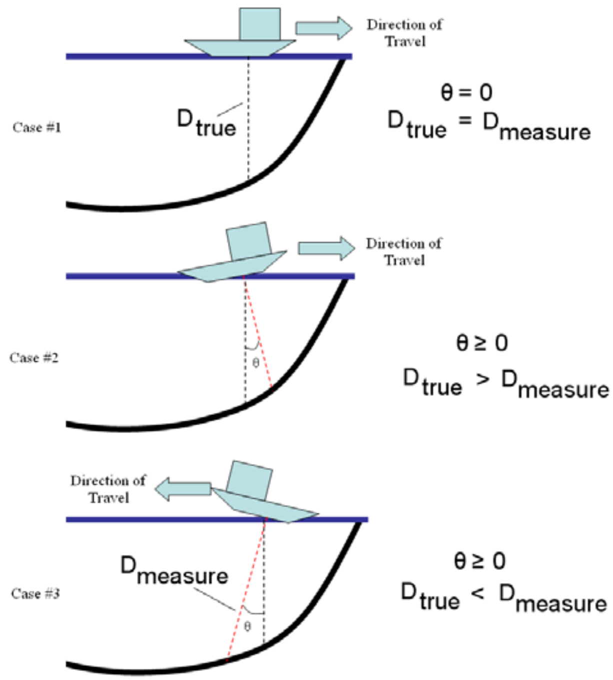


Figure 29: Measured depth changes due to survey boat orientation and bathymetric slope

In theory, without the use of a heave/pitch/roll sensor the depth at a location will be under or over measured due to survey boat orientation and bathymetric slope (See Figure 29). In practice, while the lack of a heave-pitch-roll correction does affect the accurate determination of the depths at individual sounding locations, the cross sectional area of the profile is minimally affected. In essence, across each transect the depth is measured as deeper than the true depth for the downward slope and for the flat portion of the transect and is measured as shallower than the true depth for the upward slope of the transect.

For the pre planned survey line used in this diagnostic survey the overestimate of the downward slopes are generally cancelled out by the underestimate of the upward slope giving a consistent cross sectional area regardless of boat orientation. An example of this can be seen in Figure 30. It must be noted however, that although the N-S and S-N profile cross section areas match extremely well, they both overestimate the cross sectional area of the profile due to overestimates of the relatively flat middle section of the profile in both cases.

There is a general increasing trend in the cross sectional area at speeds above 8mph which would be consistent with increased over estimation of depth of the flat portion of the transect as the boat pitch increased with speed. In addition the draft of the transducer may change at increased boat pitch and/or speed. At these higher speeds, while the boat orientation does not significantly affect the cross sectional area measurement, it is clear that the higher pitch of the boat results in an over estimation of the cross section of the profile as compared to the baseline profile.

In summary, boat orientation had little effect on determination of the cross sectional area of the profile but it did result in errors in the measurement of individual soundings and a shifting of the profile shape. This result is due to a cancellation of errors from the downward and upward slopes of the profile and hence may not hold in cases where the profile is very asymmetrical. An additional point to consider is that profiles with large sections where bathymetric slope does not vary will be overestimated because of the errors associated with boat pitch that do not cancel out. An example of this would be a profile taken along the thalweg of a lake. This effect becomes pronounced as boat speed and hence pitch increases.

A preliminary theoretical study analyzing the effect of transducer angle at various boat speeds on the measurement of the cross sectional area of some representative transects from Lady Bird Lake showed that this overestimation due to pitch at normal operating speeds is of the order of 1-1.5% (Pothina, 2009) for transects below 50 ft. deep. The analysis looked at the cross sectional area measured at various boat speeds at a variety of fixed transducer angles. This analysis did not consider the change in draft of the transducer between a stationary and moving boat or boat specific speed - transducer angle characteristics. The overestimation will also be higher when measuring deeper profiles.

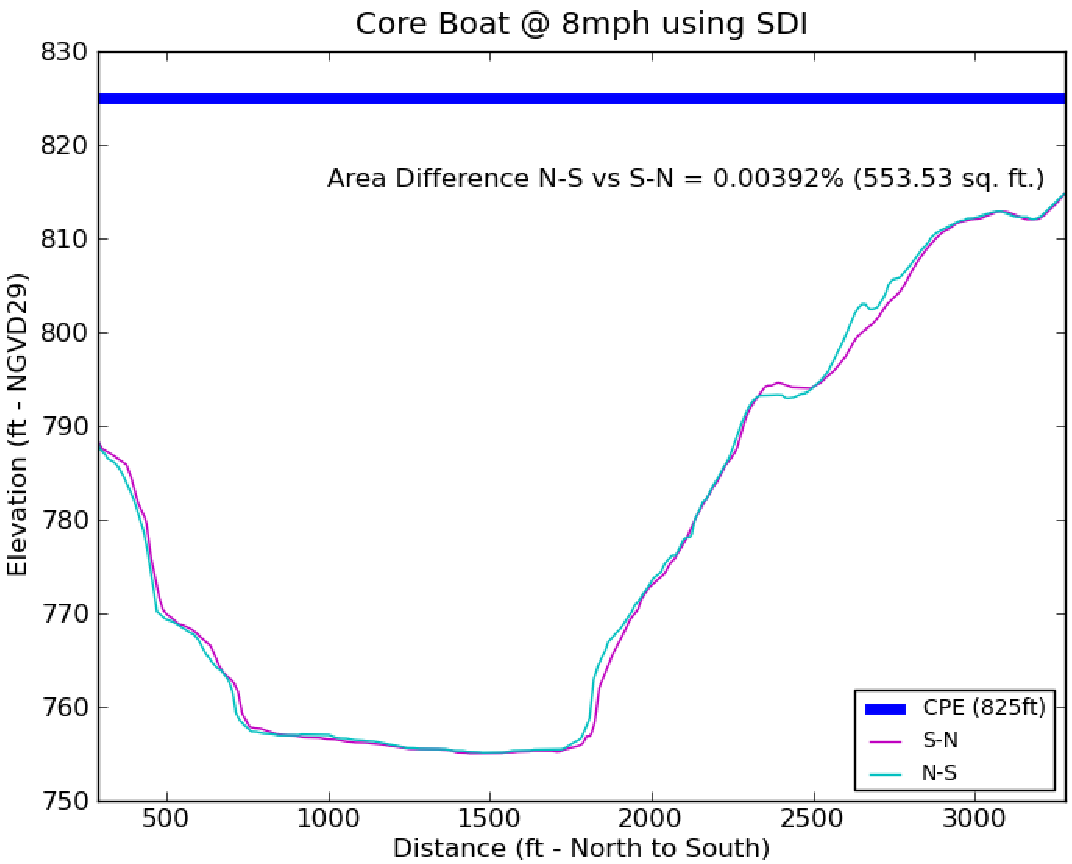


Figure 30: Diagnostic transect differences due to direction of travel for the core boat at 8 mph

3.2.2. *Individual boat characteristics and results*

3.2.2.1. Hydro boat

The hydro boat is the widest and heaviest boat TWDB uses for hydrographic surveying. The fully enclosed cabin increases the weight of the boat above the water line. These boat characteristics give the hydro boat stability in pitch (forward – backward) and roll (left – right) from wave effects. The depth sounder device must remain under water and free from turbulence during surveying for accurate results, therefore mounting placement is important to obtain accurate results (Hughes and Taube, 2000). Mounting the depth sounder on the extreme bow of the hydro boat increases effects of pitch movement and heave (upward – downward) while surveying. The depth sounder is also mounted starboard (right) of the centerline, therefore including unknown roll effects into the data. Figure 31 below examines the effects of speed and brand of depth sounder for the hydro boat.

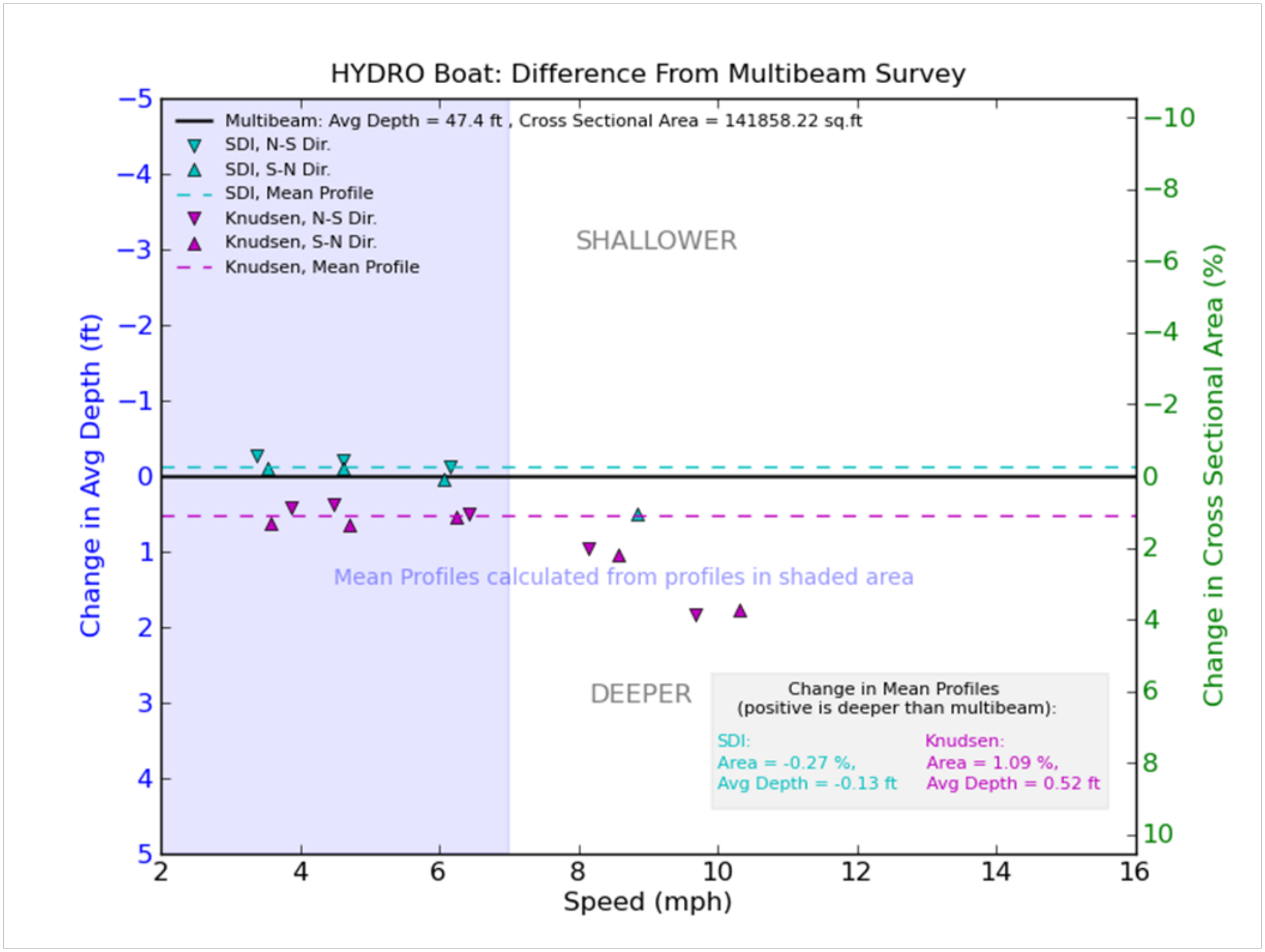


Figure 31: Boat speed and brand of depth sounder comparisons for hydro boat. Vertical scale is chosen to be consistent across all four boats.

The hydro boat provides consistent data with both brands of depth sounder at speeds of approximately 7 mph and below (shaded area in figure). Data at speeds above approximately 7 mph is not included in the average depth because an increasing depth measurement trend is present in both data sets. There is a clear bias between the SDI and Knudsen with the Knudsen measuring consistently deeper. There is no directional bias.

3.2.2.2. Core boat

The core boat is the longest boat TWDB uses for hydrographic surveying and is the only boat with a single V shaped hull design. These boat characteristics give the core boat increased lateral (forward-backward) stability. However, roll effects from waves, when compared to the triple V shaped hull design of the Hydro and ADCP boats are unknown. Figure 32 below examines the effects of speed and brand of depth sounder for the core boat.

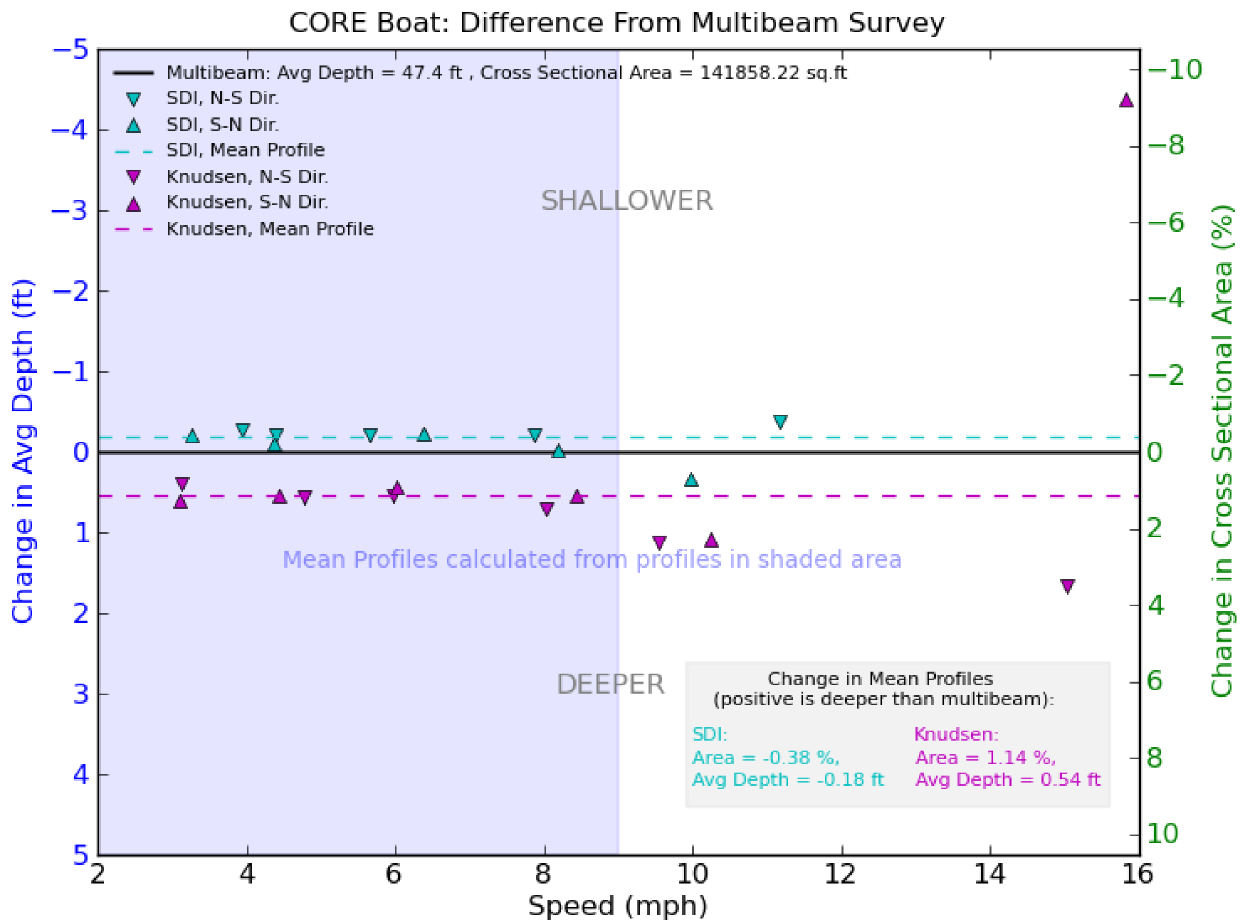


Figure 32: Boat speed and brand of depth sounder comparisons for core boat. Vertical scale is chosen to be consistent across all four boats.

The core boat provides consistent data with both brands of depth sounder at speeds of approximately 9 mph and below. Data points at speeds above approximately 9 mph are not included in the average depth because an increasing depth measurement trend in the Knudsen data and variability in the SDI data. There is a clear bias between the SDI and Knudsen with the Knudsen measuring consistently deeper. There is no directional bias.

3.2.2.3. ADCP boat

The ADCP boat is a wide and short boat TWDB uses for hydrographic surveying. The unique depth sounder placement within a specifically designed well in the middle of the hull provides maintained immersion of the depth sounder and reduces errors related to speed, pitch and roll. The in hull design also reduces the possibility of transducer damage from tree stumps. Figure 33 below examines the effects of speed and brand of depth sounder for the ADCP boat.

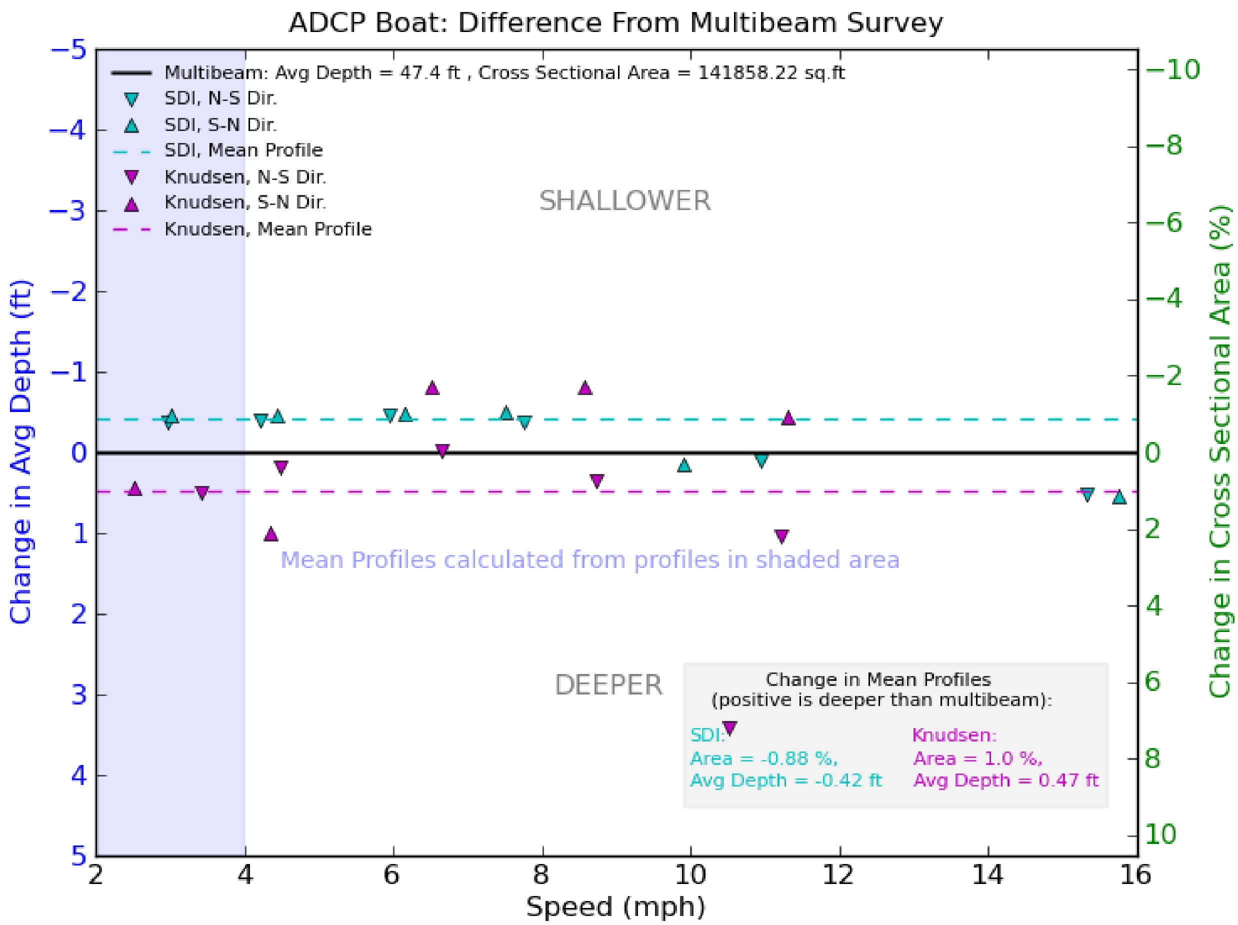


Figure 33: Boat speed and brand of depth sounder comparisons for ADCP boat. Vertical scale is chosen to be consistent across all four boats.

The ADCP boat provides consistent data with the SDI depth sounder at speeds of approximately 8 mph and below. The Knudsen data cross sections were incomplete for speeds exceeding approximately 4 mph. The Knudsen data above 4 mph were filtered based on the prior knowledge of the current surface from the multibeam data. Points within 5% of the depth of the multibeam dataset were retained and the spurious data thrown out. Figure 34 shows this procedure for one such transect. While these transects are included in Appendix B and in figure 33 for reference, they were not used in the analysis that follows since in an actual survey this type of correction would not be possible. The cause of this spurious data is unknown but is surmised to be related to the transducer well present in the ADCP boat.

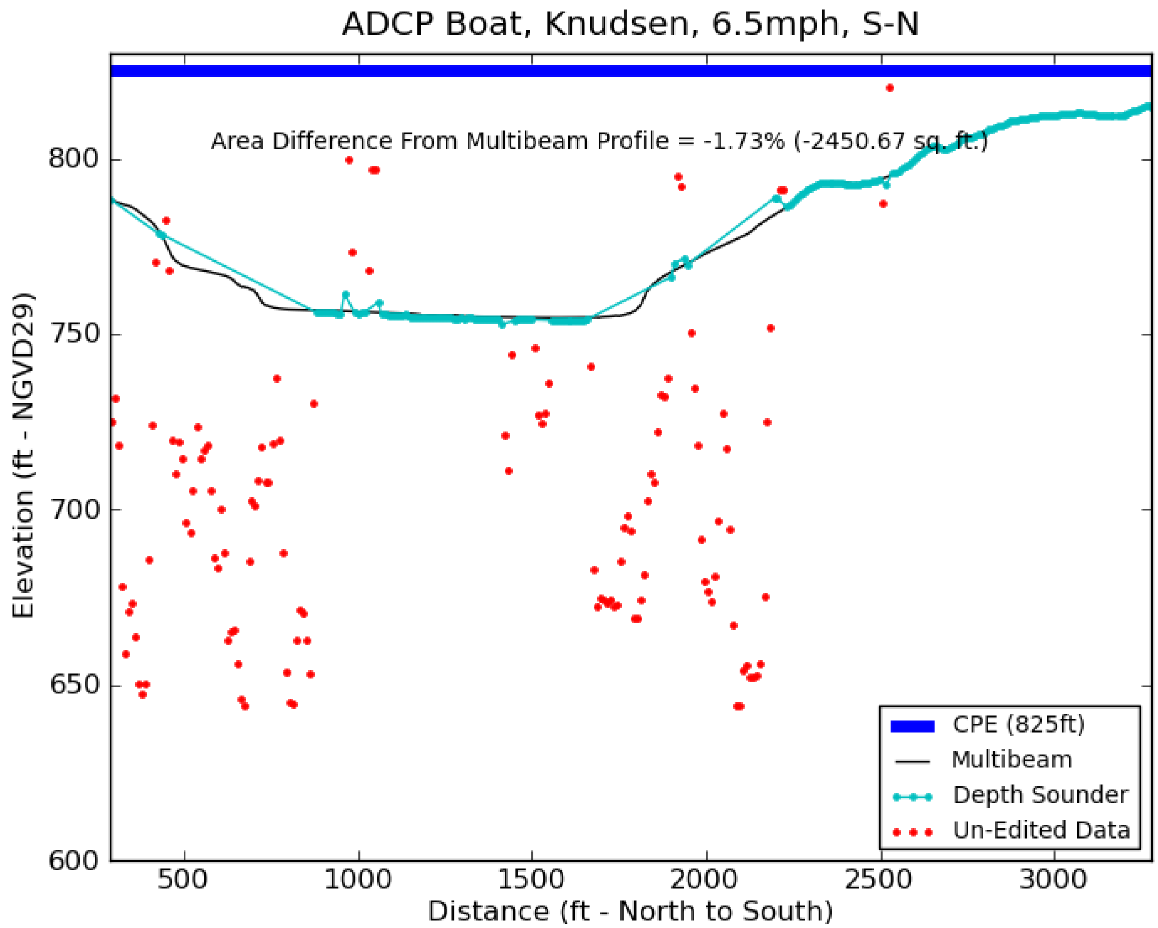


Figure 34: Example of removed spurious data

Knudsen and SDI data points at speeds above 4 mph are not included in the average depths. Although the SDI average depth is calculated from soundings below 4 mph, soundings from 4 mph to approximately 8 mph agree well with the average depth. Above 8 mph there is an increasing depth measurement trend for SDI data. There is a clear bias between the SDI and Knudsen with the Knudsen measuring consistently deeper. There is no directional bias.

3.2.2.4. Tunnel boat

The Tunnel boat is the shortest, lightest and most narrow craft TWDB uses for hydrographic surveying. The hull shape is simple and flat. Typically the tunnel boat is used to go into shallow coves and under small bridges or abutments. The depth sounder is typically located forward of the helm on the starboard side although bow mounting is possible. With this starboard placement, increased boat speed produces excessive splash into the boat, making higher speeds impractical. Figure 35 below examines the effects of speed and brand of depth sounder for the Tunnel boat.

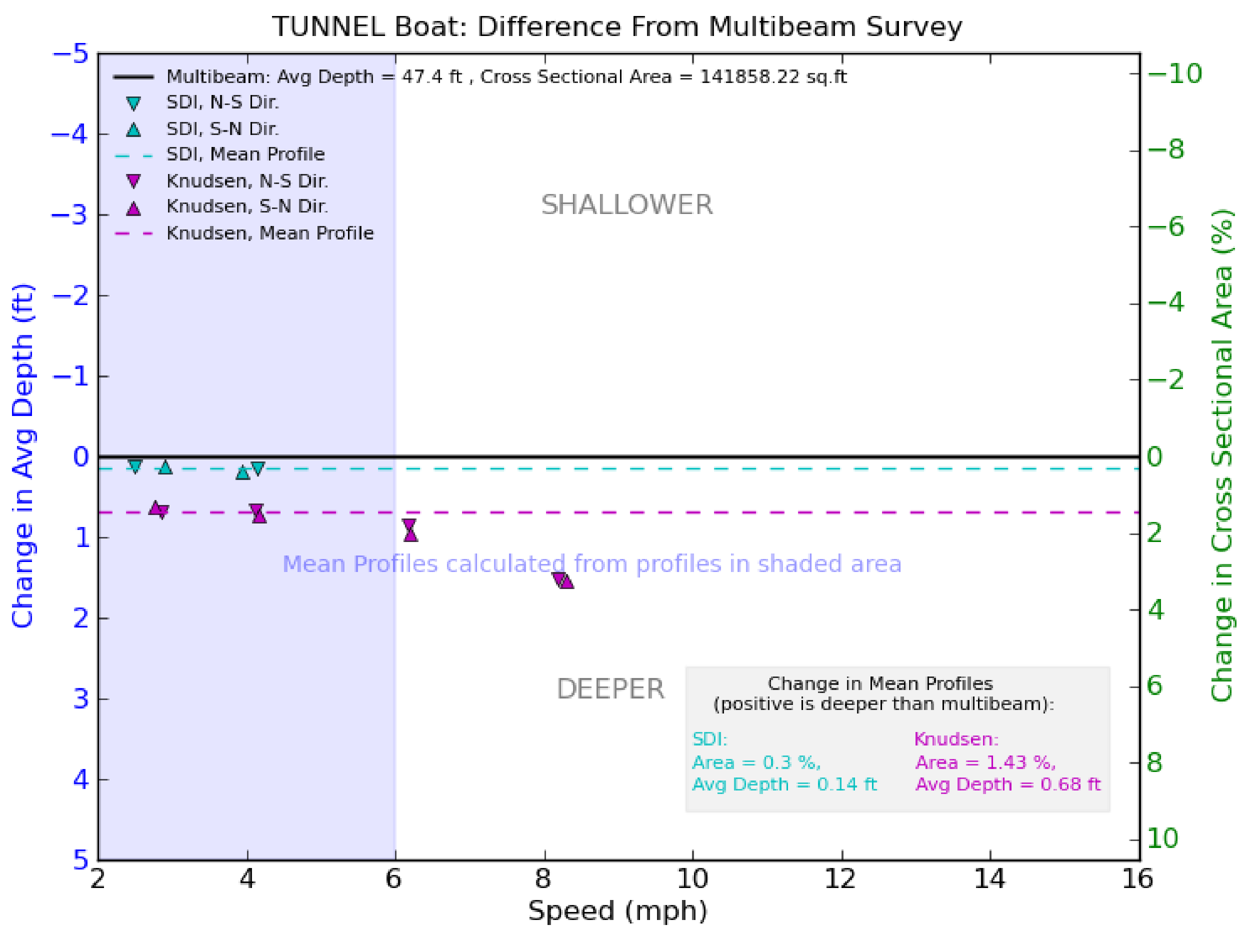


Figure 35: Boat speed and brand of depth sounder comparisons for tunnel boat. Vertical scale is chosen to be consistent across all four boats.

The tunnel boat provides consistent data with both brands of depth sounder at speeds of approximately 6 mph and below. Data points at speeds above approximately 6 mph are not included in the average depth because an increasing trend in the Knudsen data. There is a clear bias between the SDI and Knudsen with the Knudsen measuring consistently deeper. There is no directional bias.

3.3. Sediment analysis

The analysis of sediment thickness profiles from the diagnostic survey transects was limited to the SDI depth sounder. While the Knudsen depth sounder does return soundings at two frequencies (200 and 50 kHz), TWDB currently utilizes the three frequencies returned by the SDI when conducting sediment analysis, because the lower frequencies provide deeper sub-bottom profiles. The use of three frequencies (200, 50 and 24 kHz) provides sub-bottom penetration up to 8 ft. For sediment thicknesses greater than 8 ft, additional lower frequencies (12 and 4 kHz) are necessary to achieve sub-bottom penetration (Dunbar and Estep, 2008). We also note that, for sediment analysis, we do not have a baseline reference dataset as was available for the current surface analysis through the use of the multibeam survey.

3.3.1. ***Overall trends***

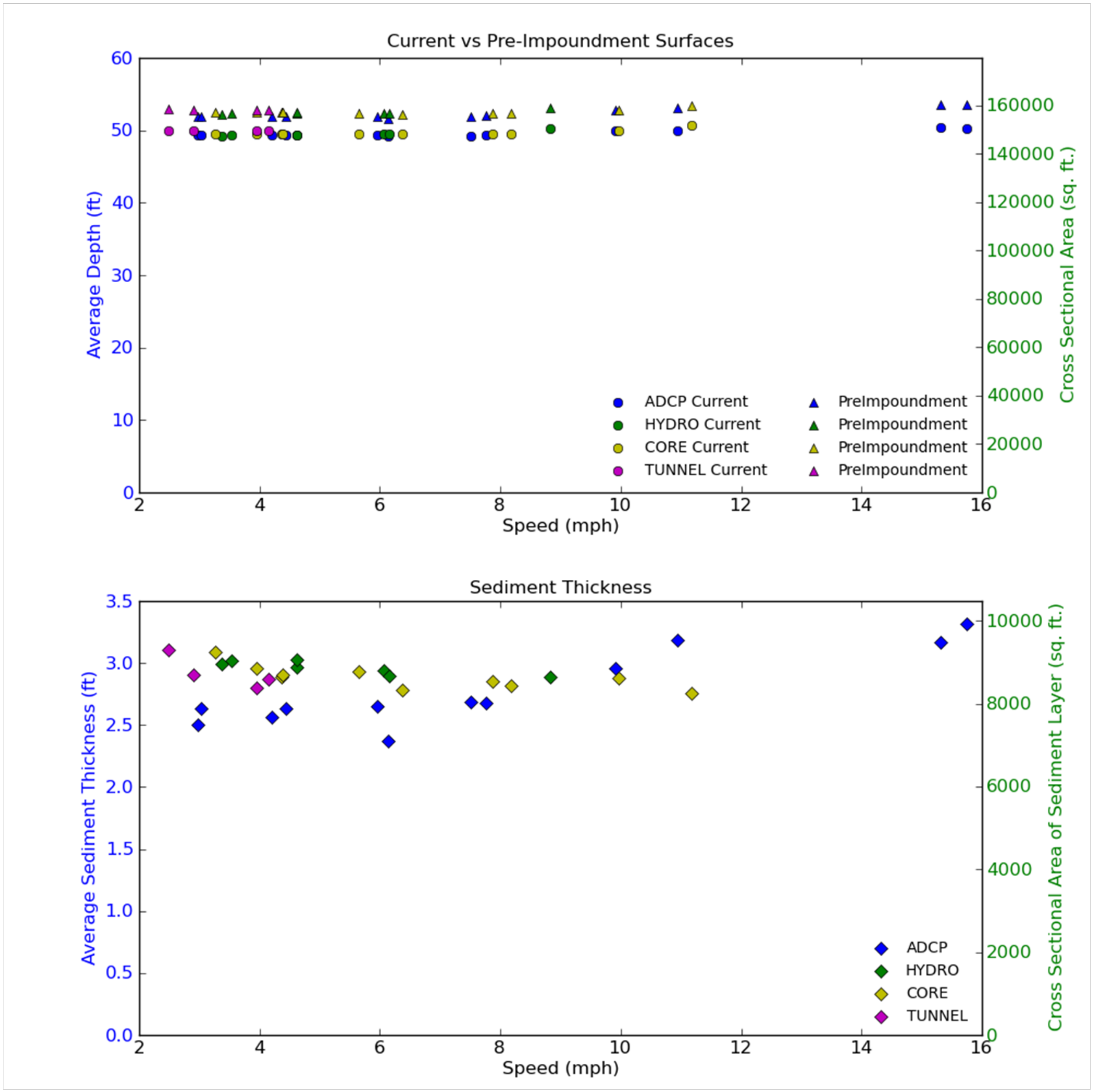


Figure 36: a) Current surface and pre-impoundment measured depths from water surface. The vertical scale is chosen to emphasize the size of sediment thickness measured to the overall transect depth; **b)** Resulting estimated sediment thickness.

No clear trends were found in the determination of sediment thickness with variations of boat, direction or speed. With the ADCP boat there is a slight increase in sediment measured with increased boat speeds while the other three boats show a slight decrease in measured sediment with increased boat speed (See Figure 36a). The sediment quantity measured by the ADCP boat was also noticeably different than the other three boats. However, it is unclear that any of these findings are actual trends. Further analysis of the data suggests that the variations in the measurements are within the precision of the sediment survey methodology currently in use and hence are not indicative of actual differences in measurement.

Uncertainties associated with the determination of the pre-impoundment surface, discussed earlier in section 2.3.1, are thought to be the main cause of the variations. A closer look at the data from the ADCP boat, showed no easily discernible reason for a difference in measurements from the other boats. One possible cause of difference is the ADCP data was the first set of profiles analyzed for the pre-impoundment surface. It is possible that if all the profiles were re-picked in random order by another trained professional or if an automated procedure were developed to pick the pre-impoundment surface, these differences may disappear. This further analysis has not been investigated as part of this project, but is a possible way to verify our hypothesis that the differences in measurement are being caused by variability in picking the pre-impoundment surface under the current methodology. Further testing of this hypothesis may reinforce the idea that the differences between the profiles in Figure 36b are within the precision of the current survey technique used by TWDB.

Another reason for the lack of trends in this data is the fact that many of the factors that affect the determination of the current surface are nullified in determination of the sediment thickness. This is because the sediment thickness is determined by the subtraction of the current surface from the pre-impoundment surface. Factors like boat angle (caused by boat speed), wave action, differences between boat mounting etc, affect the determination of these two surfaces the same way and hence the sediment thickness remains the same. This can be seen in Figure 36a where the current and pre-impoundment surfaces vary in almost the same fashion. For example, if a wave causes the current surface to be measured as 1 foot deeper than actuality the pre-impoundment surface is also 1 foot deeper and the difference is still the same.

3.3.2. *Variation across the profile*

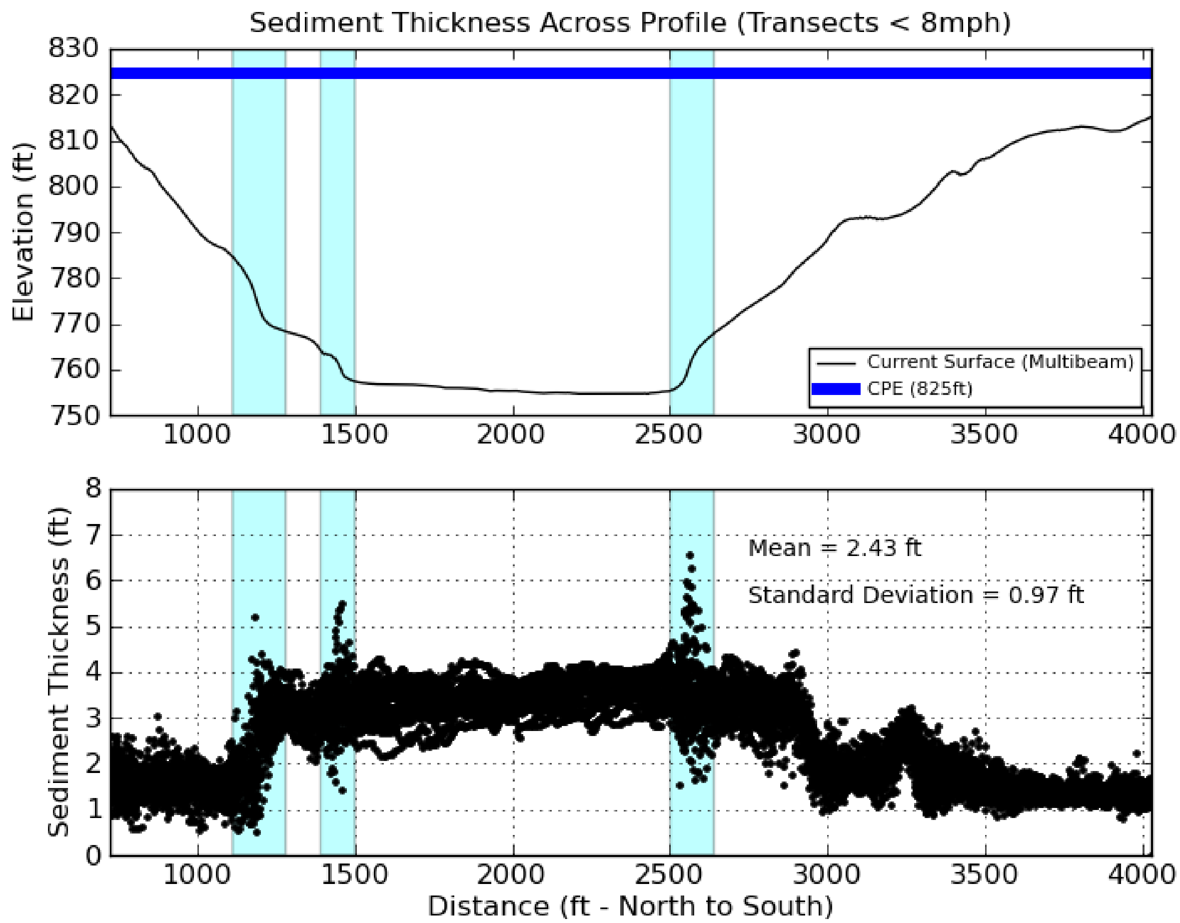


Figure 37: Sediment thickness values from all survey transects conducted at speeds less than 8mph.

The earlier analysis of current surface profiles showed minimal errors in determination of the current surface at speeds below 8 mph. Also, as discussed, variations in boat speed, direction of travel and boat are likely not to be a large source of error in determining sediment thickness. Hence, most variation in measurements from transects at speeds less than 8mph are expected to be indicative of the error associated with picking the pre-impoundment surface. In Figure 37, we show individual soundings from all transects at speeds less than 8mph.

In Figure 37, we see a high variability in sediment thickness due to pre-impoundment surface picks. The sediment thickness varies from approximately 1 to 5 ft across the diagnostic transect profile, with an average thickness of 2.43 ft. Throughout the diagnostic transect profile, the calculated sediment thicknesses are within an approximately 1ft wide band, giving the approximate accuracy of our sediment thickness measurement technique. The Baylor University *Hydrographic Survey Program Assessment* determined that the accuracy of the SDI in determining sediment thickness was of the order of a few inches and was generally less than 10% of actual thickness for sediment thicknesses of less than 8 ft (Dunbar and Estep, 2009). However, the scatter plots shown earlier in section 2.3.1.2 and here in Figure 37 does not seem to show changes in variability at different sediment thicknesses. In particular, Figure 37 seems to indicate a constant accuracy of +/- 0.5 ft as opposed to a percentage of the thickness. With this assumption, for the sediment thickness range of 1-4 ft as seen in the figure, the error in determining the sediment thickness at any particular sounding is of the order of 12.5%-50% with the highest percentage errors in areas where there is lower sediment accumulation.

Another significant finding is that the variability in measurements is very high, on the order of 3 to 6 ft at locations where the profile slope is steeper (cyan areas in Figure 37). At these locations, picking the pre-impoundment surface manually is particularly difficult and misalignments between the current surface pick and pre-impoundment pick can artificially increase the sediment thickness determination. In the original LBJ survey (Survey 1), these areas are probably sources of large local differences in sediment thickness but since they do not constitute a large percentage of the lake area they probably do not affect the overall sediment volume calculation. However, as discussed in section 2.3.3, they may be the cause significant errors depending on the interpolation scheme used to estimate sediment thicknesses between survey lines.

4. Summary and recommendations

4.1. Survey line placement strategies

The three survey line placement strategies outlined in these report (TWDB standard, SSLM and flowline algorithm) do affect volumetric estimations when used in conjunction with the standard ArcGIS Delauney triangulation interpolation for TIN generation. The volumetric estimates vary as much as 8% between survey line placement strategies. Incorporation of self-similar interpolation decreases this variability in volumetric estimations to less than 0.35% between surveys. Therefore, with the incorporation of self-similar interpolation, the three survey line placement strategies produce similar results.

The effect of the three survey line placement strategies on sediment volume estimates was hard to isolate. High variability in determination of sediment thickness at individual sounding locations between surveys made isolation of line placement variability impossible. This high variability was caused by an inability of the current manual methodology to consistently pick the pre-impoundment surface from the depth sounder returns. The following discussion should be read with that caveat in mind, since it is possible that the variations are mainly due to errors in picking the pre-impoundment surface rather that line placement. One additional note is that based on the analysis in this report, the 2007 flood is not likely the source of much of the variability.

The three survey line placement strategies exhibited a variability of less than 5.5% in sediment volume estimates without self-similar interpolation. However, it is likely that this relatively close agreement is due to a cancelation of errors in each survey due to the fact that the error in determining pre-impoundment surface seems to be non-biased and the sediment distribution differs in each survey. Application of the self-similar interpolation technique drastically increased the estimated sediment volumes in the second two strategies (SSLM and flowline algorithm,) and increased the variability between surveys to almost 20%. This may be caused by high errors in sediment thickness at locations of steep bathymetric gradient being interpolated across the channel by the self-similar algorithm. The choice of self-similar interpolation lines and direction may also play a role insofar as the application of self-similar is more difficult for the SSLM and flowline algorithm line placement strategies because of their non-parallel survey lines. In addition the choice of lines and direction was based on an analysis of the lake bathymetric characteristics, it is possible that a different set of lines based on sedimentation areas may have produced better results.

In regards to sediment analysis, the standard TWDB survey of 500 ft spacing currently provides the most reliable and spatially consistent sediment volume estimation. The SSLM and flowline algorithm survey line placement strategies may expand localized errors in sediment thickness picks through self-similar interpolation. The non-parallel survey line placement strategy incorporated in the flowline algorithm method is not directly compatible with self-similar interpolation as currently implemented.

4.2. Equipment and technique: current surface

In terms of current equipment and technique, the overall error in determining the current surface at boat speeds less than 8 mph is less than +/- 1.5% for most transects when measured in terms of the cross sectional area of a single transect. This error may be higher for deep transects. Individual boats have different speeds below which consistent data can be collected. These are listed in the recommendations section. There is a clear bias between SDI and Knudsen depth sounder readings with the Knudsen consistently taking deeper readings. The cause for this is an algorithm used by SDI to partially correct for the pitch and roll of the boat. The direction of the transect has no effect on determination of the cross sectional area of a transect but individual soundings will contain errors and in either direction the area measured can be higher than the true cross section by up to 1.5% for regular profiles. For profiles with long flat sections, like traversal along the thalweg this error may be more significant. Differences exist between the boats used and the magnitude of these differences depend on the sounder used. There seems to be a larger variation between boats when the SDI is used versus the Knudsen. It is possible this may be caused by a difference in weight of the systems (the Knudsen is lighter) combined with the lack of a heave/pitch/roll sensor in current TWDB surveys. However, the variations between boats are much smaller than the variation between the SDI and Knudsen.

Analysis of soundings taken during the three entire lake surveys and the multibeam survey data show high levels of repeatability between surveys with soundings from the various surveys matching with R-squares greater than 0.99.

4.3. Equipment and technique – pre-impoundment surface

While the determination of the current surface is robust and repeatable, large variability exists in determination of sediment thickness estimates. No clear trends were found in the determination of sediment thickness with variations of boat, direction or boat speed. SDI data were used exclusively to determine sediment thicknesses as per current TWDB practice. Sediment thickness is determined by subtracting the current surface from the pre-impoundment surface. Variations across boat, direction, and boat speed, tend to affect these two surfaces equally thus removing these variables as cause for variability in sediment thickness estimation. Since current surface estimations are robust, most inconsistency in estimating sediment thickness comes from the current methodology of determining the pre-impoundment surface.

The current methodology suffers from two major issues. The first is caused by the manual, visual nature of picking the pre-impoundment surface. This process depends on human judgment and is difficult to repeat consistently. The second issue is an inconsistency in the return signals from the SDI depth sounder at the same location during different surveys. It is currently thought that this inconsistency is caused by differences in power and gain settings for the SDI transducer, but this hypothesis remains unverified.

With these two issues in mind, based on the analysis present in this report, the average error in determining the sediment thickness at any particular sounding location is of the order +/-0.5 ft for relatively flat sections of the diagnostic survey. The error increases dramatically in areas of steep slope or slope change. The sediment thicknesses measured from the diagnostic transect vary from 1 to 4 ft, and hence errors ranging from 12.5%-50%. Errors of the order of 3-7 ft were found to occur during steep sections of the profile.

In addition, a sediment thickness estimation of Survey 1 data done separately by TWDB and BU staff shows an R-square of less than 0.42 and shows places where the difference is of the order of 2-6 ft. In this case the variability is entirely caused by the difficulty in determining the pre-impoundment surface using the current methodology.

Sediment thickness error is apparently non-biased (random), therefore the overall computed sediment volume for the lake is potentially reasonably accurate, although individual soundings may have significant error.

4.4. Recommendations and future work

Based on the findings of this report we make the following recommendations:

4.4.1. ***Survey line placement strategies***

All survey line placement strategies explored within this study provide accurate volumetric estimations when self-similar interpolation is also incorporated. The SSLM and flowline algorithm strategies may be used in conjunction with self-similar interpolation instead of the standard TWDB line placement methodology if they are estimated to save significant man hours for an overall lake study. They should not be used in surveys that combine a volumetric estimate and a sediment volume estimate.

For sediment volume surveys, the standard TWDB survey line placement strategy provides the most uniform coverage and is most compatible with the self-similar interpolation technique. The SSLM and flowline algorithm survey line placement strategies are not recommended for sediment volume surveys because the interpolation technique can potentially expand localized large errors in sediment thickness across large areas. The variability in determining sediment thickness using current processing techniques generates a higher risk in these alternate line placement strategies than in the standard TWDB methodology because the larger spacing between survey lines and the greater possibility of alignment survey lines along regions of bathymetric slope change.

4.4.2. *Boats*

All current TWDB boats are capable of delivering consistent, reliable volumetric and sediment measurements if boat operators remain below recommended speeds. Problems in determining sediment thickness are related to post processing issues described before and not due to boat characteristics or survey speed. Table 8, lists the recommended maximum speeds for each boat (subject to lake conditions). In the case of the Hydro, ADCP and Core boats speeds higher than the current TWDB standard of 6mph can be used. One exception is the ADCP boat combined with the Knudsen depth sounder. For this combination, speeds under 4 mph should be used. Above this speed, the Knudsen generated lots of spurious measurements. The Tunnel boat should be run at speeds lower than the current TWDB standard. The reliability of measurements decayed rapidly at just above 6 mph and the size of the boat and its handling characteristics indicate a choice of a lower recommended speed.

Table 9: Maximum recommended boat speeds by depth sounder

Boat	Recommended Maximum Survey Speed (mph)	
	Knudsen depth sounder	SDI depth sounder
ADCP	4	9
Core	9	9
Hydro	7	7
Tunnel	5	5

4.4.3. *Depth sounder*

Overall, both depth sounder systems give reliable data under most circumstances. The one exception, already noted above, is the use of the Knudsen in combination with the ADCP boat. There is a clear and significant bias between SDI and Knudsen measurements, the cause of which is currently thought to be due to an algorithm SDI uses to mitigate the effect of transducer angle. The SDI profiles are closer to the reference multibeam data but typically shallower, while the Knudsen profiles are deeper than the reference but are closer to each other. Since the multibeam data was collected using a pitch/heave/roll sensor theoretically the single beam data collected without such a sensor should on average take deeper readings than the multibeam reference.

Further experimentation and/or the use of a pitch/heave/roll sensor is recommended to determine/eliminate the bias between the sounders. The incorporation of a roll/pitch/roll sensor would also likely increase precision between boats, for volumetric surveying; however, it would likely provide minimal to no increase in precision for sediment surveying, between boats.

In general, SDI depth sounder is recommended over the Knudsen depth sounder for the purposes of volumetric and sedimentation analysis. The SDI depth sounder provides reliable depth readings with increases in boat speed; is less prone to losing current bottom surface tracking during data collection; and provides access to the raw data as a grayscale background image, thus easing removal of spurious data and also the ability to manually digitize the current bottom surface when bottom tracking is completely lost. The presence of this background imaging is the key advantage the SDI depth sounder has over the Knudsen even for pure volumetric surveys. The SDI also has the advantage of partially correcting for pitch/roll through the use of a software algorithm without the need for a heave/pitch/roll sensor.

4.4.4. ***Direction of travel***

The direction of travel had no effect on the determination of the cross sectional area of a profile. However, it does affect soundings at individual locations and also does shift the profile in the direction of travel. In addition, profiles with long flat sections will be overestimated. Although, in most cases, these effects are small, they could be corrected through the use of a heave/pitch/roll sensor. In the absence of the use of one such a sensor it is recommended that repeat surveys of a lake try to follow the same direction as the previous survey if comparing individual profile cross sections is considered important.

4.4.5. ***Heave/Pitch/Roll Sensor***

Several of the errors described above can be mitigated or reduced by using a heave/pitch/roll sensor in conjunction with the depth sounder. However, as noted earlier the accuracy in terms of cross sectional area of the profile without the sensor is +/- 1.5% for profiles less than 50ft deep. This is potentially higher than the existing estimates of overall survey accuracy due to other factors as mentioned at the beginning of this report. Hence, the final determination of whether to use a heave/pitch/roll sensor as a part of the standard TWDB methodology should also consider equipment cost and the additional complexity involved in the setup and use of the sensor

4.4.6. *Determination of pre-impoundment surface*

The determination of the pre-impoundment surface is currently the most problematic area of the TWDB survey methodology. While the current methodology utilizes the latest technology and techniques, the lack of repeatability and high variability in measurements make this a priority area for future improvements.

Exploration of techniques to automate or semi-automate the determination of the pre-impoundment surface should be made a high priority. This should reduce the human judgment induced variability in the determination of the pre-impoundment surface and provide for more repeatable measurements. In addition, automation has the potential to significantly reduce the man hours required for this process. This automation could potentially be accomplished through the application of edge detection algorithms currently in use in computer vision and/or seismic petroleum industries.

Regardless of how the surface is picked, manually or automatically, techniques to reduce the high errors seen near steep bathymetries should be explored. The current technique is complicated by misalignment of pixels between the current surface and pre-impoundment surface and by the difficulty is selecting these surfaces in steep locations. One possible technique to partially mitigate the first part of this problem is to interpolate the current and pre-impoundment picks to a higher resolution and then subtract the two high resolution lines rather than the low resolution pixel by pixel subtraction that is currently done.

In addition, the effect of power/gain and other settings on the return signals and hence the determination of the pre-impoundment surface needs to be explored in more detail and recommendations made on best practices. Potentially, a small scale diagnostic survey could be designed to enable the determination of these best practices.

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APPENDIX A – SDI Settings Used

Table A1 below shows the various frequencies used while surveying Lake LBJ. For transects surveyed prior to the flood event, the depth sounder settings are unknown since earlier versions of the software used did not save this information.

Table A1: SDI settings used during Surveys 1, 2, 3 and the diagnostic survey

Survey	Frequency	Cycles	Volts	Power	Gain	Hypack Version
	24	--	--	--	--	
1	50	--	--	--	--	3.3
	200	--	--	--	--	
	24	3	+/- 5	2	1	
1	50	3	+/- 5	2	2	4.3
	200	--	+/- 2.5	2	--	
	24	3	+/- 5	1	4	
1	50	4	+/- 5	1	32	4.3
	200	3	+/- 2.5	2	--	
	24	4	+/- 10	1	2	
2	50	5	+/- 5	1	4	4.3
	200	3	+/- 2.5	2	--	
	24	4	+/- 5	2	2	
2	50	6	+/- 5	2	4	4.3
	200	3	+/- 1.25	4	--	
	24	3	+/- 5	2	1	
2	50	3	+/- 5	2	1	4.3
	200	3	+/- 2.5	2	--	
	24	3	+/- 5	2	2	
3	50	3	+/- 5	2	4	4.3
	200	3	+/- 1.25	4	--	
	24	3	+/- 10	1	2	
3	50	3	+/- 10	1	4	4.3
	200	3	+/- 2.5	2	--	
	24	3	+/- 5	1	2	
3	50	3	+/- 5	2	4	4.3
	200	3	+/- 1.25	3	--	

APPENDIX B – Individual Diagnostic Survey Transects

Table B1: Summary of SDI diagnostic survey sediment measurements

Boat	Speed (mph)	Boat direction	Current surface cross-sectional area (ft^2)	Pre-impoundment surface cross-sectional area (ft^2)	Sediment cross-sectional area (ft^2)
ADCP	2.97	N-S	147,717.3	155,216.2	7,498.9
ADCP	3.02	S-N	147,599.6	155,478.0	7,878.4
ADCP	4.21	N-S	147,730.0	155,409.0	7,679.0
ADCP	4.44	S-N	147,635.3	155,510.2	7,874.9
ADCP	5.96	N-S	147,516.4	155,439.8	7,923.4
ADCP	6.14	S-N	147,429.6	154,525.0	7,095.4
ADCP	7.77	N-S	147,748.0	155,752.6	8,004.6
ADCP	7.51	S-N	147,149.0	155,198.5	8,049.5
ADCP	10.95	N-S	149,377.7	158,901.2	9,523.5
ADCP	9.91	S-N	149,346.8	158,206.6	8,859.8
ADCP	15.32	N-S	150,834.6	160,306.3	9,471.7
ADCP	15.76	S-N	150,213.0	160,137.7	9,924.6
CORE	3.26	S-N	147,951.6	157,186.2	9,234.6
CORE	3.95	N-S	148,100.3	156,950.1	8,849.9
CORE	4.36	S-N	148,312.0	156,963.8	8,651.8
CORE	4.39	N-S	148,297.4	156,998.3	8,700.9
CORE	6.37	S-N	147,960.9	156,300.8	8,339.9
CORE	5.66	N-S	148,101.2	156,874.5	8,773.3
CORE	8.18	S-N	148,374.0	156,796.8	8,422.8
CORE	7.87	N-S	148,241.0	156,777.5	8,536.5
CORE	9.97	S-N	149,635.8	158,245.0	8,609.2
CORE	11.17	N-S	151,667.2	159,908.4	8,241.2
HYDRO	3.53	S-N	147,506.5	156,533.1	9,026.6
HYDRO	3.37	N-S	147,367.5	156,334.7	8,967.2
HYDRO	4.62	S-N	147,582.1	156,467.1	8,885.0
HYDRO	4.61	N-S	147,878.5	156,949.9	9,071.5
HYDRO	6.07	S-N	147,982.3	156,781.9	8,799.6
HYDRO	6.16	N-S	148,191.9	156,859.8	8,667.9
HYDRO	8.83	S-N	150,356.1	158,999.6	8,643.5
TUNNEL	2.89	S-N	149,476.3	158,174.0	8,697.7
TUNNEL	2.49	N-S	149,305.2	158,592.1	9,286.9
TUNNEL	3.95	S-N	149,573.7	157,951.1	8,377.3
TUNNEL	4.14	N-S	149,368.5	157,970.9	8,602.4

Table B2: Comparison of single beam diagnostic profiles to multibeam baseline profile

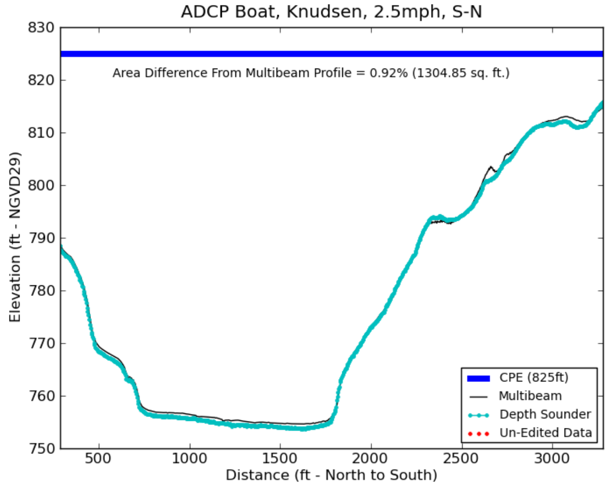
Boat	Sounder	Speed (mph)	Boat direction	Current surface cross-sectional area (ft^2)	Percent difference	Change in average depth (ft)
N/A	Multibeam	0.00	N/A	141858.22	N/A	N/A
ADCP	Knudsen	4.49	N-S	142448.52	0.416	0.197
ADCP	Knudsen	6.53	S-N	139407.55	-1.728	-0.819
ADCP	Knudsen	11.31	S-N	140547.25	-0.924	-0.438
ADCP	Knudsen	8.74	N-S	142895.07	0.731	0.346
ADCP	Knudsen	4.35	S-N	144867.51	2.121	1.005
ADCP	Knudsen	11.20	N-S	144949.54	2.179	1.033
ADCP	Knudsen	3.42	N-S	143379.29	1.072	0.508
ADCP	Knudsen	2.52	S-N	143163.06	0.920	0.436
ADCP	Knudsen	6.65	N-S	141768.67	-0.063	-0.030
ADCP	Knudsen	8.57	S-N	139447.77	-1.699	-0.805
ADCP	Knudsen	10.52	N-S	152092.84	7.215	3.420
ADCP	SDI	2.97	N-S	140712.13	-0.808	-0.383
ADCP	SDI	3.02	S-N	140512.08	-0.949	-0.450
ADCP	SDI	4.21	N-S	140671.28	-0.837	-0.397
ADCP	SDI	4.44	S-N	140506.23	-0.953	-0.452
ADCP	SDI	5.96	N-S	140500.03	-0.957	-0.454
ADCP	SDI	6.14	S-N	140398.76	-1.029	-0.488
ADCP	SDI	7.77	N-S	140743.67	-0.786	-0.372
ADCP	SDI	7.51	S-N	140382.16	-1.041	-0.493
ADCP	SDI	10.95	N-S	142146.14	0.203	0.096
ADCP	SDI	9.91	S-N	142314.38	0.322	0.152
ADCP	SDI	15.32	N-S	143412.25	1.095	0.519
ADCP	SDI	15.76	S-N	143448.85	1.121	0.531
CORE	Knudsen	3.12	N-S	143073.04	0.856	0.406
CORE	Knudsen	15.81	S-N	128792.93	-9.210	-4.365
CORE	Knudsen	5.97	N-S	143460.08	1.129	0.535
CORE	Knudsen	3.10	S-N	143681.83	1.286	0.609
CORE	Knudsen	4.44	S-N	143505.65	1.161	0.550
CORE	Knudsen	4.78	N-S	143527.86	1.177	0.558
CORE	Knudsen	6.01	S-N	143147.12	0.909	0.431
CORE	Knudsen	8.43	S-N	143484.45	1.146	0.543
CORE	Knudsen	8.04	N-S	143959.10	1.481	0.702
CORE	Knudsen	10.24	S-N	145126.76	2.304	1.092
CORE	Knudsen	9.54	N-S	145237.16	2.382	1.129
CORE	Knudsen	15.04	N-S	146839.35	3.511	1.664
CORE	SDI	3.26	S-N	141212.88	-0.455	-0.216
CORE	SDI	3.95	N-S	141075.26	-0.552	-0.262
CORE	SDI	4.36	S-N	141556.65	-0.213	-0.101
CORE	SDI	4.39	N-S	141250.95	-0.428	-0.203
CORE	SDI	6.37	S-N	141162.11	-0.491	-0.233

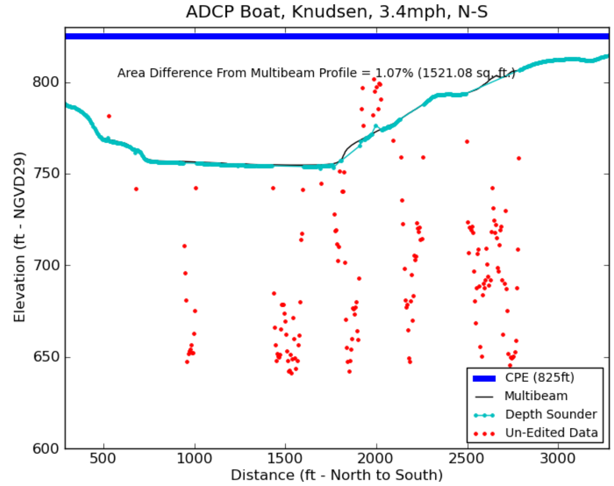
CORE	SDI	5.66	N-S	141256.07	-0.424	-0.201

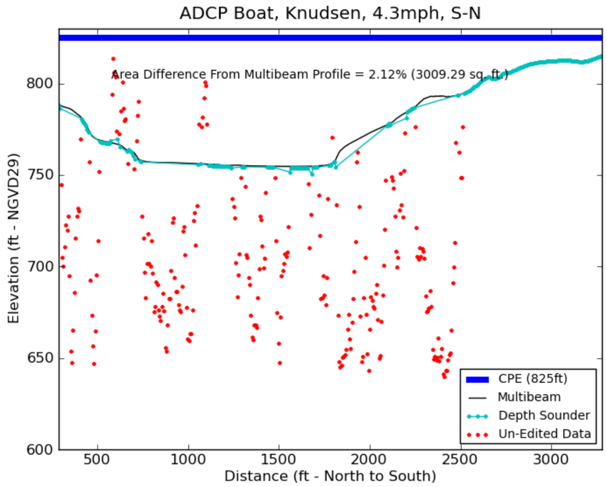
Table B2 (cont): Comparison of single beam diagnostic profiles to multibeam baseline profile

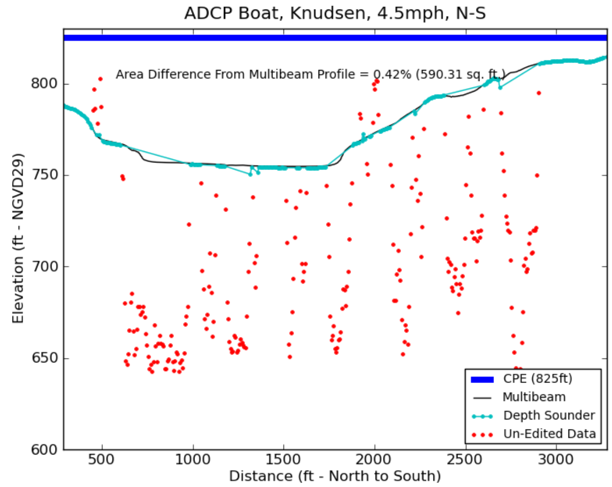
CORE	SDI	8.18	S-N	141787.76	-0.050	-0.024
CORE	SDI	7.87	N-S	141234.23	-0.440	-0.208
CORE	SDI	9.97	S-N	142842.55	0.694	0.329
CORE	SDI	11.17	N-S	140736.91	-0.790	-0.375
HYDRO	Knudsen	3.58	S-N	143712.47	1.307	0.620
HYDRO	Knudsen	3.87	N-S	143104.27	0.878	0.416
HYDRO	Knudsen	4.72	S-N	143778.85	1.354	0.642
HYDRO	Knudsen	4.48	N-S	142956.56	0.774	0.367
HYDRO	Knudsen	6.25	S-N	143501.12	1.158	0.549
HYDRO	Knudsen	6.42	N-S	143358.44	1.058	0.501
HYDRO	Knudsen	8.57	S-N	144968.65	2.193	1.039
HYDRO	Knudsen	8.14	N-S	144700.75	2.004	0.950
HYDRO	Knudsen	9.05	S-N	101534.15	-28.426	-13.473
HYDRO	Knudsen	9.69	N-S	147333.94	3.860	1.830
HYDRO	Knudsen	10.31	S-N	147161.04	3.738	1.772
HYDRO	SDI	3.53	S-N	141577.15	-0.198	-0.094
HYDRO	SDI	3.37	N-S	141029.84	-0.584	-0.277
HYDRO	SDI	4.62	S-N	141550.36	-0.217	-0.103
HYDRO	SDI	4.61	N-S	141261.83	-0.420	-0.199
HYDRO	SDI	6.07	S-N	141961.94	0.073	0.035
HYDRO	SDI	6.16	N-S	141473.52	-0.271	-0.129
HYDRO	SDI	8.83	S-N	143358.18	1.057	0.501
TUNNEL	Knudsen	2.85	N-S	143886.22	1.430	0.678
TUNNEL	Knudsen	2.77	S-N	143752.97	1.336	0.633
TUNNEL	Knudsen	4.11	N-S	143857.00	1.409	0.668
TUNNEL	Knudsen	4.16	S-N	144067.44	1.557	0.738
TUNNEL	Knudsen	6.17	N-S	144444.57	1.823	0.864
TUNNEL	Knudsen	6.19	S-N	144705.66	2.007	0.951
TUNNEL	Knudsen	8.18	N-S	146387.48	3.193	1.513
TUNNEL	Knudsen	8.31	S-N	146492.75	3.267	1.548
TUNNEL	SDI	2.89	S-N	142246.98	0.274	0.130
TUNNEL	SDI	2.49	N-S	142208.41	0.247	0.117
TUNNEL	SDI	3.95	S-N	142396.50	0.379	0.180
TUNNEL	SDI	4.14	N-S	142295.45	0.308	0.146

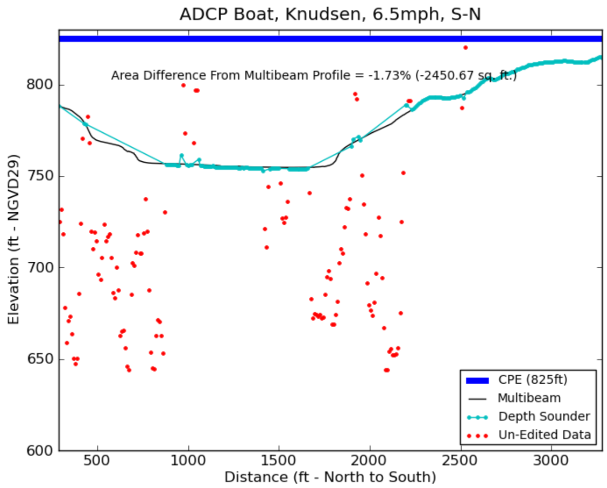
Knudsen depth sounder – ADCP boat

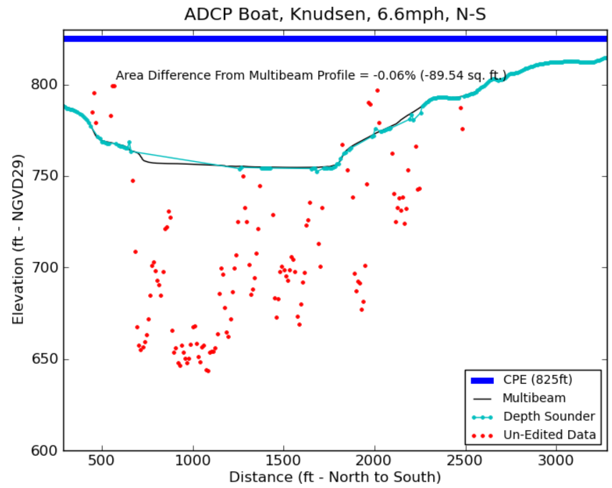


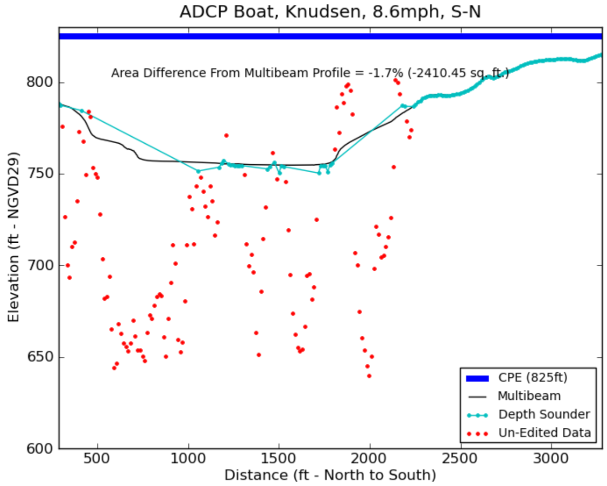


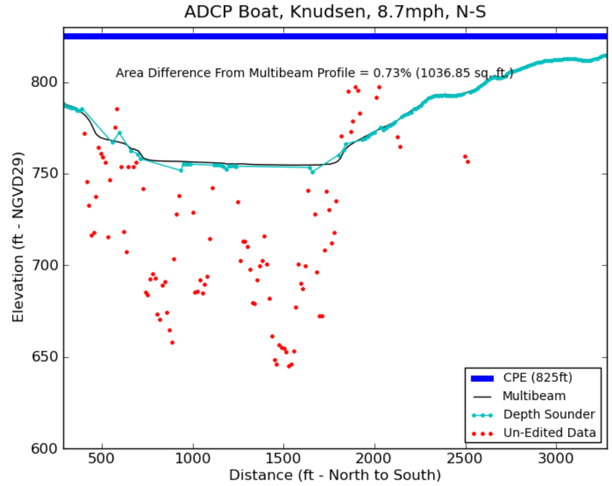


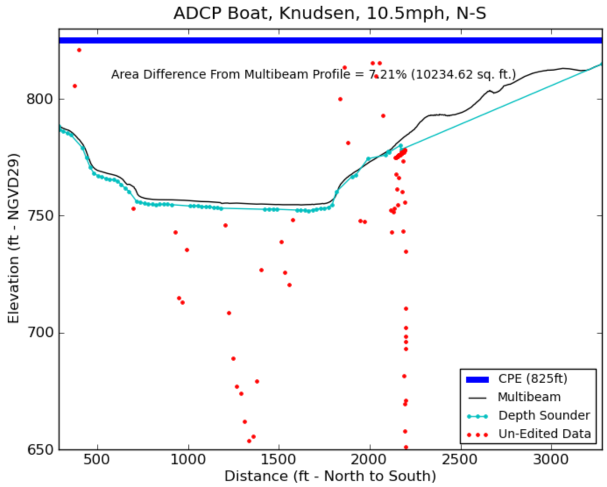


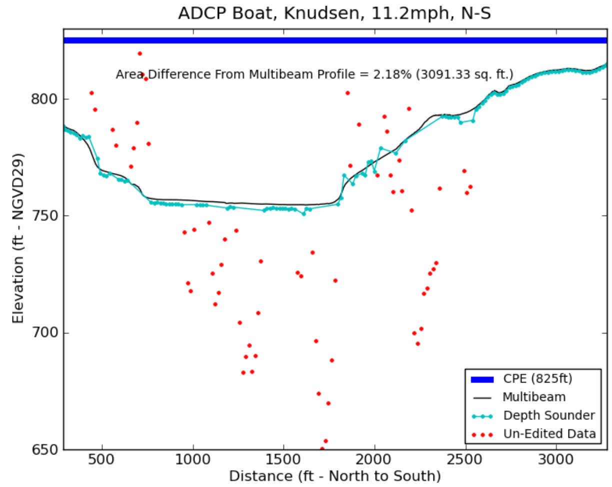


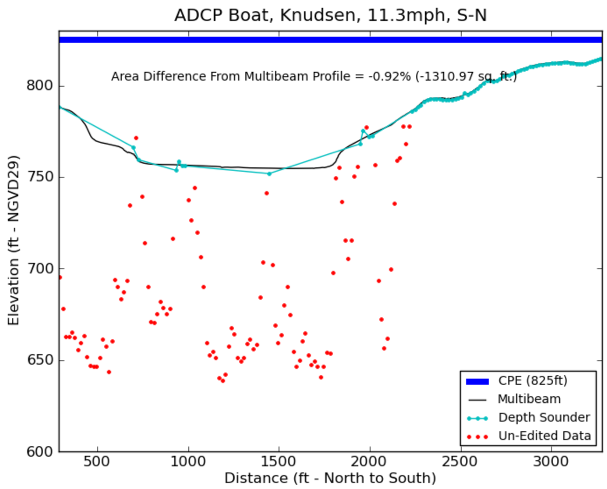



ADCP Boat, Knudsen, 8.6mph, S-N
Area Difference From Multibeam Profile = -1.7% (-2410.45 sq. ft.)
Elevation (ft - NGVD29)
Distance (ft - North to South)
CPE (825ft)
Multibeam
Depth Sounder
Un-Edited Data

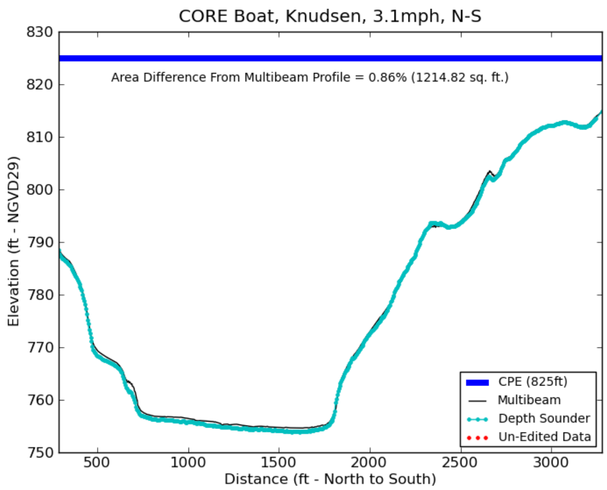

ADCP Boat, Knudsen, 8.7mph, N-S
Area Difference From Multibeam Profile = 0.73% (1036.85 sq. ft.)
Elevation (ft - NGVD29)
Distance (ft - North to South)
CPE (825ft)
Multibeam
Depth Sounder
Un-Edited Data

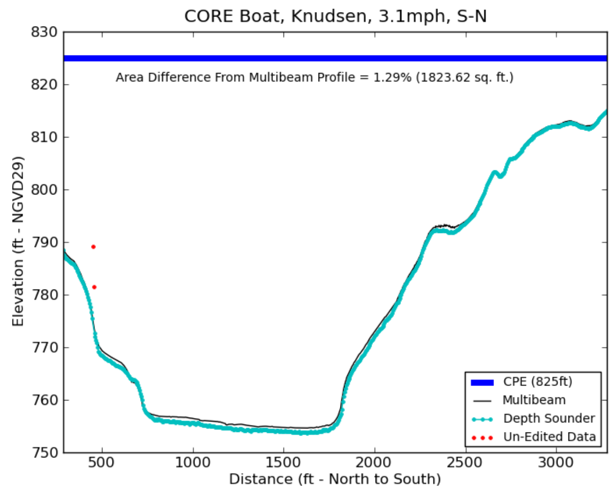

ADCP Boat, Knudsen, 10.5mph, N-S
Area Difference From Multibeam Profile = 7.21% (10234.62 sq. ft.)
Elevation (ft - NGVD29)
Distance (ft - North to South)
CPE (825ft)
Multibeam
Depth Sounder
Un-Edited Data

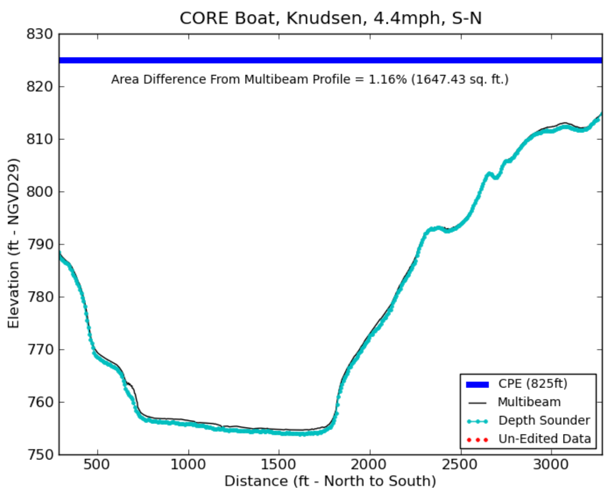

ADCP Boat, Knudsen, 11.2mph, N-S
Area Difference From Multibeam Profile = 2.18% (3091.33 sq. ft.)
Elevation (ft - NGVD29)
Distance (ft - North to South)
CPE (825ft)
Multibeam
Depth Sounder
Un-Edited Data

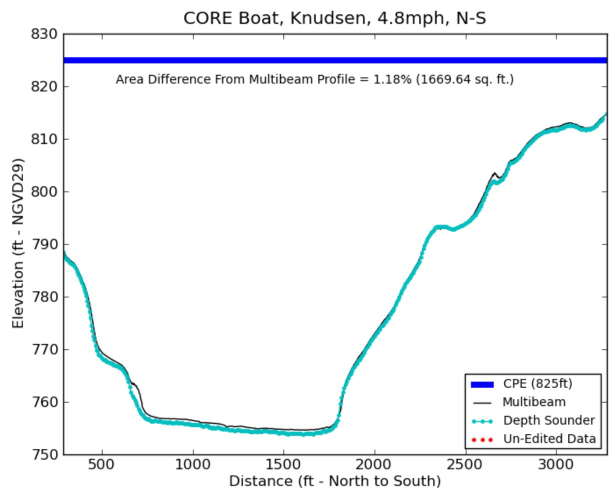

ADCP Boat, Knudsen, 11.3mph, S-N
Area Difference From Multibeam Profile = -0.92% (-1310.97 sq. ft.)
Elevation (ft - NGVD29)
Distance (ft - North to South)
CPE (825ft)
Multibeam
Depth Sounder
Un-Edited Data

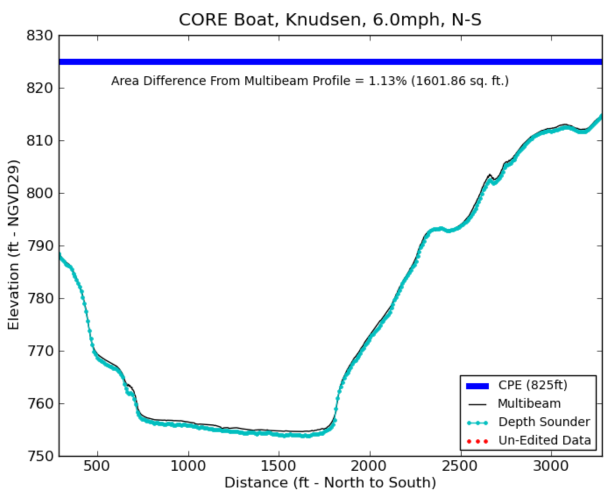
Knudsen depth sounder – CORE boat

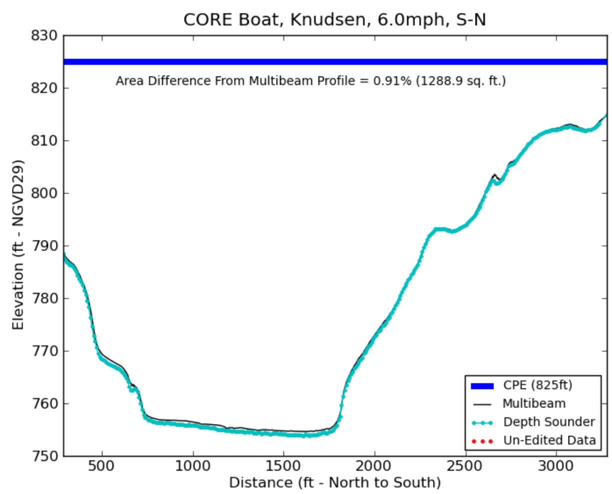


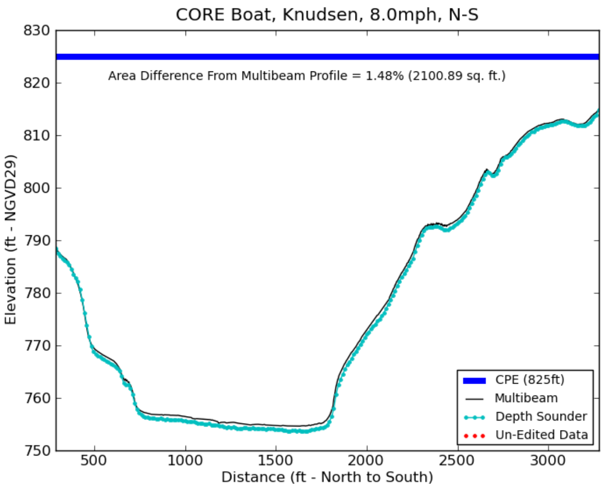


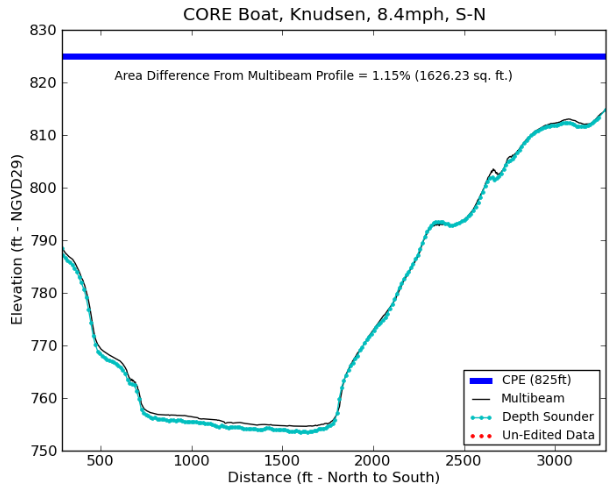


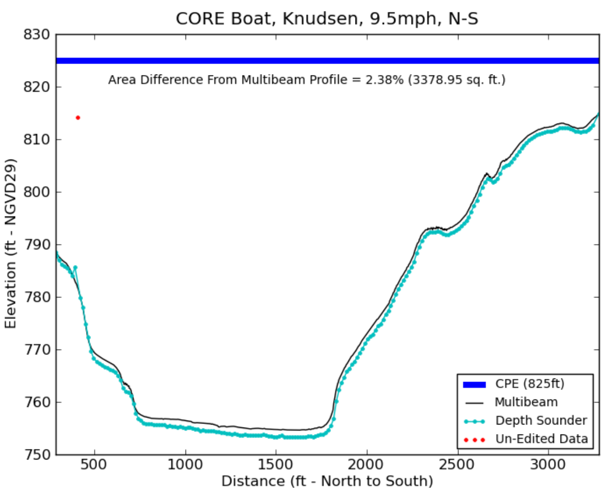


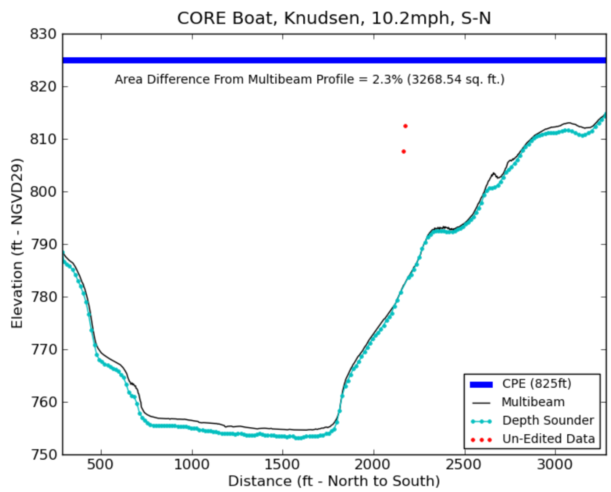


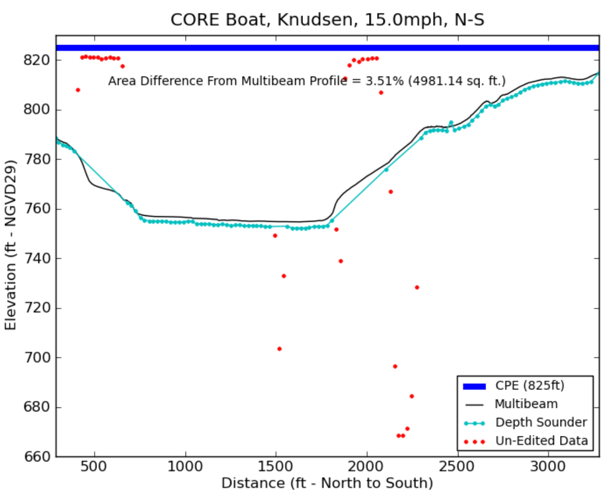


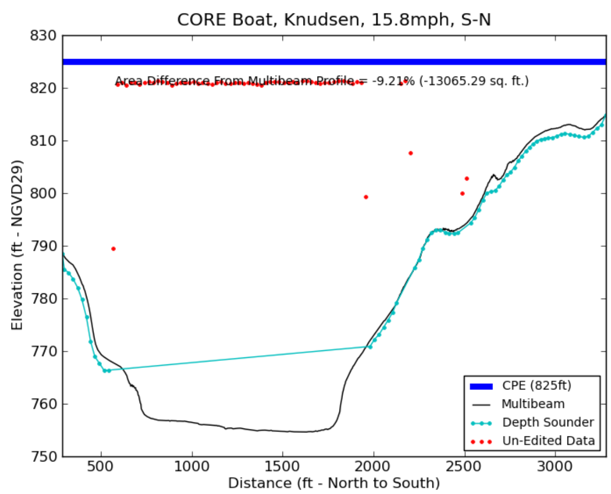

CORE Boat, Knudsen, 8.0mph, N-S
Area Difference From Multibeam Profile = 1.48% (2100.89 sq. ft.)
CPE (825ft)
Multibeam
Depth Sounder
Un-Edited Data
Elevation (ft - NGVD29)
Distance (ft - North to South)


CORE Boat, Knudsen, 8.4mph, S-N
Area Difference From Multibeam Profile = 1.15% (1626.23 sq. ft.)
CPE (825ft)
Multibeam
Depth Sounder
Un-Edited Data
Elevation (ft - NGVD29)
Distance (ft - North to South)

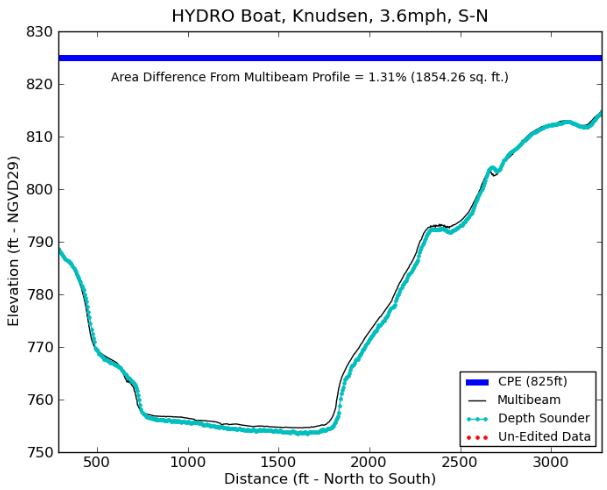

CORE Boat, Knudsen, 9.5mph, N-S
Area Difference From Multibeam Profile = 2.38% (3378.95 sq. ft.)
CPE (825ft)
Multibeam
Depth Sounder
Un-Edited Data
Elevation (ft - NGVD29)
Distance (ft - North to South)

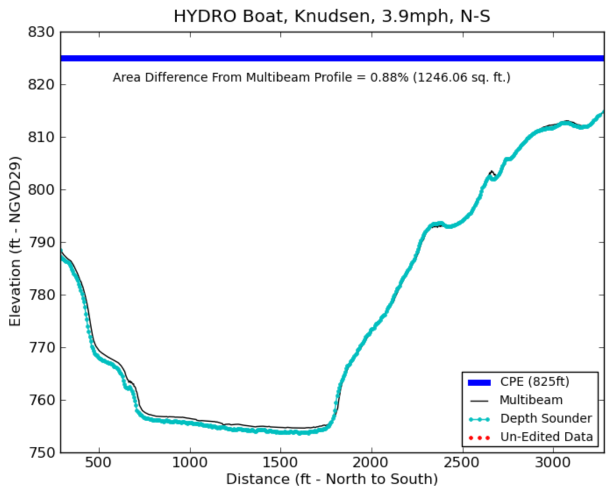

CORE Boat, Knudsen, 10.2mph, S-N
Area Difference From Multibeam Profile = 2.3% (3268.54 sq. ft.)
CPE (825ft)
Multibeam
Depth Sounder
Un-Edited Data
Elevation (ft - NGVD29)
Distance (ft - North to South)

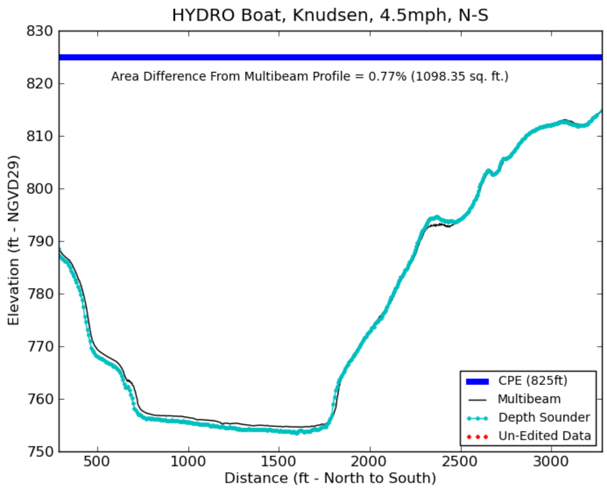

CORE Boat, Knudsen, 15.0mph, N-S
Area Difference From Multibeam Profile = 3.51% (4981.14 sq. ft.)
CPE (825ft)
Multibeam
Depth Sounder
Un-Edited Data
Elevation (ft - NGVD29)
Distance (ft - North to South)

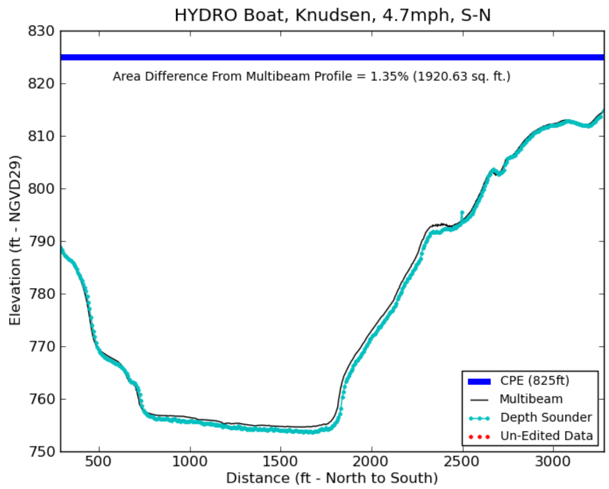

CORE Boat, Knudsen, 15.8mph, S-N
Area Difference From Multibeam Profile = -9.21% (-13065.29 sq. ft.)
CPE (825ft)
Multibeam
Depth Sounder
Un-Edited Data
Elevation (ft - NGVD29)
Distance (ft - North to South)

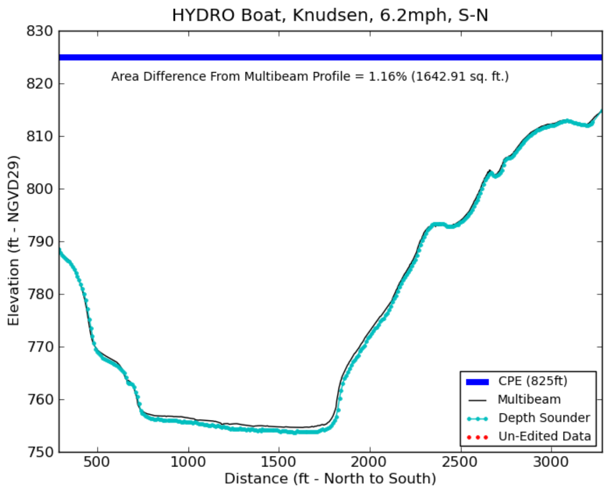
Knudsen depth sounder – HYDRO boat

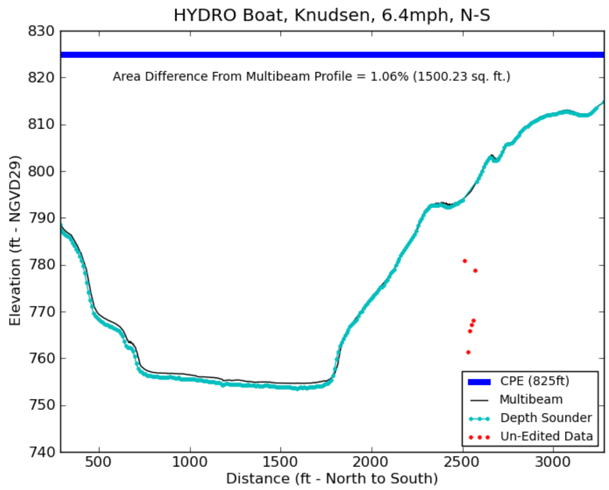


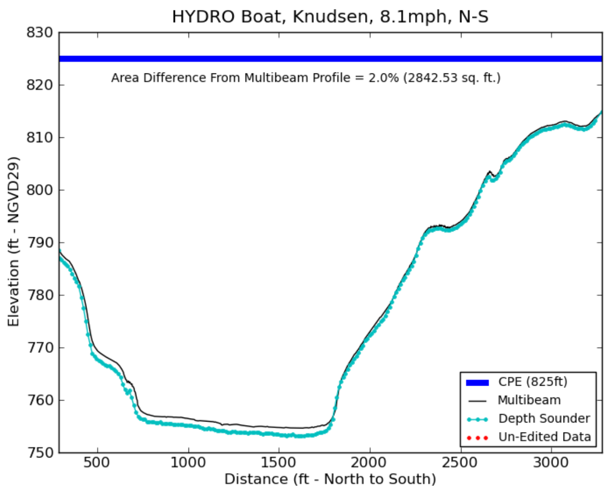


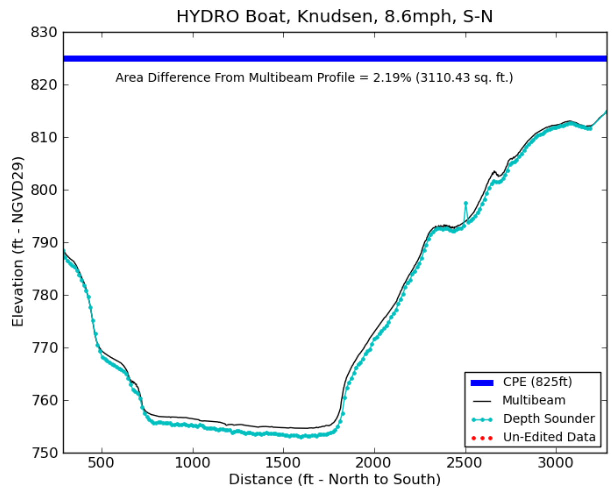


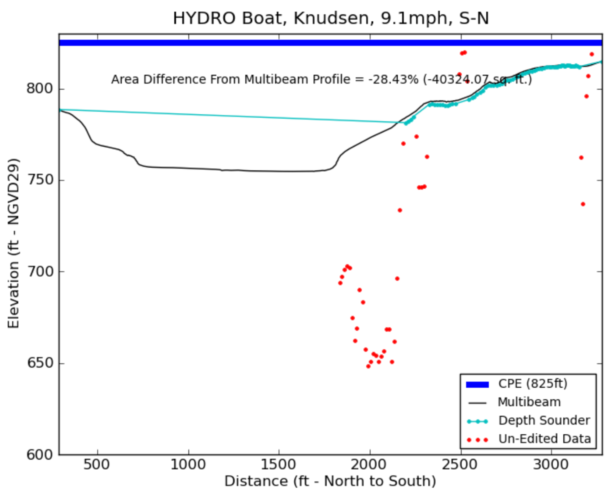


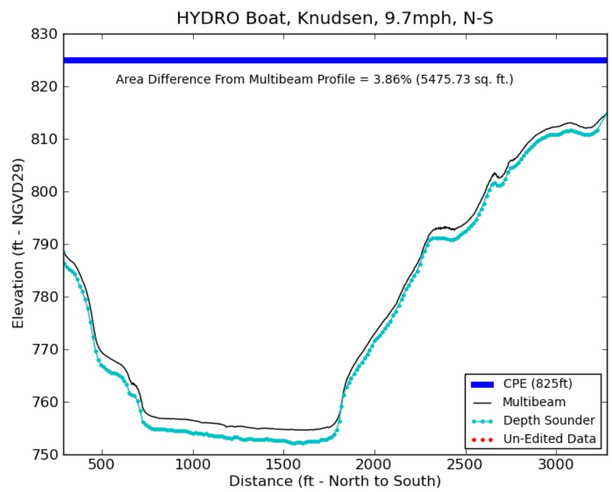


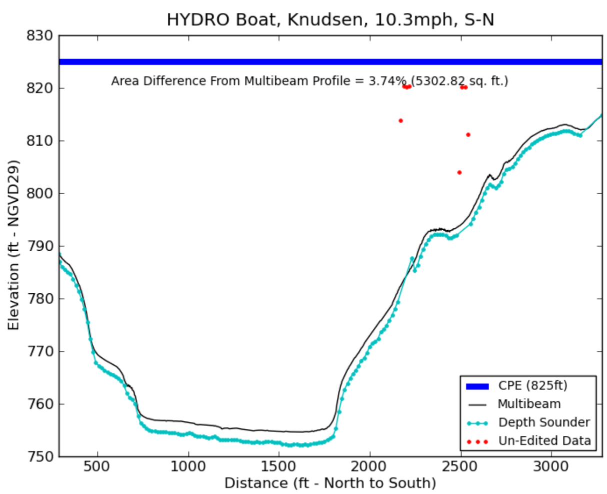



HYDRO Boat, Knudsen, 8.1mph, N-S
Area Difference From Multibeam Profile = 2.0% (2842.53 sq. ft.)
Elevation (ft - NGVD29)
Distance (ft - North to South)
CPE (825ft)
Multibeam
Depth Sounder
Un-Edited Data

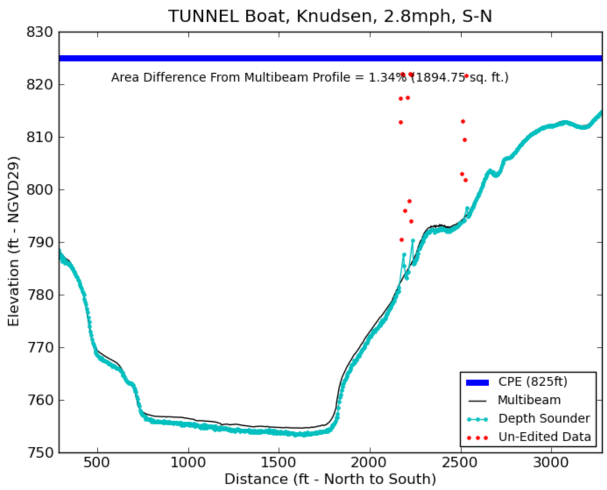

HYDRO Boat, Knudsen, 8.6mph, S-N
Area Difference From Multibeam Profile = 2.19% (3110.43 sq. ft.)
Elevation (ft - NGVD29)
Distance (ft - North to South)
CPE (825ft)
Multibeam
Depth Sounder
Un-Edited Data

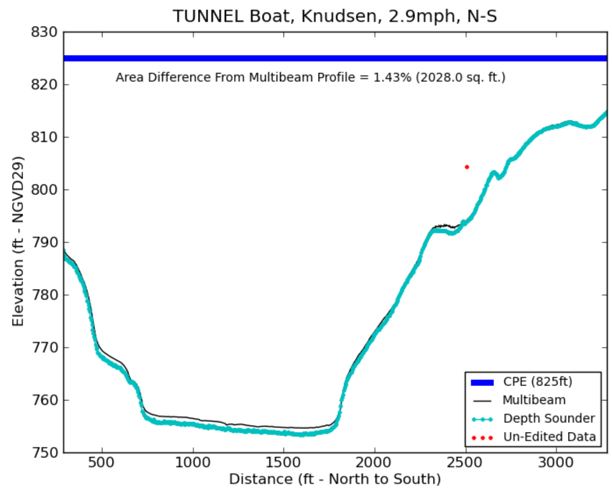

HYDRO Boat, Knudsen, 9.1mph, S-N
Area Difference From Multibeam Profile = -28.43% (-40324.07 sq. ft.)
Elevation (ft - NGVD29)
Distance (ft - North to South)
CPE (825ft)
Multibeam
Depth Sounder
Un-Edited Data

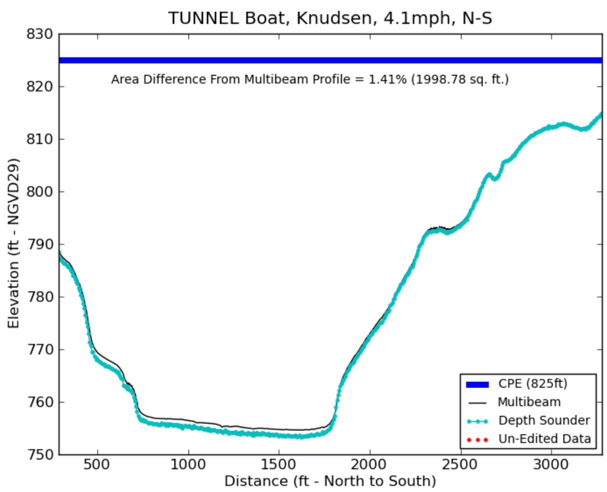

HYDRO Boat, Knudsen, 9.7mph, N-S
Area Difference From Multibeam Profile = 3.86% (5475.73 sq. ft.)
Elevation (ft - NGVD29)
Distance (ft - North to South)
CPE (825ft)
Multibeam
Depth Sounder
Un-Edited Data

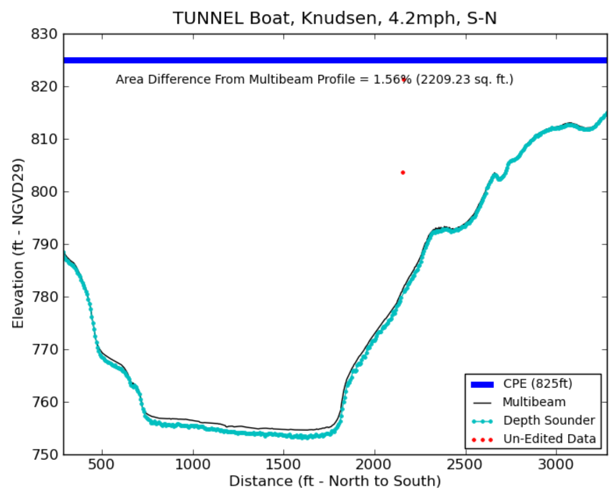

HYDRO Boat, Knudsen, 10.3mph, S-N
Area Difference From Multibeam Profile = 3.74% (5302.82 sq. ft.)
Elevation (ft - NGVD29)
Distance (ft - North to South)
CPE (825ft)
Multibeam
Depth Sounder
Un-Edited Data

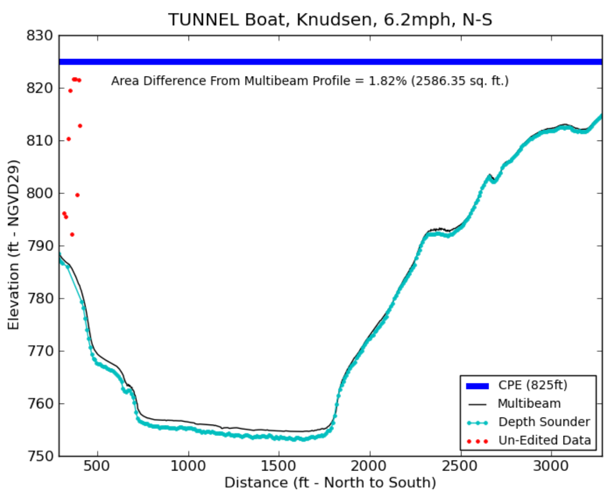
Knudsen depth sounder – TUNNEL boat

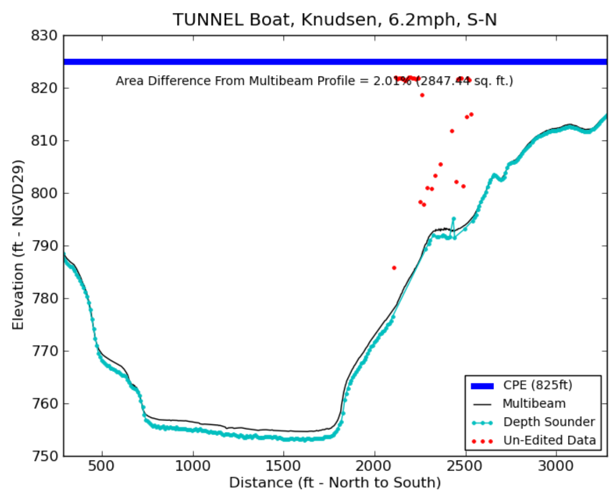


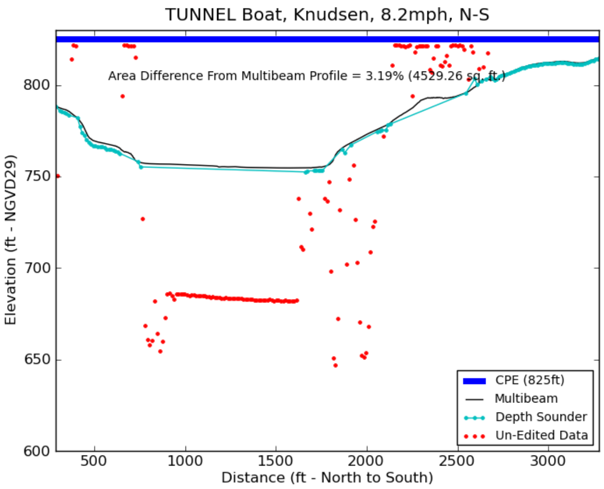




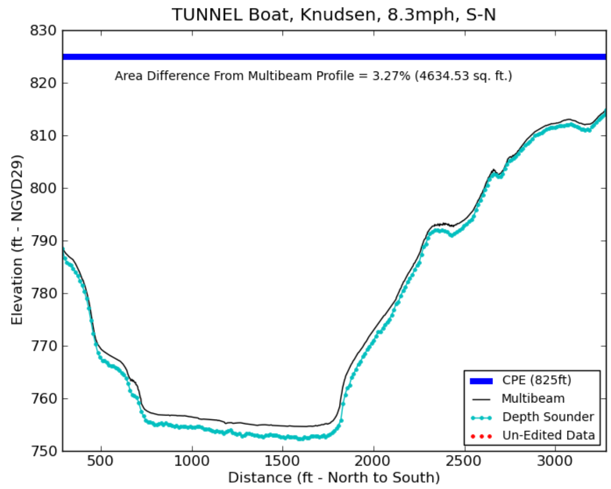








TUNNEL Boat, Knudsen, 8.2mph, N-S
Area Difference From Multibeam Profile = 3.19% (4529.26 sq. ft.)
Elevation (ft - NGVD29)
Distance (ft - North to South)
CPE (825ft)
Multibeam
Depth Sounder
Un-Edited Data

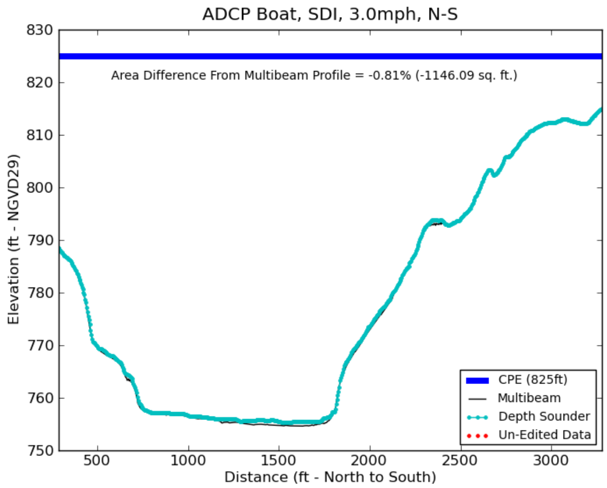


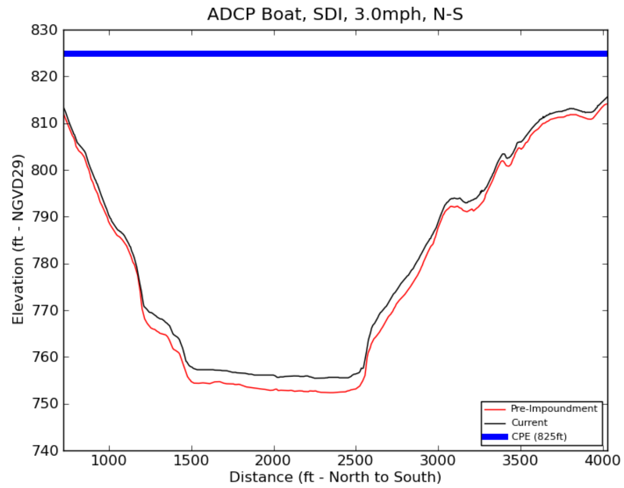
TUNNEL Boat, Knudsen, 8.3mph, S-N
Area Difference From Multibeam Profile = 3.27% (4634.53 sq. ft.)
Elevation (ft - NGVD29)
Distance (ft - North to South)
CPE (825ft)
Multibeam
Depth Sounder
Un-Edited Data

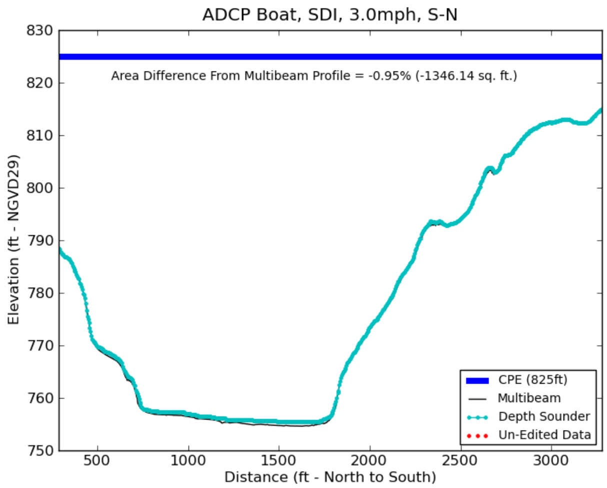
SDI depth sounder – ADCP boat

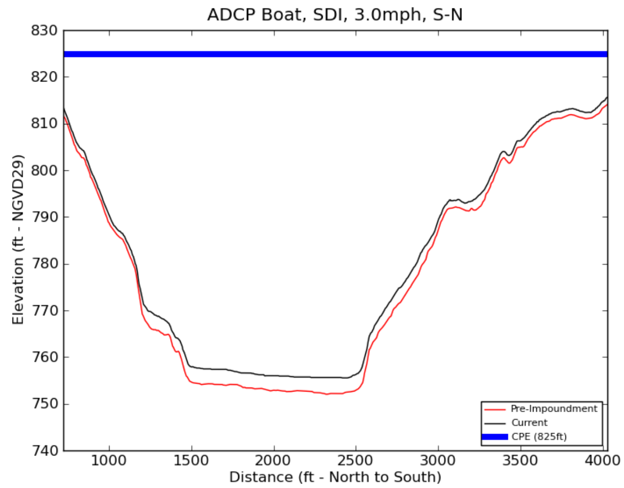
Current Surface

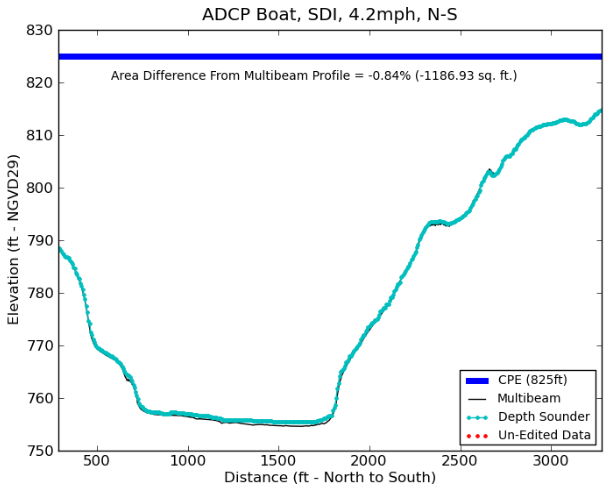
Pre-Impoundment Surface

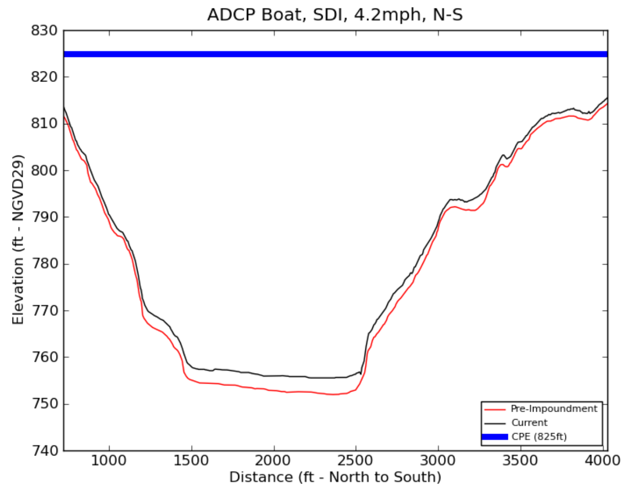






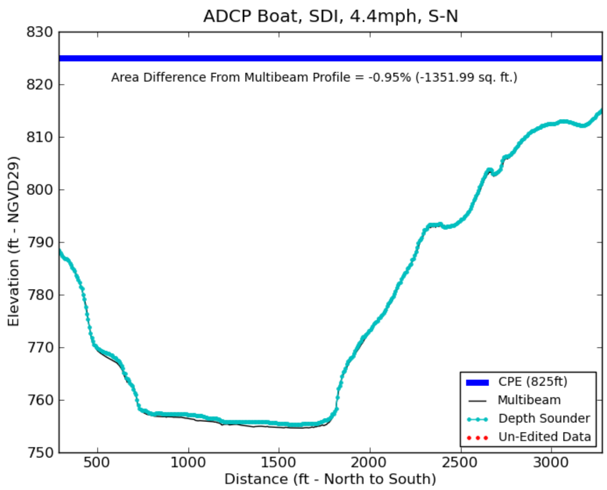


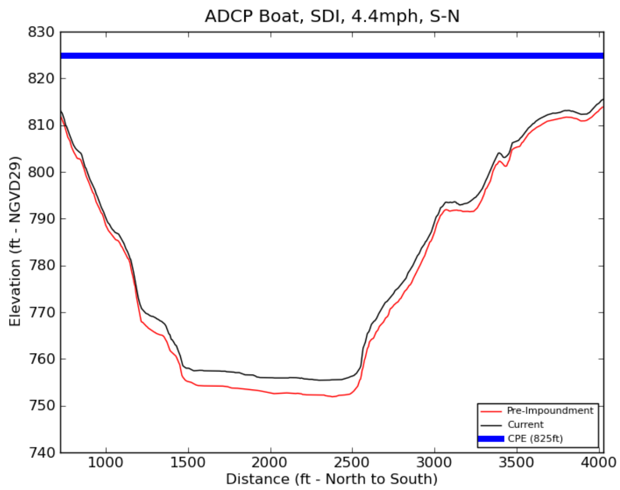


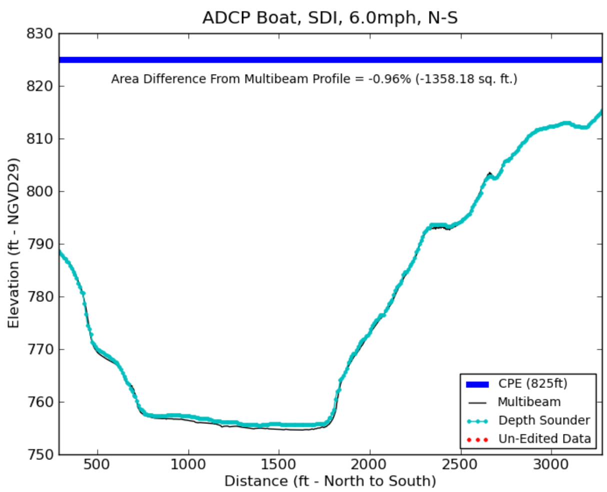


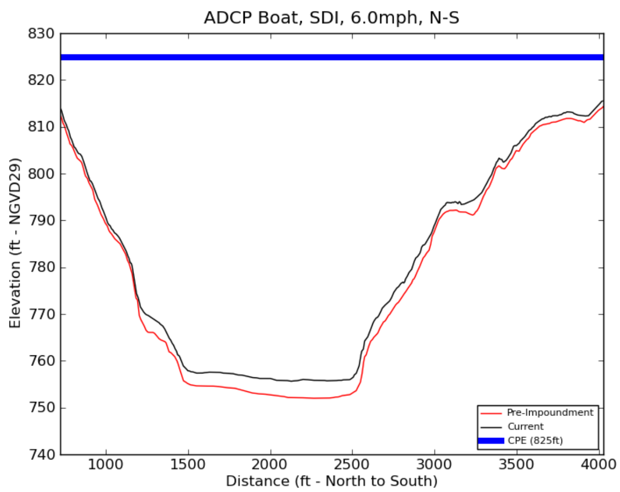
Current Surface

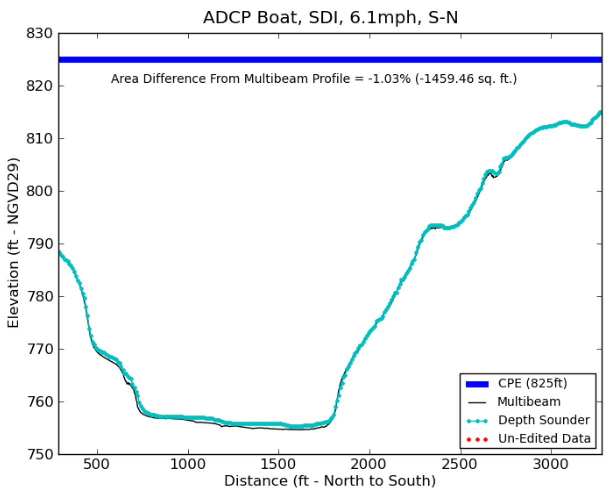
Pre-Impoundment Surface

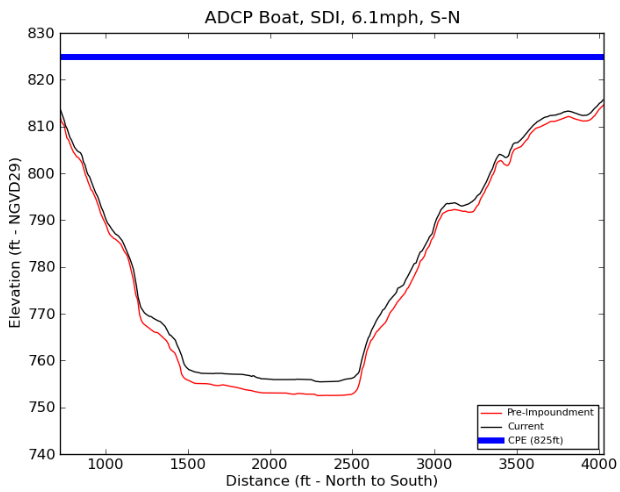






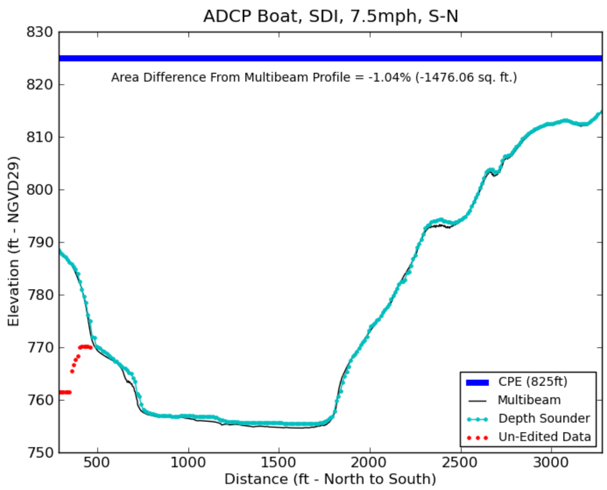


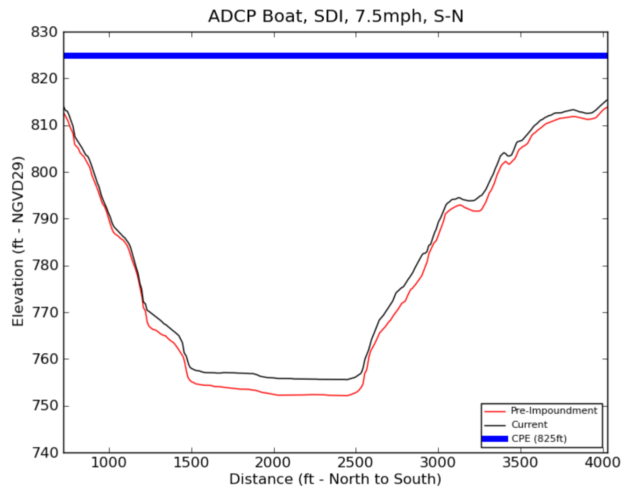


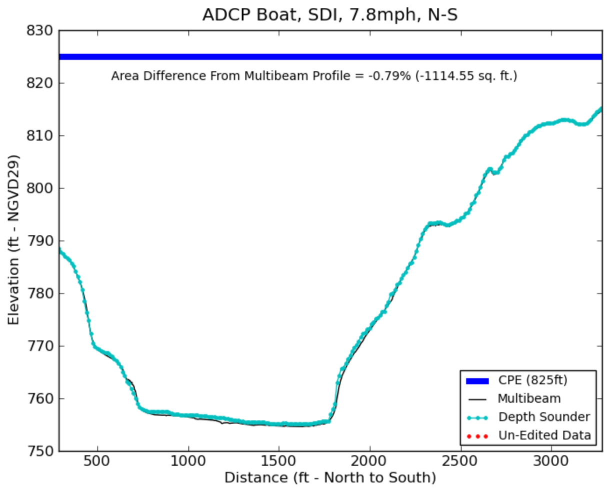


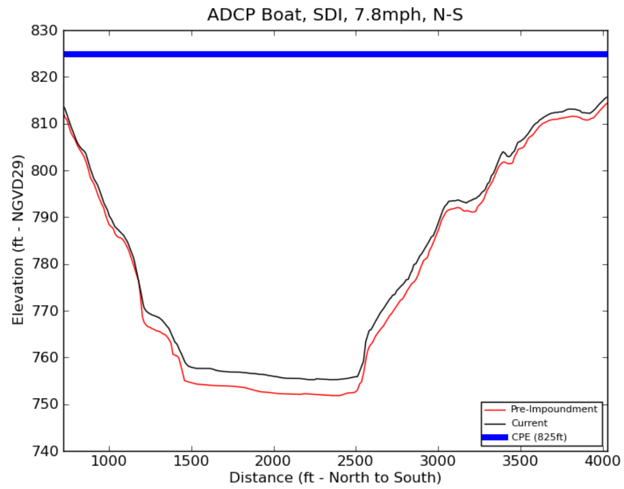
Current Surface

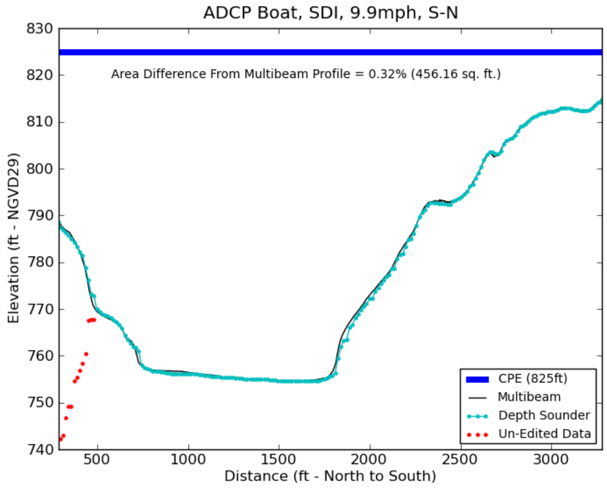
Pre-Impoundment Surface

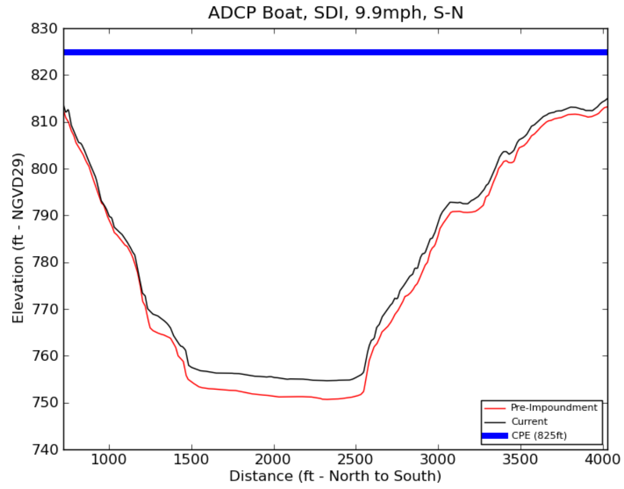






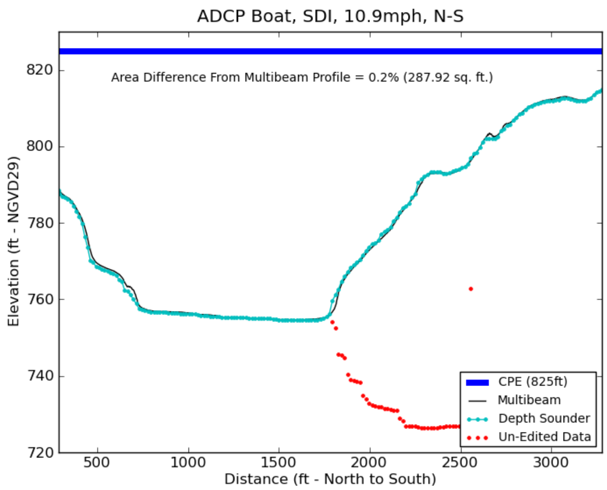


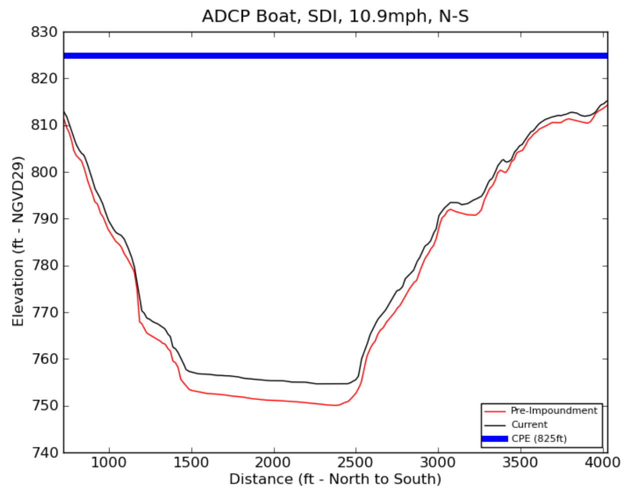


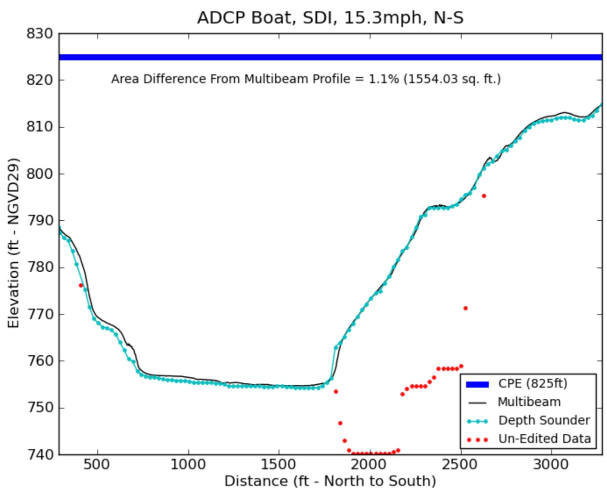


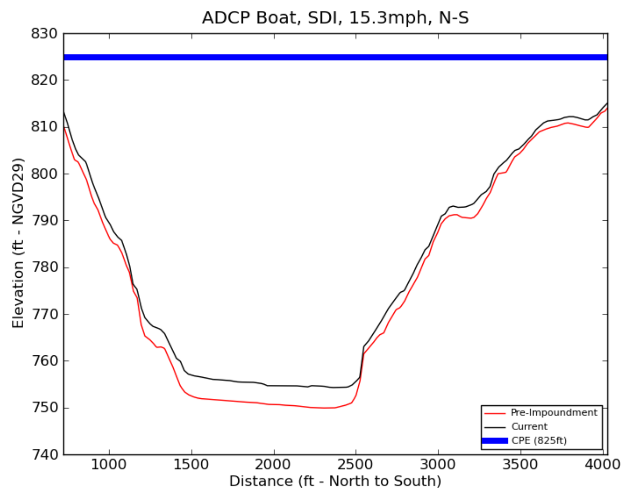
Current Surface

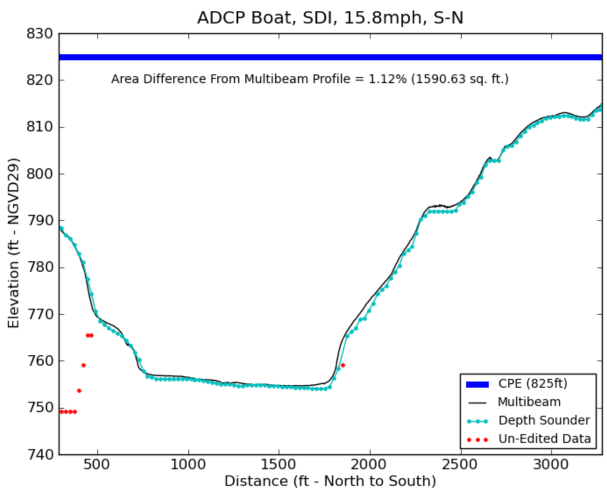
Pre-Impoundment Surface

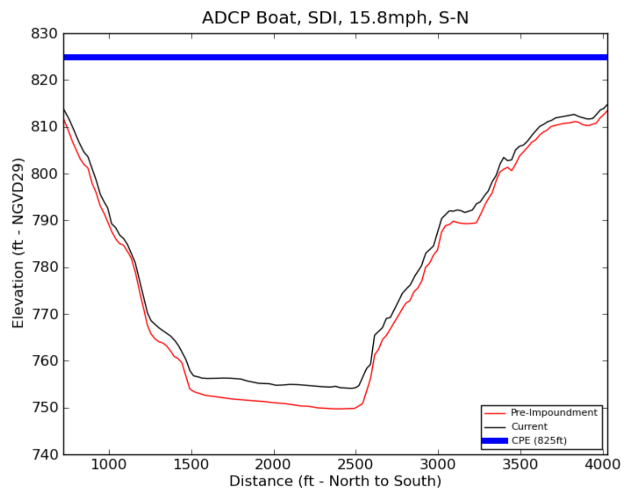






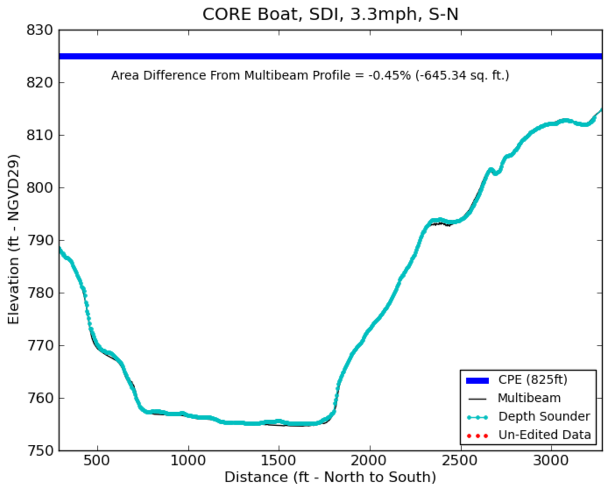


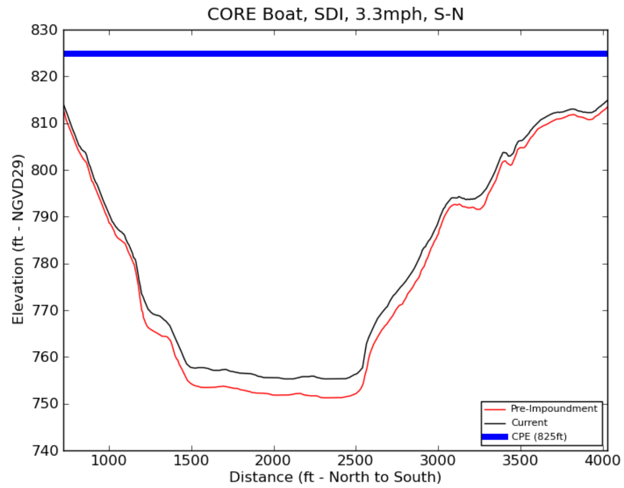


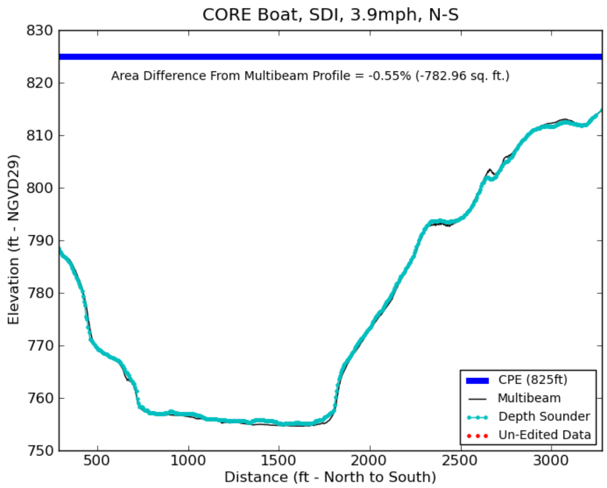


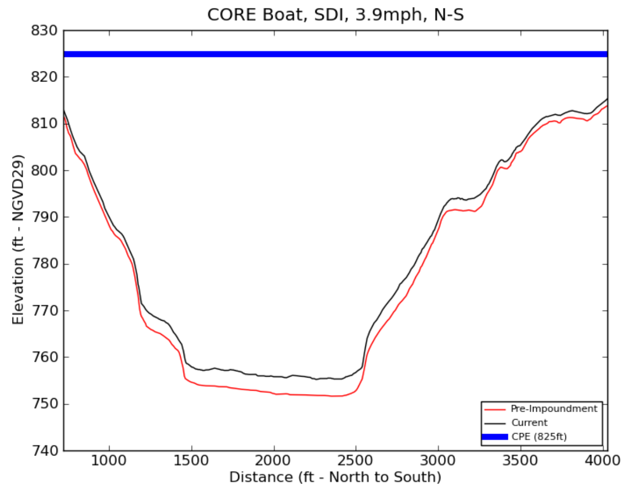
SDI depth sounder – CORE boat
Current Surface

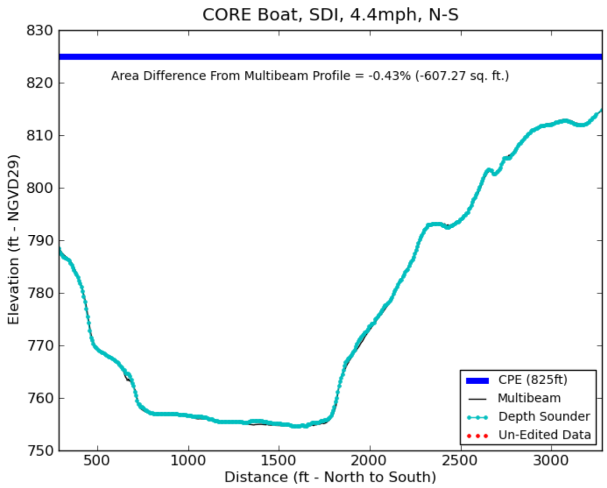
Pre-Impoundment Surface

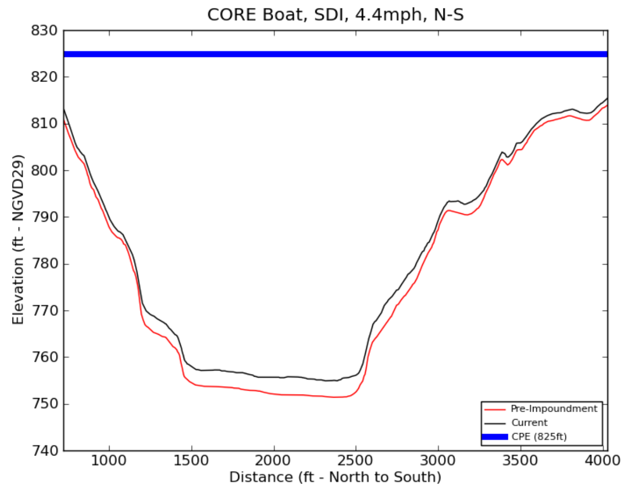




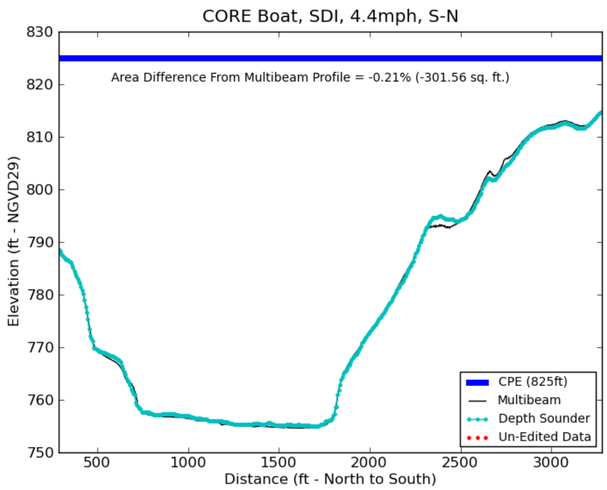


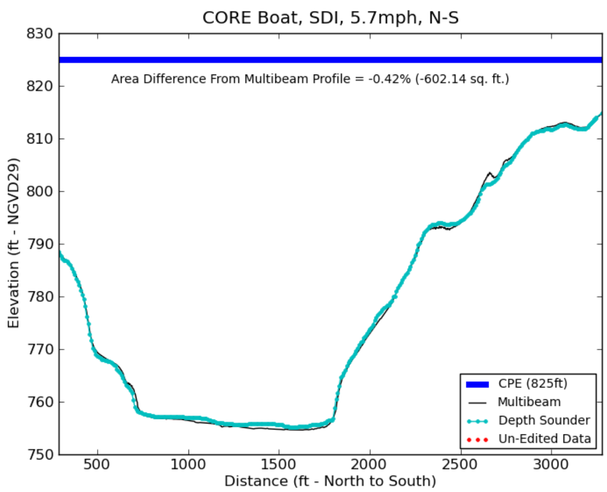


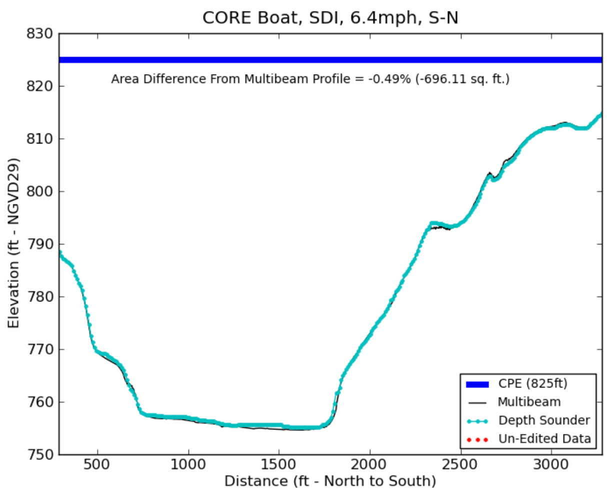




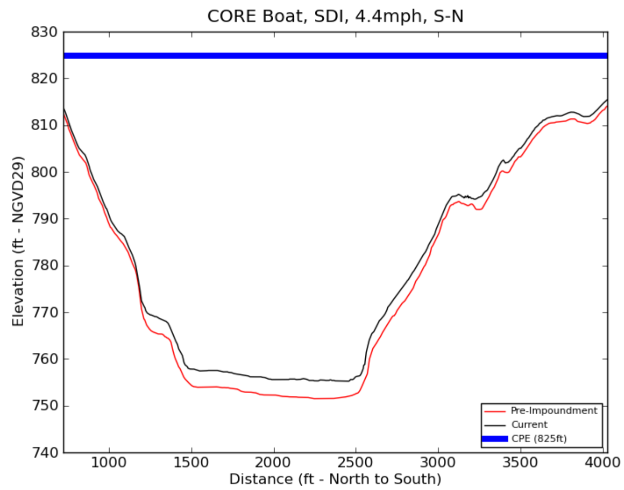
Current Surface

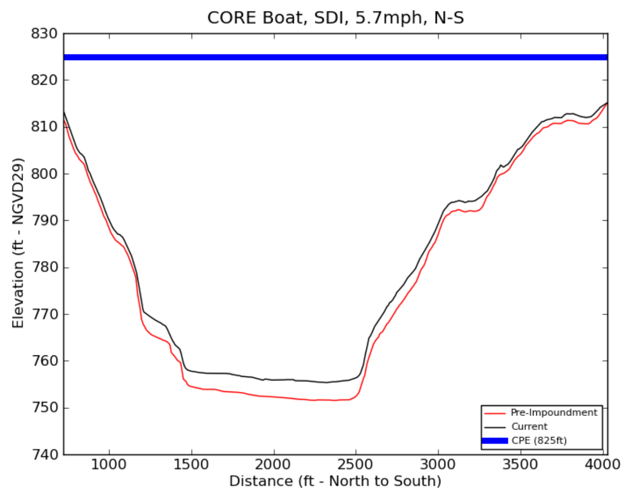


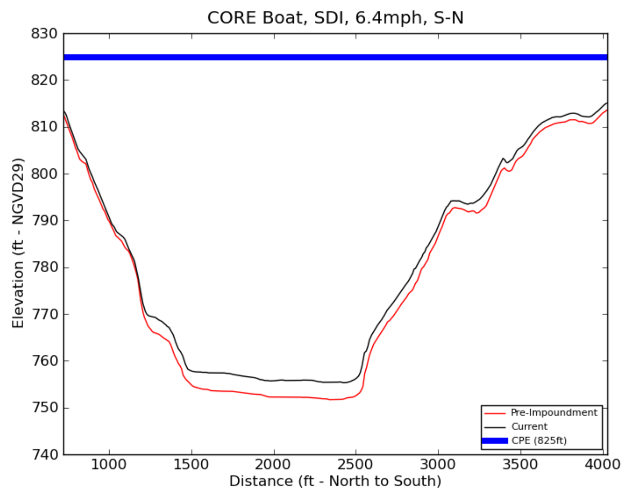




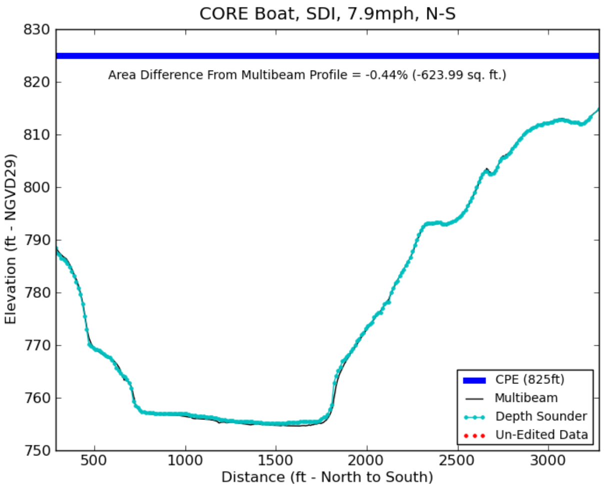
Pre-Impoundment Surface

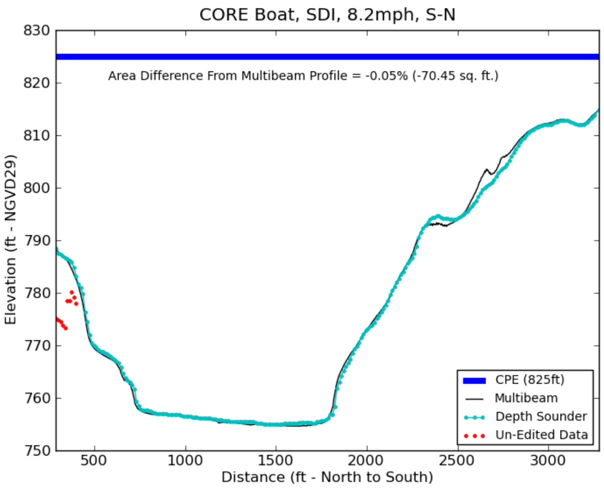


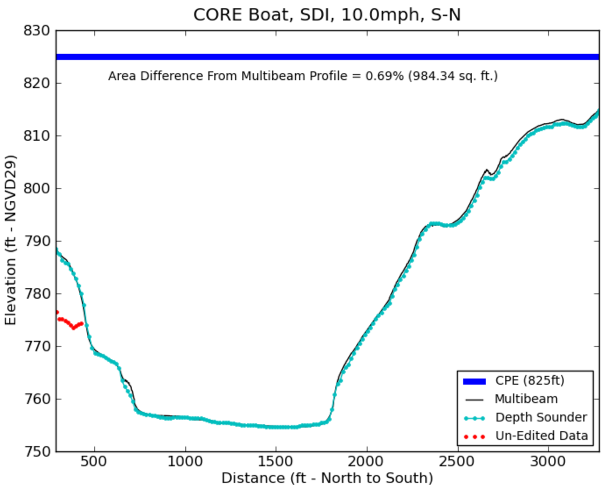




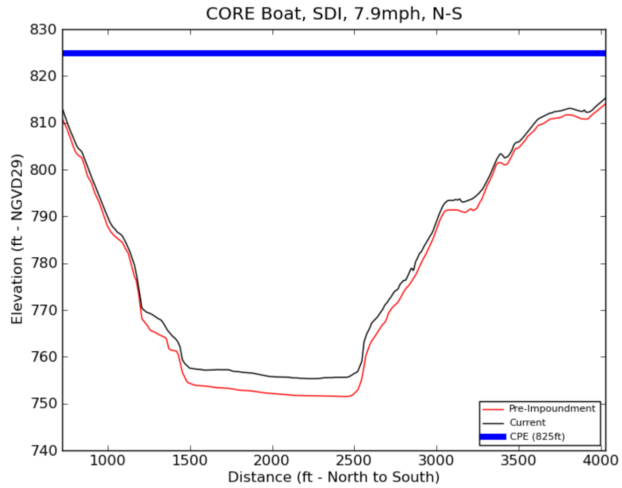
Current Surface

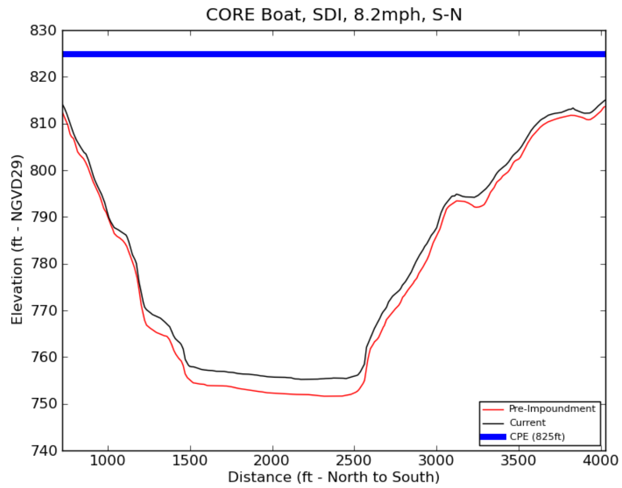


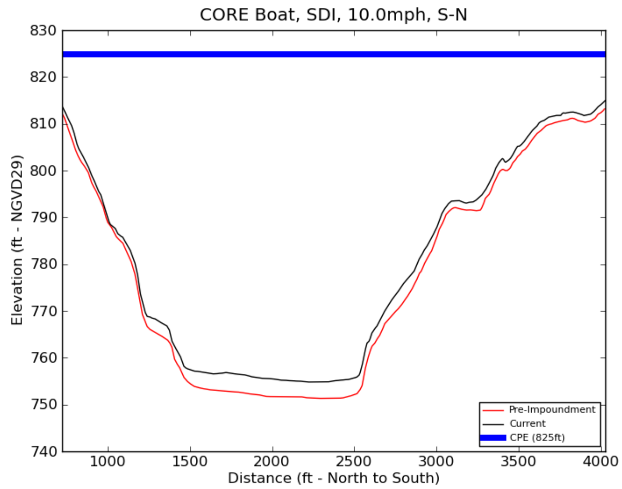




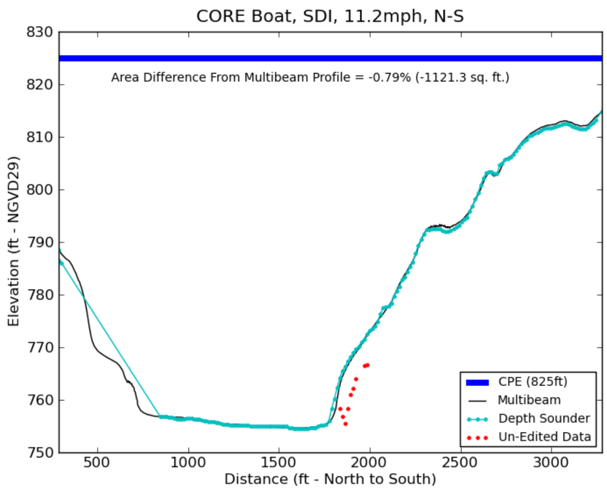
Pre-Impoundment Surface



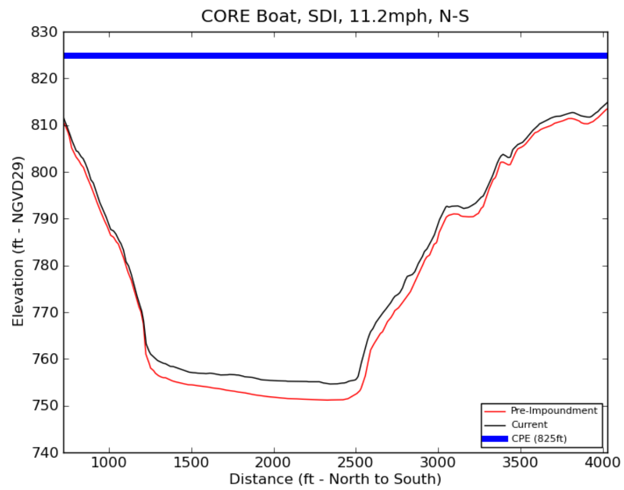




Current Surface



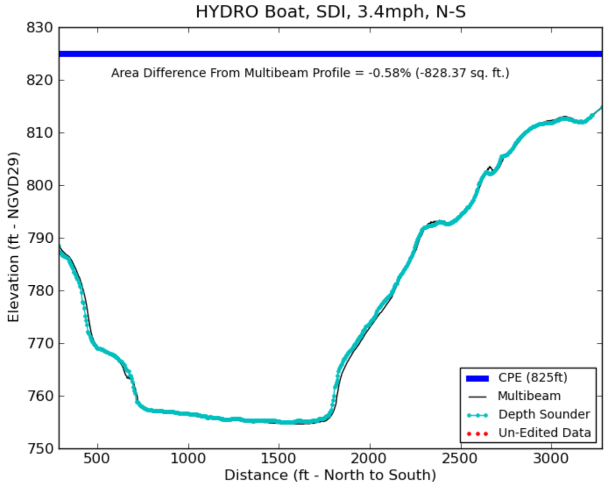
Pre-Impoundment Surface

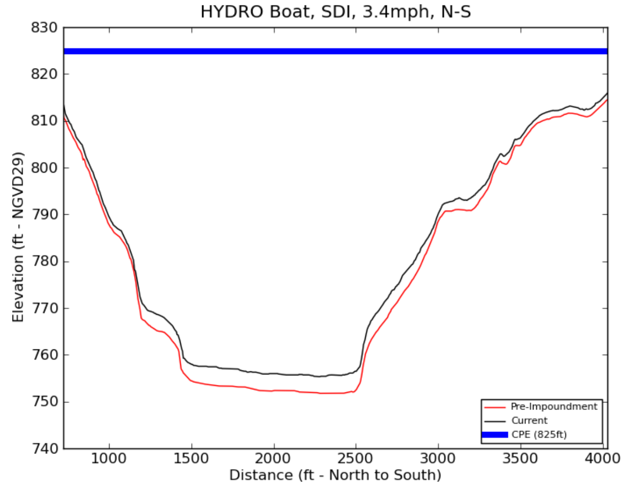


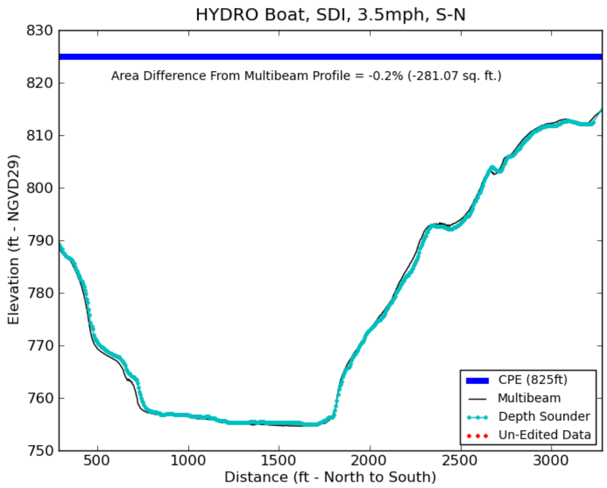
SDI depth sounder – HYDRO boat

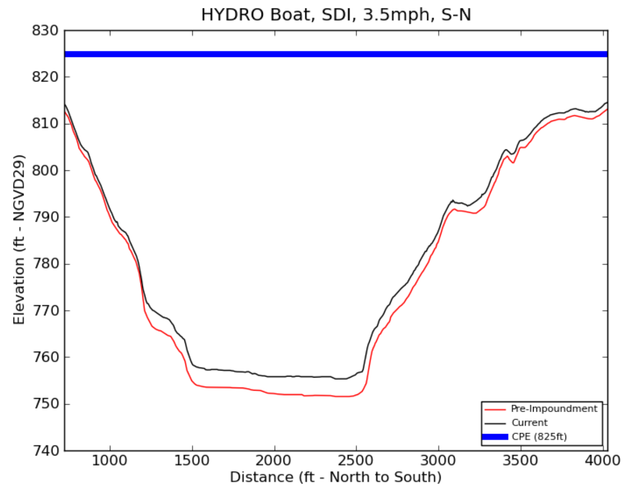
Current Surface

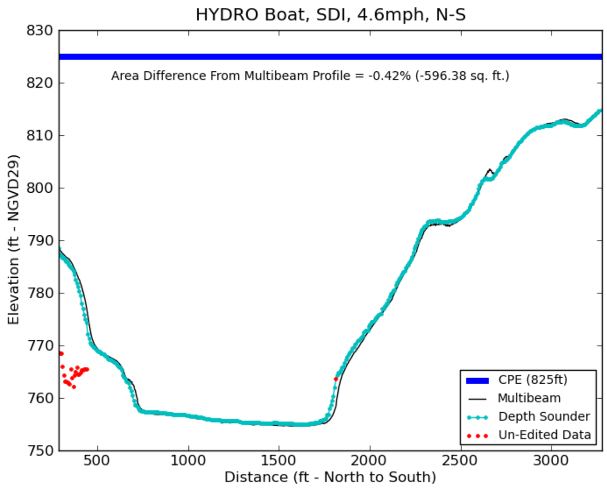
Pre-Impoundment Surface

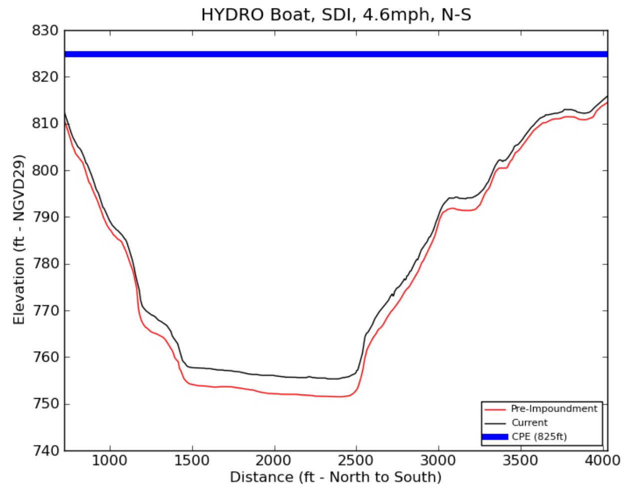




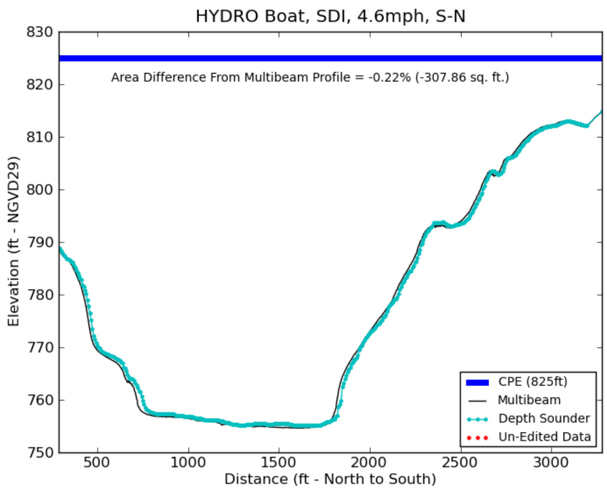


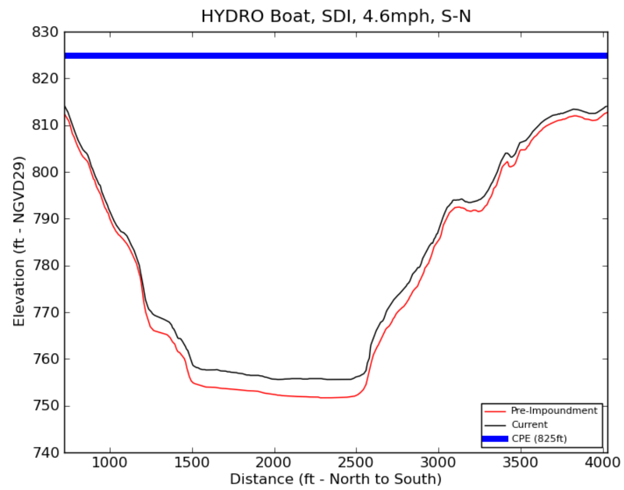


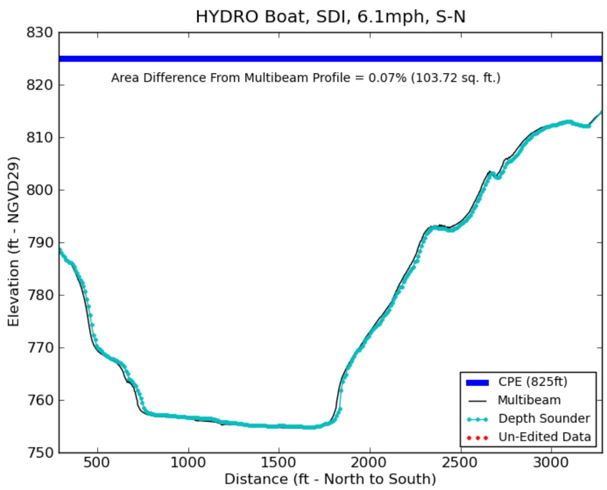


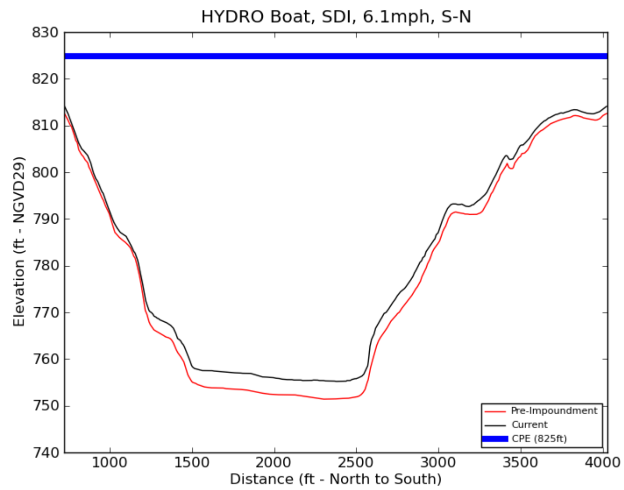


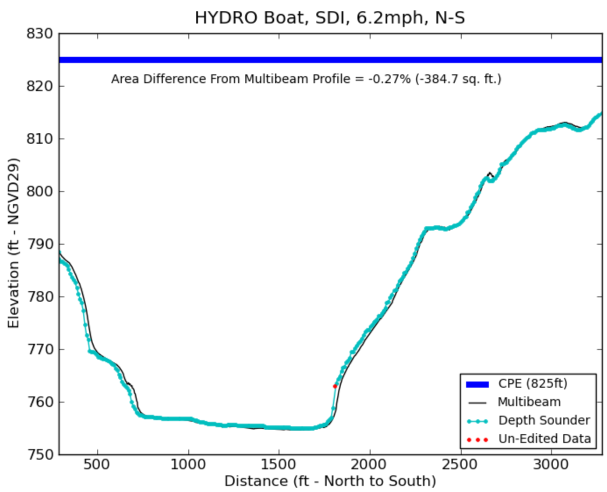
Current Surface	Pre-Impoundment Surface

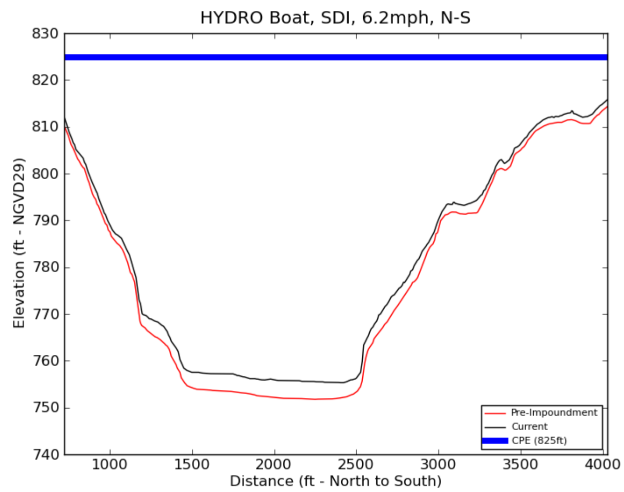




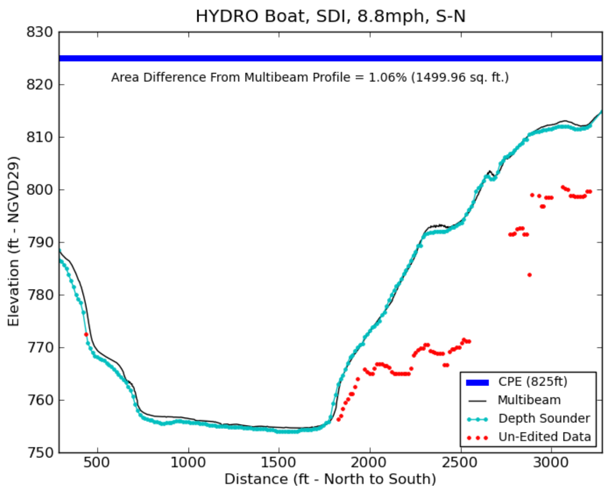




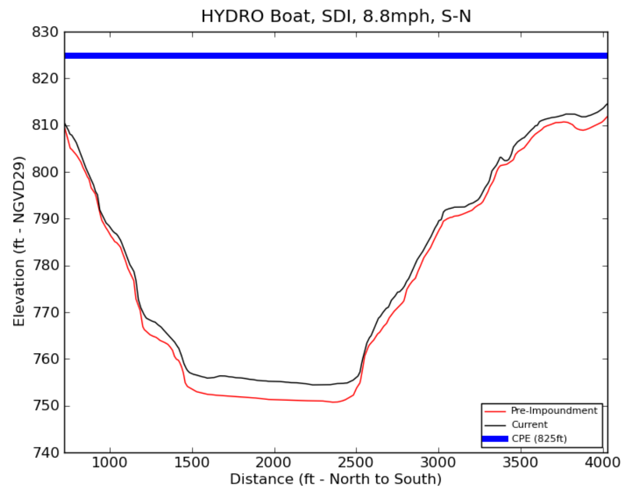




Current Surface



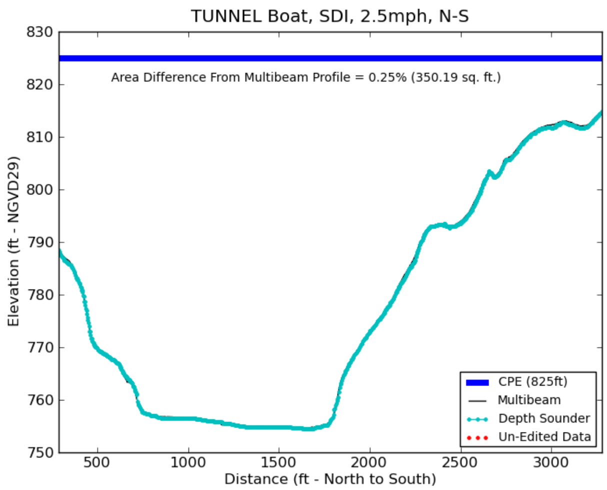
Pre-Impoundment Surface

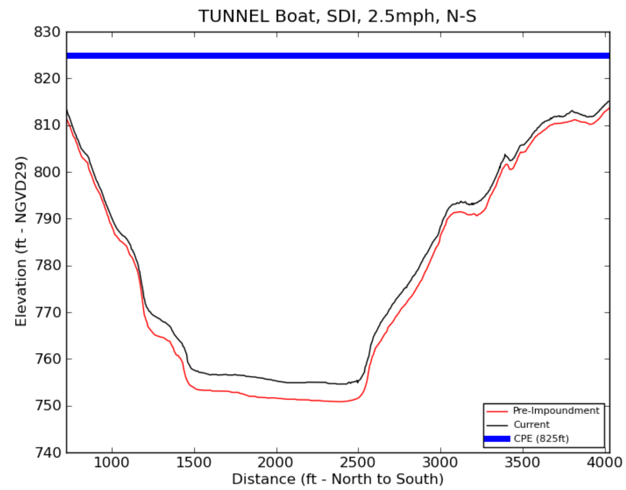


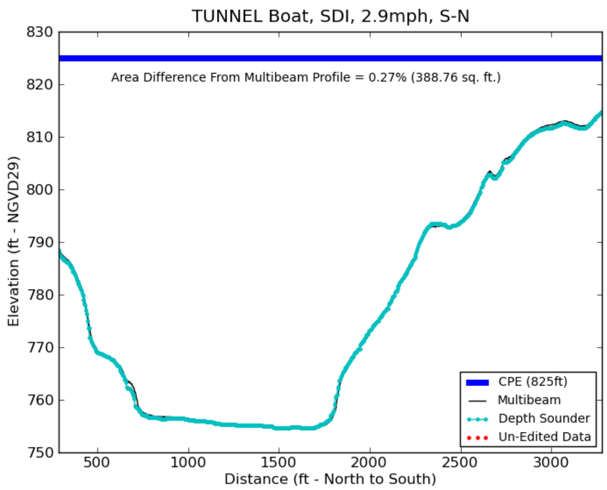
SDI depth sounder – TUNNEL boat

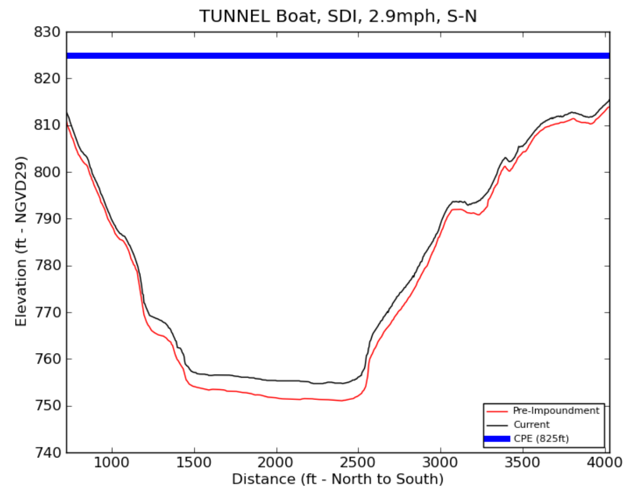
Current Surface

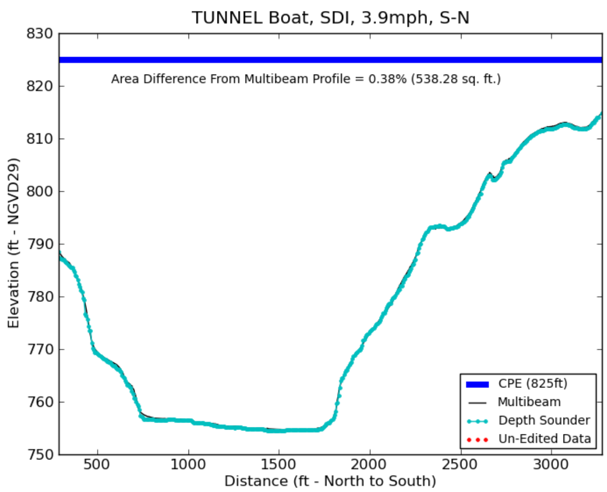
Pre-Impoundment Surface

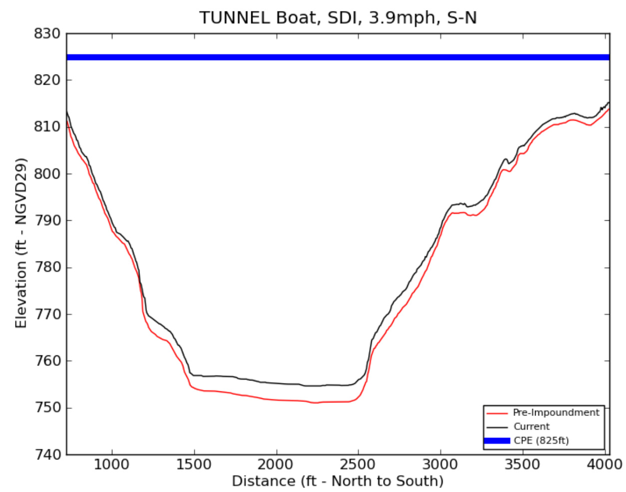




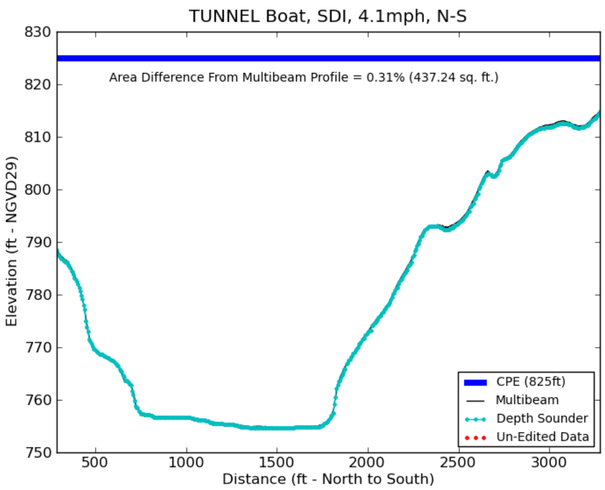








Current Surface



Pre-Impoundment Surface