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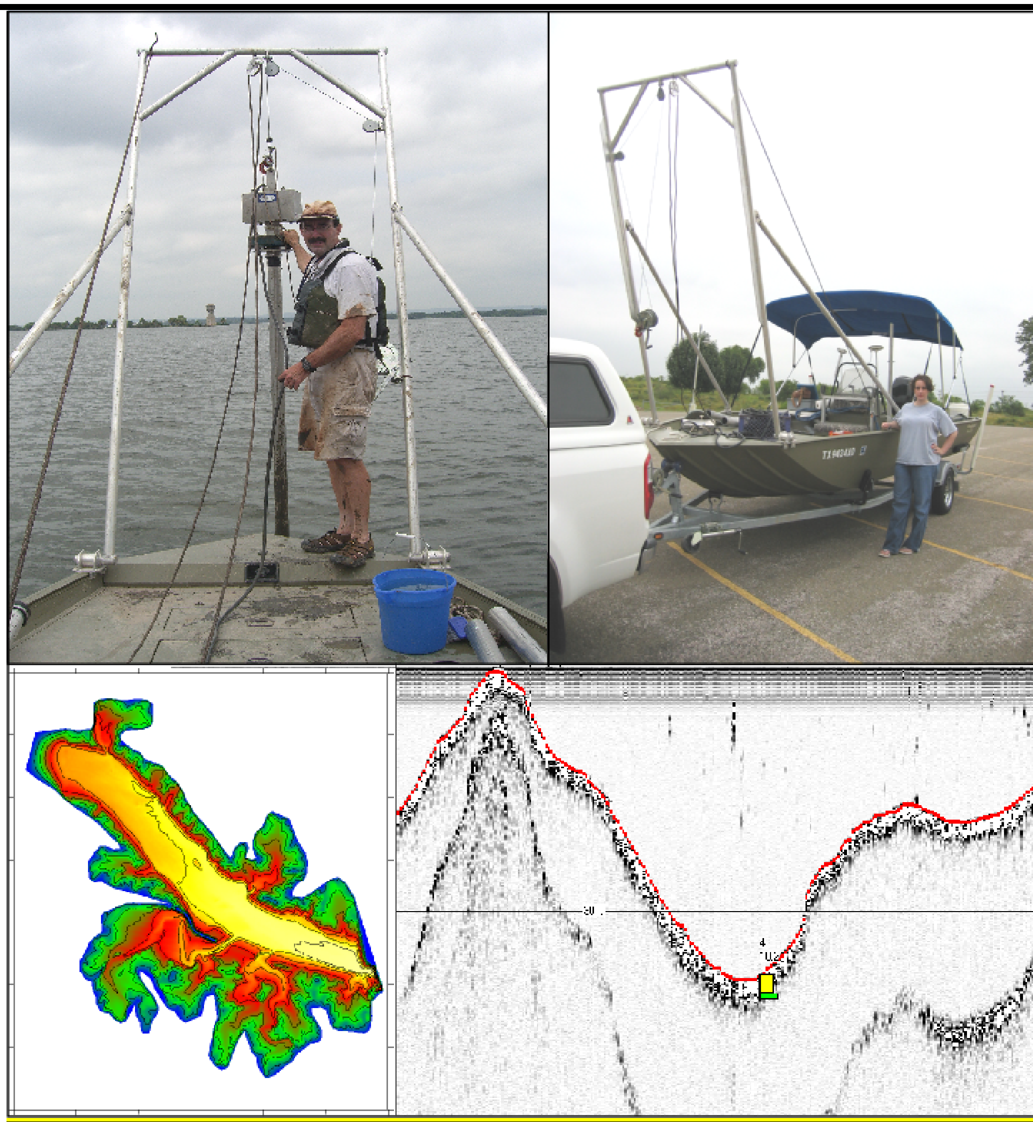


By John A. Dunbar and Heidi Estep

Final Report **April 2009**

Summary

Baylor University Department of Geology (BU) participated in a larger project with the Texas Water Development Board (TWDB) studying hydrographic survey methods, by collecting seven multi-frequency acoustic profiles and seven sediment cores in Lake Lyndon Baines Johnson (LBJ). The profiles were repeats of profiles previously collected by TWDB as part of its standard survey of the reservoir. The comparisons indicate that the two acoustic profiling systems used by TWDB and BU produce comparable results. The systems allow point measurements of sediment thickness to be made with better than 10% accuracy, for sediment thicknesses up to 8 ft. For greater thicknesses, the 12 kHz signal available on the BU system, but not on the TWDB system was needed to penetrate to the base of sediment. Through analysis of Cesium-137 concentration, BU identified the 1964 peak of Cesium-137 deposition in three cores. These measurements imply an average volume loss rate of 0.27%/yr since 1964. At this volume-loss rate, two hydrographic surveys collected 10 yr apart would need to measure the water volume of Lake LBJ to within +/-0.83 to constrain the sedimentation rate to within 10%. BU also used an in-house mapping program DepthMap, to map water depth and compute water volumes from TWDB survey data from Lake Marble Falls, Inks Lake, and Lake Buchanan. The results were compared to volumes produced by TWDB using an in-house interpolation program followed by mapping and volume calculation using ArcGIS™. Volumes produced by the two approaches agreed to well within 1% in all cases. To evaluate the influence of survey profile spacing on volume accuracy, BU extracted simulated profiles at spacings ranging from 100 to 2000 ft from a high-density multi-beam survey collected by an independent contractor. Volume calculations based on the extracted profile sets were compared to the volume based on the full multi-beam survey. The results indicate that the volume error associated with the TWDB standard 500 ft profile spacing is less than 1%, whereas error for larger spacings can exceed 1%. Reducing the profile spacing to less than 500 ft does not guarantee improved volume accuracy. BU tested a proposed method of predicting volume error versus profile spacing based on analysis of one or more acoustic profiles collect along the axis of the reservoir, orthogonal to the intended trend of the regular survey profiles. The method was tested by comparing the predicted error range versus profile spacing with that produced by the profile sets extracted from the multi-beam data. The results indicate that the method produces reasonable estimates of the range of volume error for profile spacings up to 1000 ft. For spacings larger than 1000 ft the method breaks down, likely as a result of reduced sampling within tributary arms of the reservoir, not sampled by the axial profile.

Project Background

The Texas Water Development Board (TWDB) maintains a cost-recovery, Hydrographic Survey Program that performs hydrographic surveys to determine water and sediment volume in reservoirs throughout Texas. Since the establishment of this program in 1991, the TWDB has surveyed over 100 reservoirs. In the past ten years, Baylor University Department of Geology (BU) has also had a group involved in water reservoir surveys. Most of the reservoirs surveyed by BU are small, many of them PL-566 flood control reservoirs, which can be surveyed in one day. Although the scale of the reservoirs surveyed by the two groups is different, the methods and instrumentation are similar. In this project TWDB and BU collaborate to investigate the accuracy of modern reservoir survey methods.

The technology used to survey water reservoirs has improved dramatically in the last 30 years with the advent of differential Global Positioning System (DGPS) navigation, improved acoustic profiling systems, and computer mapping programs (Dunbar et al., 1999). However, there have been no definitive studies on the accuracy achieved with these new tools. There is also no standard method for designing hydrographic surveys to achieve a given level of accuracy. This project addresses these two deficiencies. The approach taken was for TWDB to conduct sediment surveys of four Highland Lakes on the Texas Colorado River, Lake Marble Falls, Inks Lake, Lake Lyndon Baines Johnson (LBJ), and Lake Buchanan, using its standard methods and equipment. TWDB processed the survey results using its standard methods and software. To evaluate the accuracy of these surveys, additional data were acquired by two independent contractors, Hydrographic Consultants Inc., of Houston TX and BU.

Hydrographic Consultants Inc. collected and processed a multi-beam survey of the deepwater region in the southern third of Lake LBJ. Multi-beam technology is a relatively new acoustic profiling method that has the advantage over conventional (single-beam) profilers of collecting multiple acoustic profiles spaced at close intervals, offset from the survey vessel track line with a single pass (Ferrari, 2006). One 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. Another limitation is that no sub-bottom profiling version of multi-beam is currently available. Hence, multi-beam cannot be used to measure the sediment thickness directly, as is the case with some single-beam systems. Where it works, multi-beam provides the best spatial sampling and hence the most accurate hydrographic survey available. In this study the multi-beam results for the deepwater part of Lake LBJ are used as "ground true" against which the conventional single-beam water depth results are evaluated.

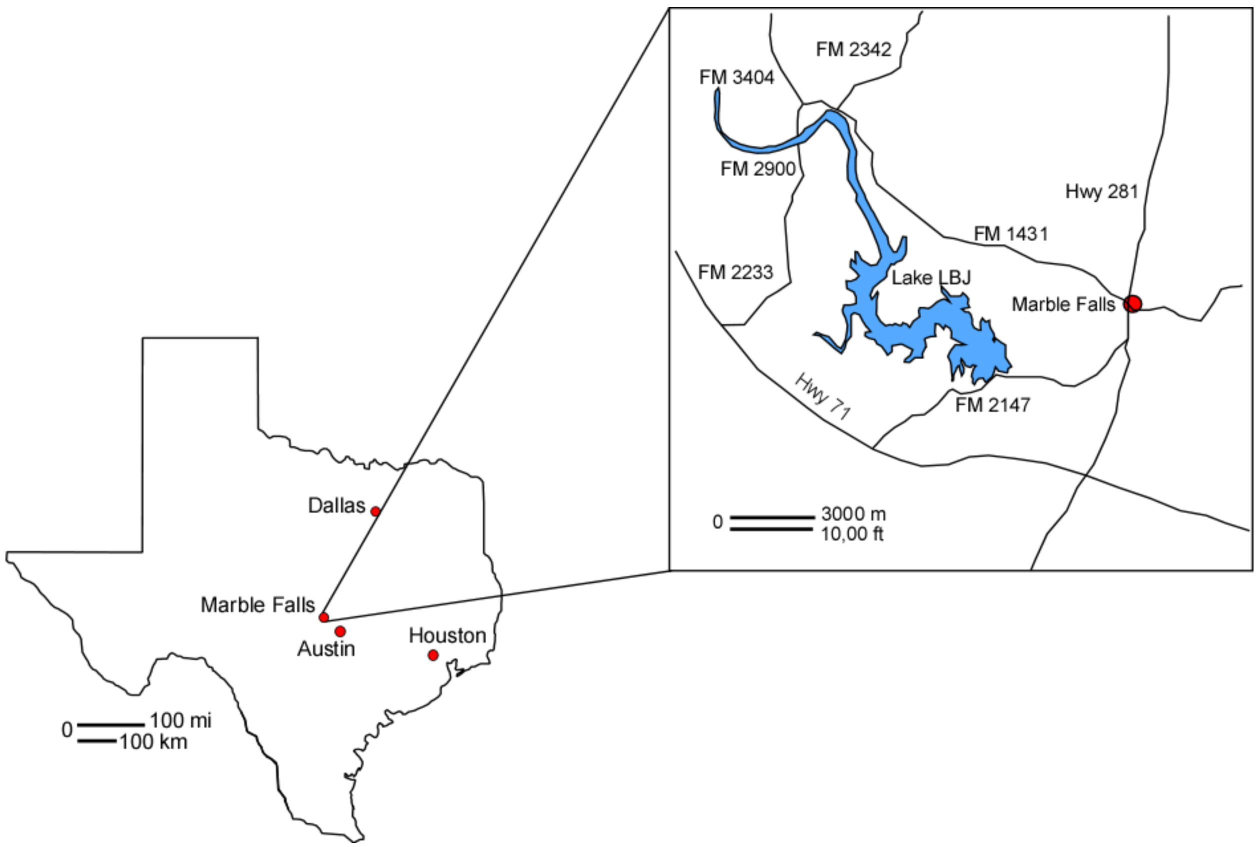


Figure 1. Location map for Lake LBJ.

BU retraced selected TWDB acoustic profiles within Lake LBJ using an experimental acoustic profiling system to independently determine the repeatability of individual profiles and compare the relative effectiveness of the two systems (Figure 1). BU also collected sediment cores along the selected profiles to directly measure the sediment thickness and to determine average sedimentation rates since 1964 using the Cesium-137 dating method (Ritchie et al., 1986). Cores that penetrated the entire post-impoundment sediment layer and sampled the underlying pre-impoundment surface were used as "ground true" against which the acoustically determined sediment thicknesses were evaluated. BU also contributed to the evaluation of the TWDB surveys by independently interpreting TWDB profiles collected in three of the reservoirs to test for differences in the human element duirng the data reduction process. To provided an independent test of the mapping and volumetric computations of TWDB, BU used an in-house mapping program DepthMap, to produce water depth maps and water volumes for Lake Marble Falls, Inks Lake, and Lake Buchanan base on TWDB survey data. BU also evaluated the relationship between profile spacing and water volume accuracy using the multi-beam data from Lake LBJ. The results were compared to accuracy predictions using a proposed reservoir survey design method. This report describes the methods and results of the work of BU in the overall study of reservoir survey accuracy.

Methods

Acoustic profiling

Modern sediment surveys of water reservoirs are conducted by traversing reservoirs along preplanned, parallel profiles in vessels equipped with acoustic fathometers and DGPS navigation systems (USACE, 1989; 2001). The data are used to map the bathymetry and to compute the water storage capacity at the conservation pool elevation. The volume of post-impoundment sediment is then inferred indirectly from the apparent change in water capacity between the time of impoundment or a previous survey and the current survey. This approach relies on having an accurate previous survey. In cases in which a prior survey is not available or the accuracy of the previous survey is in doubt, combined bathymetric and sub-bottom profiling systems are used to map the thickness of post-impoundment sediment directly (Dunbar et al., 1996; 1997; 1999). Combined fathometer and sub-bottom surveys are done using multi-frequency acoustic profiling systems with signal frequencies ranging from a few kilohertz (kHz) to 200 kHz. These systems produce signals and record bottom returns for each frequency, multiple times per second, so that precisely co-located profiles at the different signal frequencies are collected simultaneously. Full-waveform digital recordings of the acoustic returns are made during the survey so that profiles at individual signal frequencies or combinations of multiple frequencies can be redisplayed and interpreted during post-survey processing. The high-frequency signals are used to map the water bottom, to determine the remaining reservoir storage capacity. The low frequency signals are used to map the base of sediment, to determine the sediment volume.

Both TWDB and BU use multi-frequency fathometer/sub-bottom profiling systems made by Specialty Devices, Inc. of Wylie, Texas (SDI). The TWDB system is SDI's standard system for water reservoir surveying. It has three signal frequencies, of 24, 50, and 200 kHz. Signals at all three frequencies are digitized at 100,000 samples per second. Accurate digital recording of analog signals requires a minimum of 2 samples per cycle (Shannan, 1949). This requires a minimum of 400,000 samples per second for the 200 kHz signal. To avoid errors associated with under sampling, the analog 200 kHz signal is rectified, so that both negative and positive parts of the signal are made positive. Then the rectified analog signal is low-pass filtered electronically to 50 kHz before being past to the digitizer. This avoids sampling error and for normal bathymetric surveying, the small loss in resolution is not important.

BU currently uses an experimental profiling system from SDI that has five frequencies (12, 24, 50, 125, and 200 kHz). The experimental system was designed to investigate the internal stratigraphy within reservoir sediments. The digitizer is programmable and can be set to digitize at arbitrary rates up to 1 megahertz (mHz). To accurately sample the 200 kHz signal without pre-filtering, all the signals are digitized at 500,000 samples per second. The increased time-sample resolution is an advantage for mapping internal stratigraphy, but offers no advantage for mapping overall sediment thickness. The only potential advantage of the experimental system for mapping sediment thickness may be the greater penetration afforded by the addition of the 12 kHz signal. This could allow mapping thicker post-impoundment sediment intervals than is possible with the 24 kHz signal. The disadvantage of the experimental system is that the rate at which recordings for each frequency can be made is limited by the number of samples stored, which is five times greater for the experimental system than for the TWDB system. Also, with all signal frequencies activated, the experimental system collects five signal frequencies compared to three for the TWDB system. Hence, the spatial separation of individual recordings made by the experimental system is 8.3 times greater than that of the TWDB system, with survey vessels traveling at the same speed.

To test the repeatability of acoustic measurements made by TWDB, BU collected seven acoustic profiles with the experimental SDI system that repeated profiles previously collected by TWDB using the standard SDI system. The BU profiles were also used to evaluate the potential advantage of the additional signal 12 kHz signal frequency. The seven profiles were spaced along the length of Lake LBJ, from the southeastern most part of the reservoir near the dam to the riverine section in the extreme northwest portion of the reservoir. To retrace the profiles collected by the TWDB, the geographic positions of each measurement made along the seven lines were extracted from the TWDB survey data, reformatted, and entered as track lines in the survey navigation software HYPACK. To minimize the differences in the spatial resolutions of the two systems, all five frequencies used by the experimental system were recorded only on one profile, to compare the relative penetration of the different signal frequencies. For most other comparison profiles, the 12 and 125 kHz signals were turned off on the experimental system and only the 24, 50, and 200 kHz signals were recorded. To better match in spatial resolutions of the two systems, the survey speed BU used during acquisition with the experimental system was reduced to approximately 2 miles per hour, compared to the normal survey speeds of 5 to 6 miles per hour during the TWDB surveys. While collecting the repeat profiles, BU attempted to follow the original TWDB profiles as closely as possible.

Sediment Coring and Analysis

Sediment core samples were collected along the repeated profiles to directly measure the sediment thickness and to determine the long-term sedimentation rate at the core sites. The sediment cores were collected using a submersible vibracoring system. Vibracoring is a standard method for obtaining cores of unconsolidated sediment with little or no bypass of sediment around the core tube (Lanesky et al., 1979; Smith, 1984). BU's vibracore runs on 24-volt DC current supplied by two 12-volt trolling motor batteries. The vibration causes the sediment to liquefy in a region a few millimeters thick near the core tube wall, allowing the tube to slide into the sediment with little drag. This device collects 3 inch diameter cores up to 12 ft in length in soft sediment. One core site was selected along each of the repeated profiles by examining the previously recorded TWDB acoustic profiles. The goal was to pick sites with a range of sediment thicknesses, but which did not exceed the 12 ft penetration limit of the corer. The field procedure was to anchor the survey vessel as close to the pre-selected core site as possible, collect the core, and record the true geographic position of the core location. When the repeat profile was collected, care was taken to past over the core site as closely as possible.

Collected cores were capped in the field and brought back to BU's core laboratory for analysis. In the laboratory, the cores were cut open lengthwise for visual inspection to identify the depth to the pre-impoundment surface. Pre-impoundment surfaces in reservoirs are commonly characterized by abrupt changes in physical properties, such as water content and penetration resistance, as well as visually recognizable changes in composition and texture. In many cases intact terrestrial plant roots are found in buried soils. In other cases fine-grained post-impoundment sediment is deposited directly over poorly sorted sediment with large angular clasts, which are too large to be transported within the reservoir.

After visual inspection, the cores were sub-sampled in 5 cm increments for water content analysis, penetration resistance measurements, and Cesium-137 dating. Penetration resistance is determined by measuring the force required to drive a 1 in. diameter, ¼ in. tall disk into confined sediment samples. Water content by mass of the sediment is determined by weighing samples wet, drying the samples for 24 hours at 106 °C, and then weighing the samples again. The water content is given by the fractional change in the mass of the sediment sample from its wet to dry state (ASTM, 2001)

$$wc = \frac{m_{wet} - m_{dry}}{m_{wet}}, \tag{1}$$

where m_{wet} is the mass of the sediment sample in its field condition and m_{dry} is the mass of the same sample after drying.

An estimate of the sedimentation rate in a reservoir is needed to determined how often sediment surveys should be conducted and how accurate those surveys need to be to constrain the sedimentation rate to a given accuracy (Ferrari, 2006). BU estimated the long-term average sedimentation rate in Lake LBJ using Cesium-137 analysis of the sediment cores. Cesium-137 analysis is a standard method for identifying date lines in sediment cores in lakes and water reservoirs that correspond to changes in fallout rates of atmospheric Cesium-137 (Ritchie et al., 1986; Ritchie, 1998; Van Metre et al. 2003; 2004). Cesium-137 is a component of radioactive fallout from atmospheric nuclear tests in the 1950s and 1960s, which has a half-life of 30.2 yr. Significant fallout of radioactive Cesium-137 began in North America in 1954 ± 2 yr and reached a peak in 1964 ± 2 yr (Ritchie et al., 1986). Cesium-137 analyses were performed on each 5 cm sub-sample of four selected cores. The concentration of Cesium-137 was determined by placing 25 g of powered and sieved sediment in a 50x9 mm Petri dish and placing the dish in a lead-shielded chamber containing a Germanium gamma ray detector. The gamma rays emitted by the sample that fall within a Gaussian window about 661.65 KeV were counted for 80,000 s (22.2 hr). The identification of the 1964 peak in Cesium-137 in the cores makes it possible to determine the average sedimentation rate from 1964 to present. To convert point estimates of the sedimentation rate to an estimated volume loss rate, BU multiplied the average annual deposition rate by the area of the reservoir.

In addition to determining long-term average depositions rates in cm/yr, Cesium-137 dates in cores can also be used to compare deposition rates for different time periods. However, if the lengths of core segments between dates were used directly in these calculations, the resulting rate comparisons would be distorted by differences in compaction with depth in the cores. For this reason BU compared sediment rates between time intervals in terms of the dry mass deposition rate per square centimeter per year, using the following relationship

$$d_i = \frac{\rho_{db}^{i} L_i}{\Delta t_i}, \tag{2}$$

where d_i is the dry mass deposition rate (g/cm^2/yr) during the ith time interval, ρ_{db}^{i} is the average dry bulk density in terms of the mass of dry sediment grains per unit volume of wet sediment within the core segment corresponding to the ith time interval (g/cm^3), L_i is the length of the core segment associated with the ith time interval (cm), and Δt_i is the length of the ith time interval (yr).

Mapping and Volumetrics

Modern reservoir sediment surveys produce tens of thousands of water depth measurements spaced a few feet apart along parallel profiles spaced a few hundred feet apart over the reservoir. These data are converted into continuous water depth maps and used to compute water storage volumes using computer mapping programs. The accuracy of a survey depends in part on the accuracy of the water measurements and in part on the mapping process. Commercially available grid-based contouring programs, such as Surfer™, are not well suited to mapping reservoirs, due to the scale of the problem and the complexity of the shape of reservoirs. TWDB uses ArcGIS™, augmented by an in-house interpolation program for mapping and volumetric analysis. ArcGIS generates a triangulated irregular network (TIN) surface model of the water bottom by forming triangles with sides that connect water depth measurements. For profile data, this results in surface models composted of long, thin triangles that extent between profiles along two sides and between adjacent points along profiles on one short side. The result is a poor representation of the water bottom surface. To avoid this problem, TWDB uses an in-house interpolation program to infill the regions between profiles with linearly interpolated estimates of the water depth prior to the application of ArcGIS. This results in triangles that are closer to equilateral in shape and smoother surface models of the water bottom.

As a test of TWDB's approach to mapping and volumetrics, BU applied its own in-house mapping and volumetrics program DepthMap, to the surveys of Lake Marble Falls, Inks Lake and Lake Buchanan. DepthMap was developed for mapping small flood control reservoirs. Like ArcGIS, DepthMap generates TIN surface models, but its approach differs from that of ArcGIS. DepthMap initially fills the region within the reservoir shoreline with regularly spaced points in the horizontal plane with unassigned depth values. It then forms triangles connecting the infill points together and with points along the shoreline to produce a flat TIN surface covering the reservoir with nearly equilateral triangles. The map of the water bottom is found by solving a constrained optimization problem to assign the depth values of the triangle corners such that the TIN surface is as smooth as possible, while also requiring the triangle facets to pass through the measured water depth values in a least-squares sense. DepthMap produces accurate maps of flood control reservoirs in a matter of minutes. However, the approach taken is not ideal for large water supply reservoirs. In its original form, DepthMap did not account for islands within reservoirs, which are not common in flood control reservoirs. The Depthmap algorithm was modified to include islands for this project. Solving for the water depth as an optimization problem also places limits on map resolution. The limit of addressable storage on the computer system limits the number of triangles that can be used to represent the water bottom. For 32-bit systems, the storage limit is approximately 3.75 gigabytes. For these systems, the maximum problem size is on the order of 100,000 triangles, constrained to pass through 20,000 measurements. In mapping large water supply reservoirs with surface areas of many thousands of acres, TWDB is required to honor features of the shoreline, such as islands, peninsulas, and inlets, on the scale of a few tens of feet. To accurately represent features of this scale with TIN models requires triangles with side lengths of the same size or smaller. For many large water supply reservoirs, the number of triangles required would exceed the storage limit of 32-bit systems. For example, covering the 6,450 acre surface of Lake LBJ with triangles that are 25 ft on a side would require approximately 900,000 triangles and would require days of computational time on the fastest available personal computers. The storage-limit problem could be solved by separating the computation parts of DepthMap into a command-line executable program compiled to run on 64-bit systems. Computation times could be reduced by further optimization of the algorithm and parallelizing the algorithm to take advantage of multi-core CPUs. To reduce the scale of the computational problem for this study, comparison calculations were made using triangles with 50 to 250 ft side lengths in DepthMap.

Profile Spacing Evaluation

In addition to the accuracy of the individual water depth measurements and the mapping method, the number and distribution of measurements acquired influences the accuracy of reservoir surveys. The spacing of measurements along profiles is controlled by the water depth and the speed of the instruments used. This leaves the spacing of profile lines as the main design decision made in planning reservoir surveys. The goal is to pick the profile spacing such that the water bottom is nearly uniform between profiles. In general, it is not possible to choose the profile spacing without some prior knowledge of the bathymetric variability within the reservoir. The U.S. Bureau of Land Management (BLM) suggests starting with 300 ft profile spacing and monitoring bottom irregularly during the survey (Ferrari, 2006). If large changes in bathymetry occur between profiles, the crew should adjust to closer spacing. If little change occurs between profiles, larger spacing can be used. Ferrari cites examples in which profile spacing as close as 100 ft were required and other examples in which spacing as large as 2000 ft were adequate. He gives one example in which profiles collected perpendicular to the normal profile orientation were used to confirm that 2000 ft profile spacing was adequate.

As a standard practice, TWDB conducts hydrographic surveys with 500 ft profile spacing. In this study, TWDB compared the results of its standard survey of the deep portion of Lake LBJ with that of a multi-beam survey. The processed multi-beam data set consists of over 2.2 million points, spaced approximately 10 ft apart, which in terms of reservoir surveying amounts to continuous coverage. The comparison between the TWDB standard survey and the multi-beam survey incorporates differences in the accuracy of individual measurements as well as error associated with differences in measurement spatial density. To better constrain error associated with profile spacing, BU performed a series of calculations based on the multi-beam data set alone. This was done by starting with the TWDB line files used to plan the Lake LBJ survey. A series of geographic points spaced 5 ft apart was generated along each of the TWDB lines. A separate algorithm then searched through the multi-beam data to find the four multi-beam points bracketing each line point. Water depth at the four multi-beam points was then linearly interpolated the line points. This process extracts depth determined by multi-beam surveying along individual profiles, simulating the data that would be collected along the profiles by a single-beam profiler. DepthMap was then used to generate bathymetric maps and compute volumes based on the extracted profiles. The error associated spatial sampling at a given profile spacing was then determined by comparing the resulting volume to that for the full multi-beam data set. To determine the variation in spatial sampling error versus profile spacing, the original TWDB 500 ft profile set was interpolated to profiles spaced at 100, 200, 300, and 700 ft and decimated to produce profiles spaced at 1000, 1500, and 2000 ft. Also, to evaluate how linear interpolation between profiles before mapping influences accuracy, linear interpolated infill points were generated between extracted profiles at 500, 1000, 1500, and 2000 ft prior to mapping. The results of all volume calculations were then evaluated by comparison with the volume determined from the full multi-beam data using DepthMap.

Survey Design

The evaluation of spatial sampling error versus profile spacing determined by methods described in the last section applies to Lake LBJ, but does not necessarily apply to other reservoirs. The method of choosing profile spacing used by the BLM is subjective and is not easily applied in a consistent way. In this study, BU evaluated a quantitative approach for estimating the profiles spacing required to achieve a specified survey accuracy. The method is similar to the approach used by the BLM to evaluate the adequacy of profile spacing after the fact (Ferrari, 2006). The purposed method involves collecting one or more preliminary profiles in the direction perpendicular to the intended orientation of the regular survey profiles. These preliminary profiles would normally be oriented parallel to the long axis of the reservoir. The preliminary profiles sample the variability of water depth between the future survey profiles. To estimate the survey error associated with different profile spacings, the preliminary profiles are resampled at different spatial sample intervals, which correspond to profile spacings that could be used in the survey. Water depth is determined at selected positions along the preliminary profiles by linear interpolation between the closely spaced water depth measurements. Each resample point corresponds to a point on a crossing profile in a hypothetical survey. Although it is customary to space survey profiles at regular intervals over reservoirs, this approach is completely general. It is possible to experiment with different profile spacings in different parts of a reservoir or to continuously vary the profile spacing along the axial of a reservoir. For a given resampling of a preliminary profile, the contribution to the total volume ΔV_s, per sample interval in the survey profile direction Δx, is determined by converting the resampled profile into a closed polygon and computing its cross-sectional area (Selby, 1974).

$$\Delta V_s = \frac{1}{2}\left\{ \sum_{i=1}^{N_s - 1} \left[x_i f(x_{i+1}) - x_{i+1} f(x_i) \right] + x_{N_s} f(x_1) - x_1 f(x_{N_s}) \right\} \Delta x \, . \qquad (3)$$

where $f(x_i)$ are the water depth values along the preliminary profile at sample locations x_i, $i = 1, 2, 3, \ldots N_s$, and N_s is the number of sample intervals at the specified resample spacing.

To estimate the percent volume error that would occur if the full survey were conducted at a given profile spacing s, we compute the percent difference in the volume slice between the full-resolution and resampled profiles

$$E_s = 100\left(\frac{\Delta V_s - \Delta V}{\Delta V}\right), \qquad (4)$$

where E_s is the predicted percent volume error associated with a proposed profile spacing s, and ΔV is the cross-sectional area of the axial profile at full sample resolution.

The predicted percent volume error given by Equation 4 is a function of both the resample spacing and the specific locations of the individual resampled points along the preliminary profiles. For a given resample spacing, the choice of resample point locations may happen to be aligned with changes in bathymetry in such a way that the resulting error is small. In other cases, the resampled point positions may happen to fall in such a way that the resulting error is large. To account for the variability in the volume error for a given resample spacing, the starting point of the resample sequence is shifted in small increments over a distance of one resample interval and the mean and the 95% confidence interval is computed. This gives a range of possible error associated with a given resample interval. To estimate the error versus resample spacing, a sweep is made through a range of resample intervals, computing the mean and confidence interval of the expected error for each resample interval. If multiple axial profiles are collected, the estimated volume error associated with each profile would be weighted by the corresponding portion of the total reservoir volume associated with each tributary arm. In this way axial profiles along each arm of a complexly shaped reservoir could be included in the overall volume error estimate.

Results

Acoustic Profiling Results

Before beginning the project, BU and TWDB selected six primary and six backup core locations along profiles previously surveyed by TWDB. BU repeated seven of the twelve candidate profiles and collected an axial profile over the length of the main body of Lake LBJ from July 9 to August 1, 2007 (Figure 2). A list of core locations and associated acoustic profiles is given in Table 1. Figures 3 to 28 compare the repeat acoustic profiles collected by BU with the originals collected by TWDB and with the measured sediment thicknesses within the cores. BU Profile 07071011 (Figures 3, 4 and 5) was collected along TWDB profile 07050435 (Figure 6), with all five frequencies of the experimental profiling system activated. BU Profile 07071011 indicates that 125 kHz signal in the experimental system provides essentially the same image of the water bottom as the 200 kHz signal. Hence, the addition of the 125 kHz signal is not expected to be advantageous to reservoir surveying for water volume. However, the 12 kHz signal penetrates more deeply into the bottom than the 24 kHz (Figure 4) and indicates that at some spots along Profile 07071011 the base of sediment is deeper than the maximum penetration of the 24 kHz signal (Figure 5). To match horizontal resolution between BU's experimental system and TWDB's standards system, most of the remaining repeat profiles were collected with the 125 and 12 kHz transducers turned off. The 200 kHz records from both instruments imaged the water bottom clearly, but did not penetrate significantly into the post-impoundment fill. Hence, except for the results on the profiles through Core Site 1, the 200 kHz results are not shown.

Taken as a whole, the comparisons between the repeat (BU) and original (TWDB) profiles indicate that, in most areas of the reservoir, the same survey results would have been achieved with either profiler. Once the acoustic character of the base of sediment is established with co-located sediment cores and acoustic profiles, the sediment thickness can be measured acoustically to an accuracy of a few inches, depending on acoustic contrast between the pre-impoundment surface and the thickness of the sediment. Where there is little acoustic contrast between the pre-impoundment surface and the post-impoundment sediment, the contact appears gradational on the acoustic records and the base of sediment is more difficult to pinpoint. This is also true for sediment thicknesses near the limit of penetration of the lowest frequency signal available. The gradational response of the base of sediment results in uncertainty in the sediment thickness measurement. The potential error in sediment thickness measurement was estimated by comparing the uncertainty in the base of sediment with the total sediment thickness. Overall, it is possible to make point measurements of sediment thickness from the acoustic record to well within 10% of the actual sediment thickness observed in the cores (Figures 5, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, and 28).

There were also differences in the image quality of profiles produced by the two acoustic profiling systems. The higher spatial sample rate of the standard SDI profiler (TWDB) is evident throughout. This results in clearer and more easily interpreted profiles. For surveys of large reservoirs, which require maximum survey vessels speed for efficient data acquisition, the high spatial sample rate of the standard SDI profiler is a significant advantage. In areas of the reservoir in which the post-impoundment sediment is 8 ft thick or less, the base of post-impoundment sediment corresponds to the base of strong returns of the 50 or 24 kHz signals. This is true for both systems, although there are differences in which signal frequency correlates best with the base of sediment in different locations. This is likely due to differences in power and signal gain settings between the two systems. In areas in which the sediment thickness exceeds 8 ft, the 50 and 24 kHz signals did not penetrate to the base of sediment. In these cases a lower frequency signal, such as the 12 kHz signal of the experimental system, is required to map the base of sediment. Evidence from BU Profile 07071011, through Core Site 1, indicates that the 12 kHz signal can penetrate up to 12 ft of sediment.

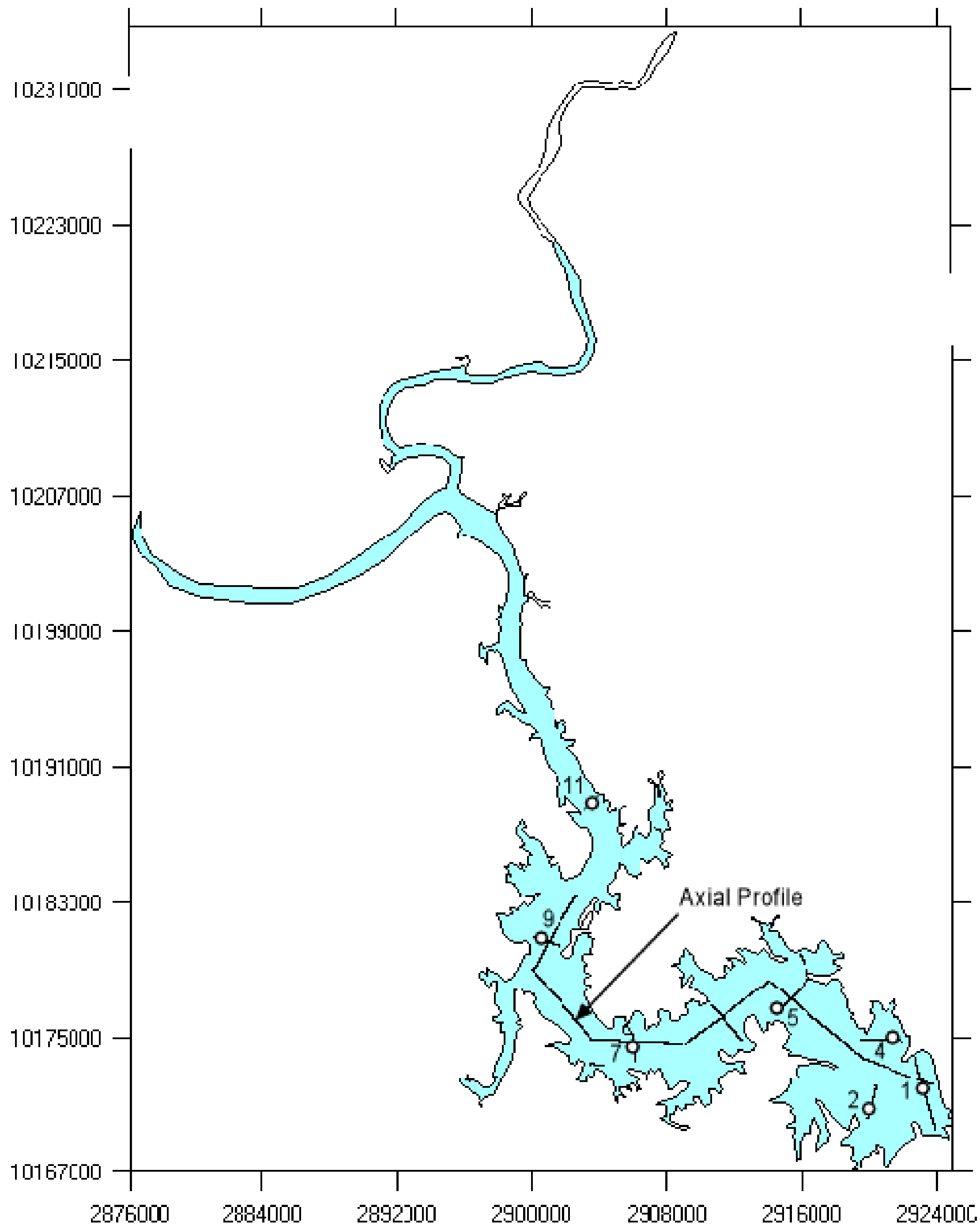
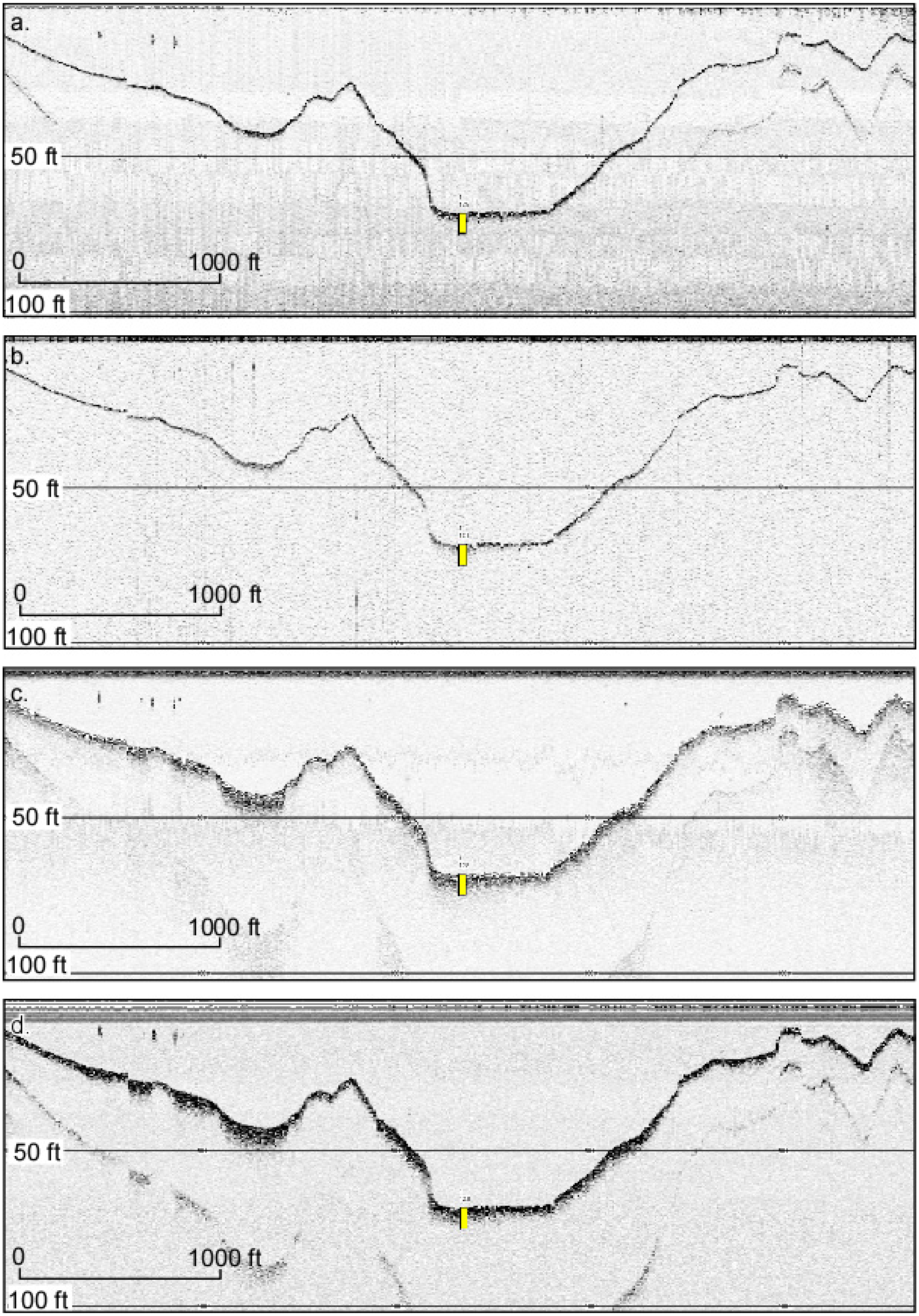


Figure 2. Location map of acoustic profiles and cores collected by BU on Lake LBJ. Core locations are marked with circles. The cores were collected from July 9 to 11, 2007. Repeat acoustic profiles through the core locations and along the axial of the reservoir were collected from July 9 through August 1, 2007. Geographic coordinates are Texas State Plane, Central Zone, feet.

Table 1. Core locations and repeat profiles collected by BU verses TWDB profiles. Easting and Nothings are in Texas State Plane, Central Zone, feet.

Core Site Number	Easting (ft)	Northing (ft)	BU Profile	Distance from BU Profile (ft)	TWDB Profile	Distance from TWDB Profile (ft)
1	2923288.8	10171917.1	07071011	12.8	07050435	5.1
2	2920085.6	10170724.9	07080102	31.9	-	-
4	2921460.5	10174947.1	07080103	10.2	07051403	15.4
5	2914655.6	10176758.0	07080105	3.2	07050720	1.9
7	2906050.9	10174402.7	07080107	28.1	07050815	10.1
9	2900609.0	10180854.0	07080109	4.2	07050840	6.0
11	2903640.0	10188777.0	07071021	2.1	07050915	9.3


a.
50 ft
0
1000 ft
100 ft
b.
50 ft
0
1000 ft
100 ft
c.
50 ft
0
1000 ft
100 ft
d.
50 ft
0
1000 ft
100 ft

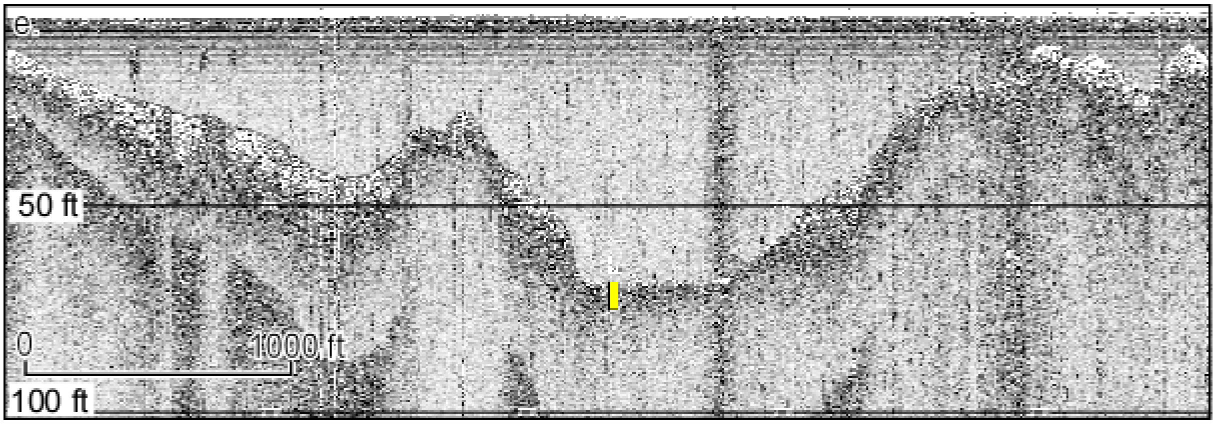
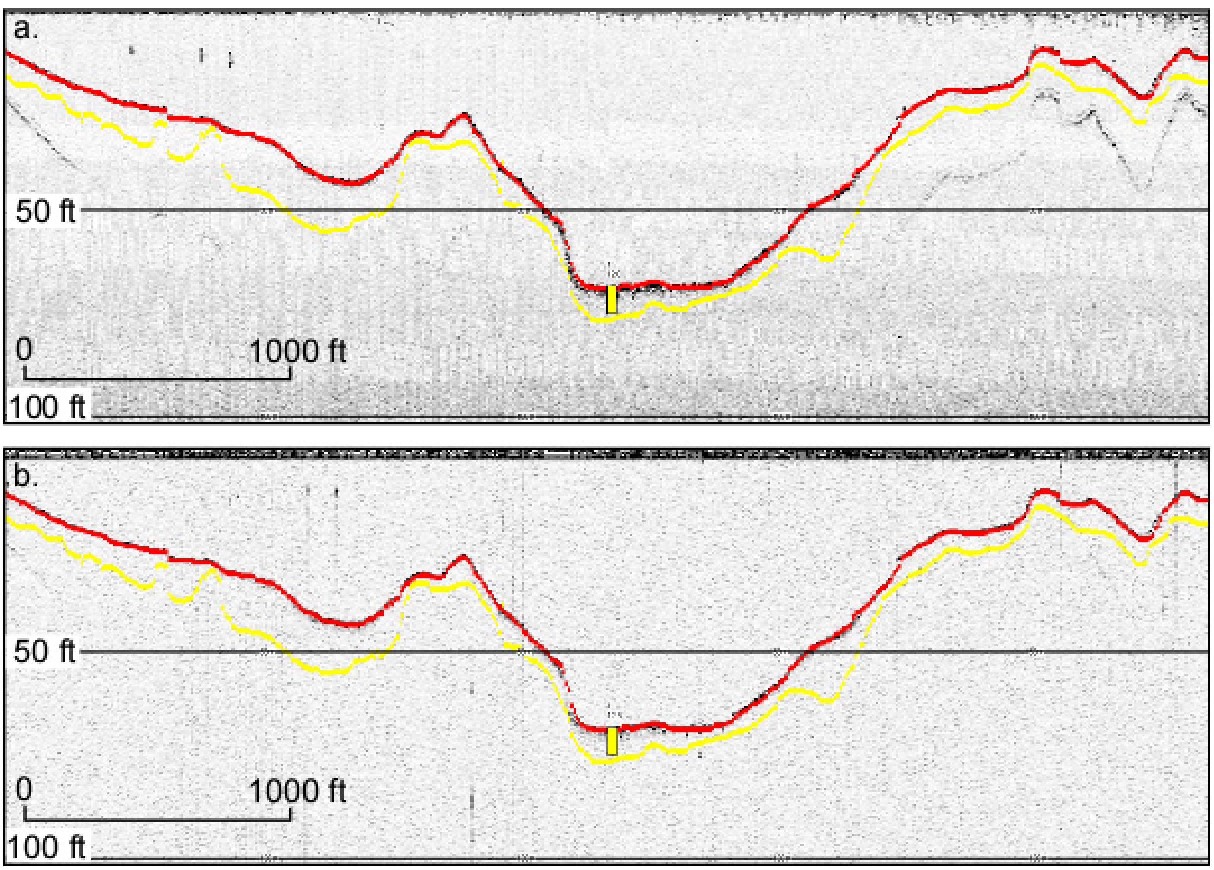


Figure 3. BU acoustic Profile 07071011 with five frequencies active. (a) 200 kHz. (b) 125 kHz. (c) 50 kHz. (d) 24 kHz. (e) 12 kHz. The yellow bar indicates the length of Core 1. This profile is a repeat of TWDB profile 07050435, shown in Figure 6.



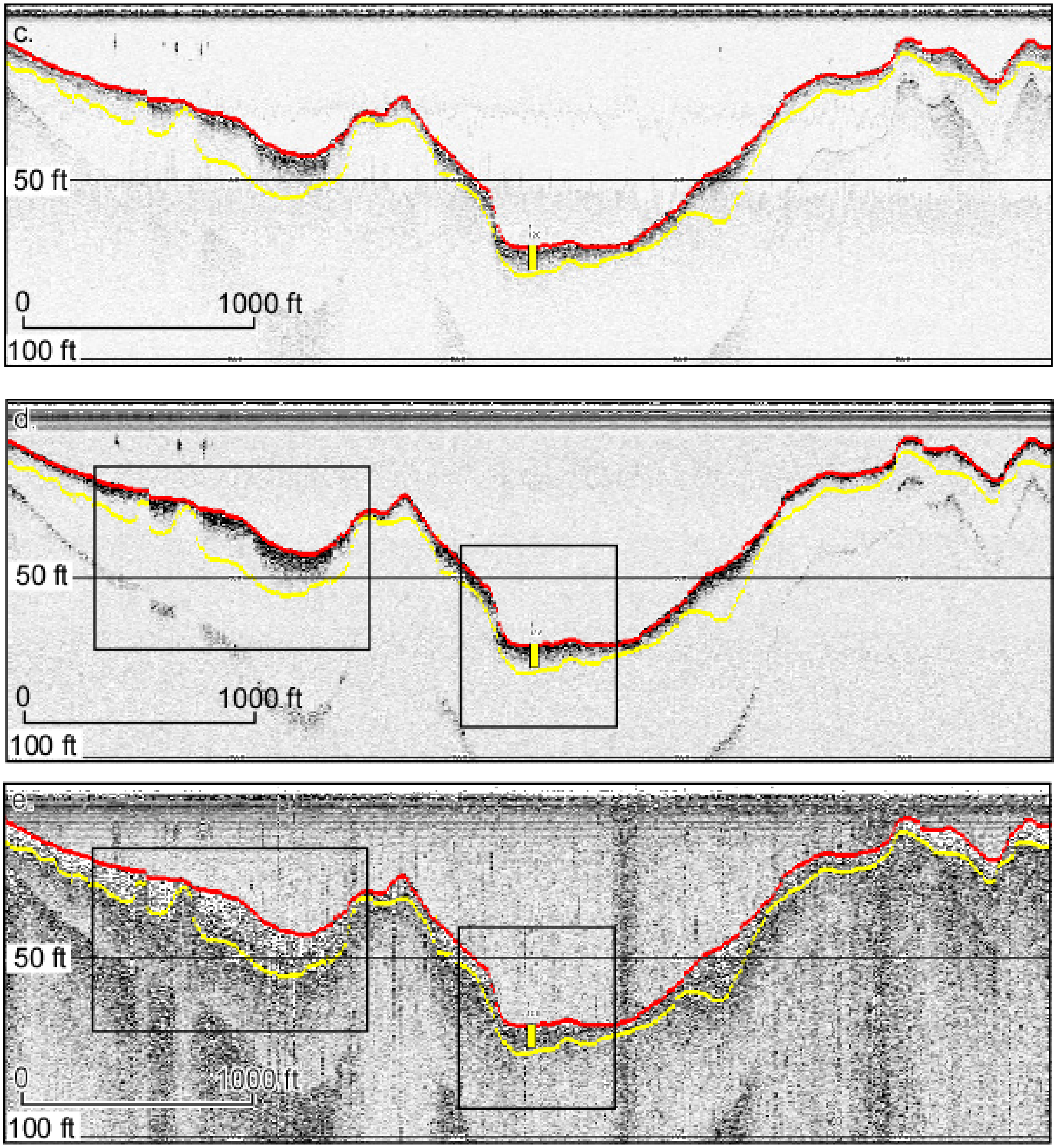


Figure 4. BU acoustic Profile 07071011 with water bottom and base of sediment. (a) 200 kHz. (b) 125 kHz. (c) 50 kHz. (d) 24 kHz. (e) 12 kHz. The yellow bar indicates the length of Core 1, which is 6.9 ft (2.1 m). The red curve indicates the water bottom. The yellow curve indicates the interpreted base of sediment. Rectangles indicate expanded views shown in Figure 5.

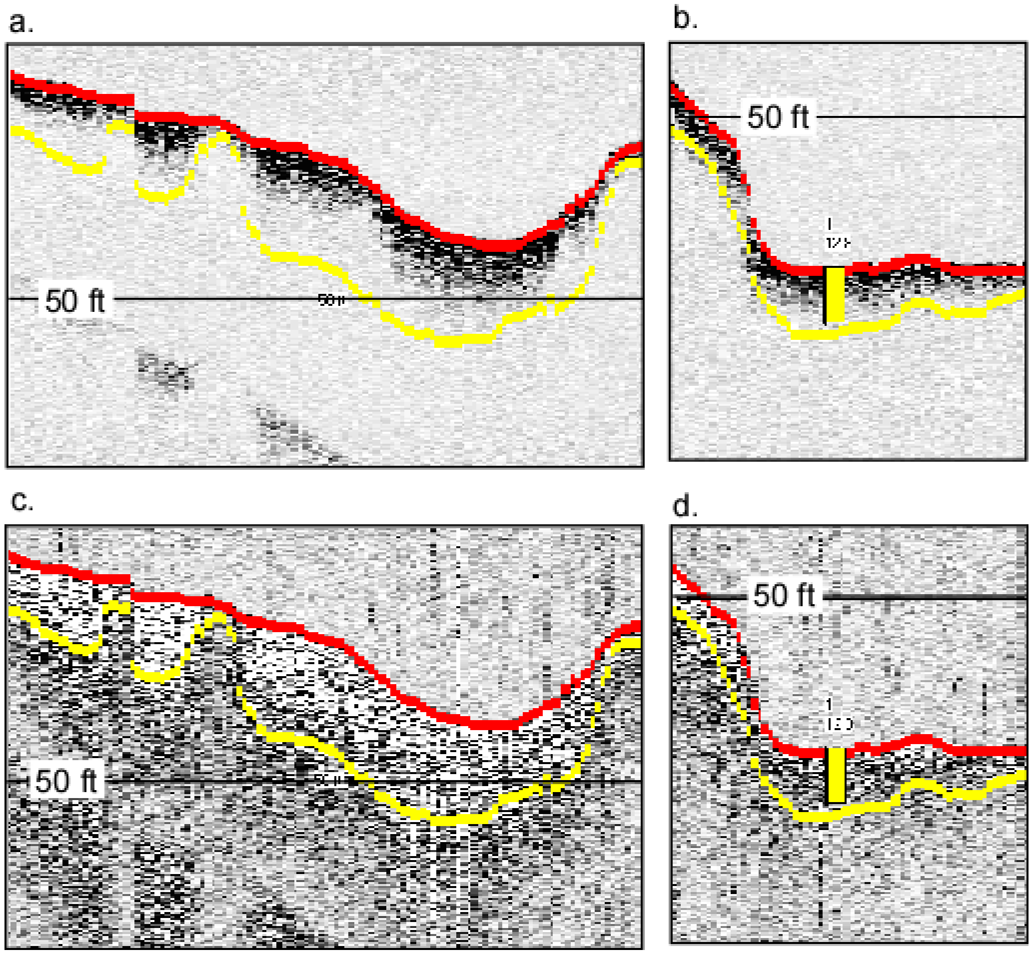


Figure 5. Expanded views of BU Profile 07071011. (a) Expanded view of left rectangular area in Figure 4 for the 24 kHz signal. (b) Expanded view near Core 1 for the 24 kHz signal. (c) Expanded view of left rectangular area in Figure 4 for the 12 kHz signal. The maximum sediment thickness in this section is determined acoustically to be 12.1 ft (3.8 m), within this expanded view. (d) Expanded view near Core 1 for the 12 kHz signal in Figure 4. The apparent sediment thickness at the core site determined acoustically is 7.9 ft (2.4 m). The thickness of pre-impoundment sediment in Core 1 is 6.9 ft (2.1 m). Core 1 did not sample pre-impoundment surface.

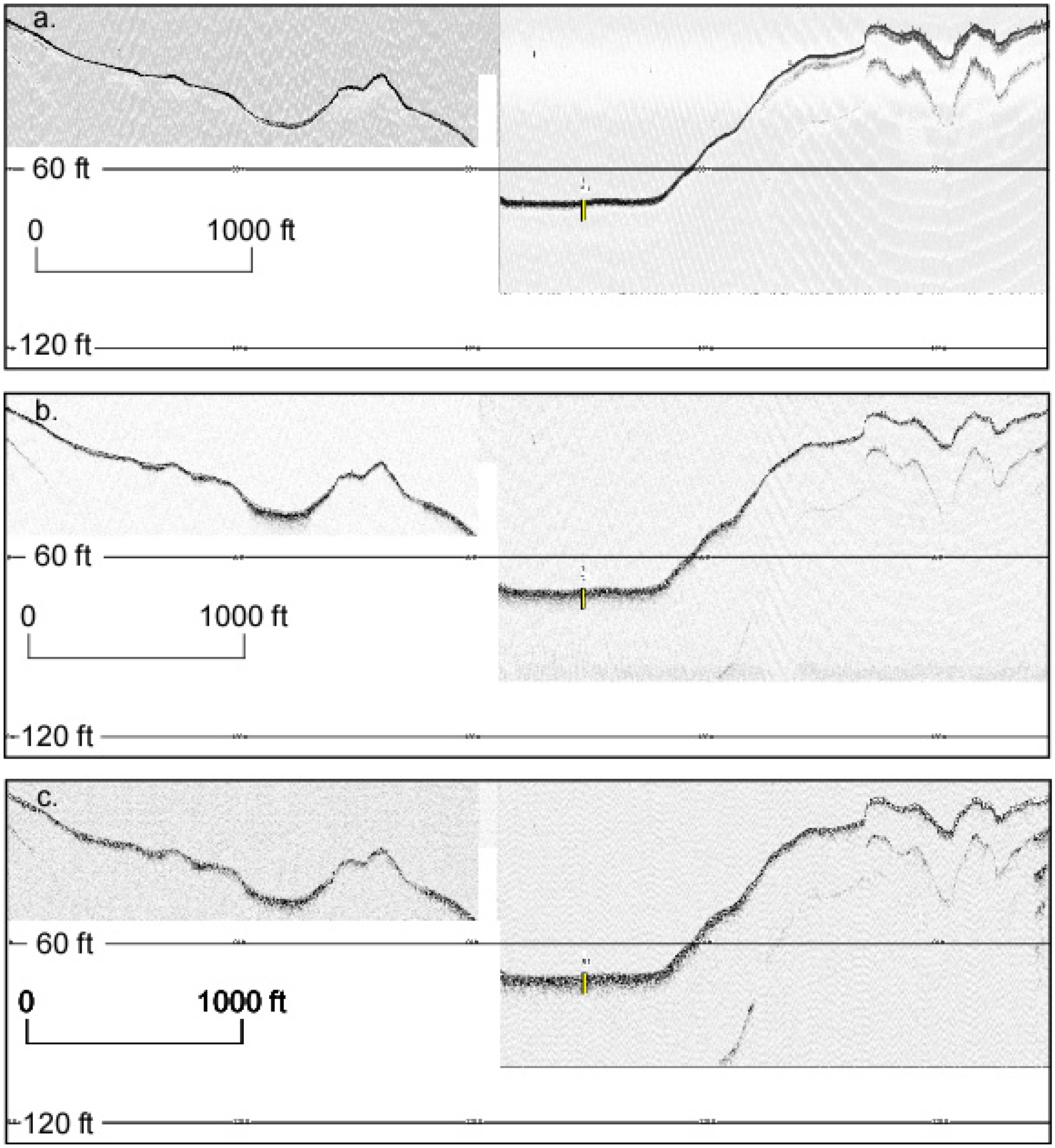


Figure 6. TWDB profile 07050435 through Core Site 1. (a) 200 kHz. (b) 50 kHz. (c) 25 kHz. The yellow bar indicates the length of Core 1, which is 6.9 ft (2.1 m).

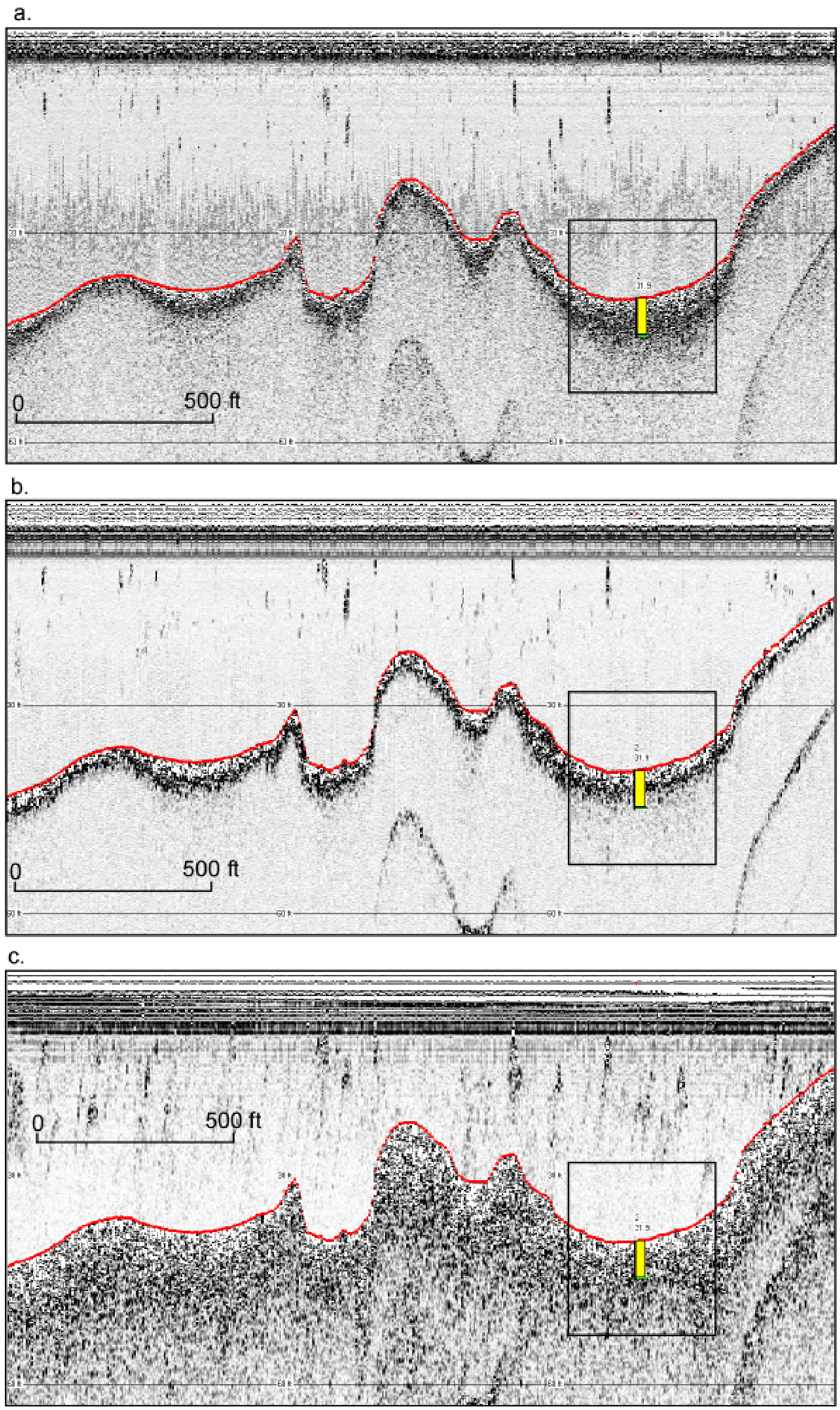


Figure 7. BU Profile 07080102 through Core 2. (a) 50 kHz. (b) 24 kHz. (c) 12 kHz. The yellow bar indicates the location of Core 2, which is 5.3 ft (1.61 m) long. The green segment at its base indicates the pre-impoundment surface. An expanded view of the area within the box is shown in Figure 8.

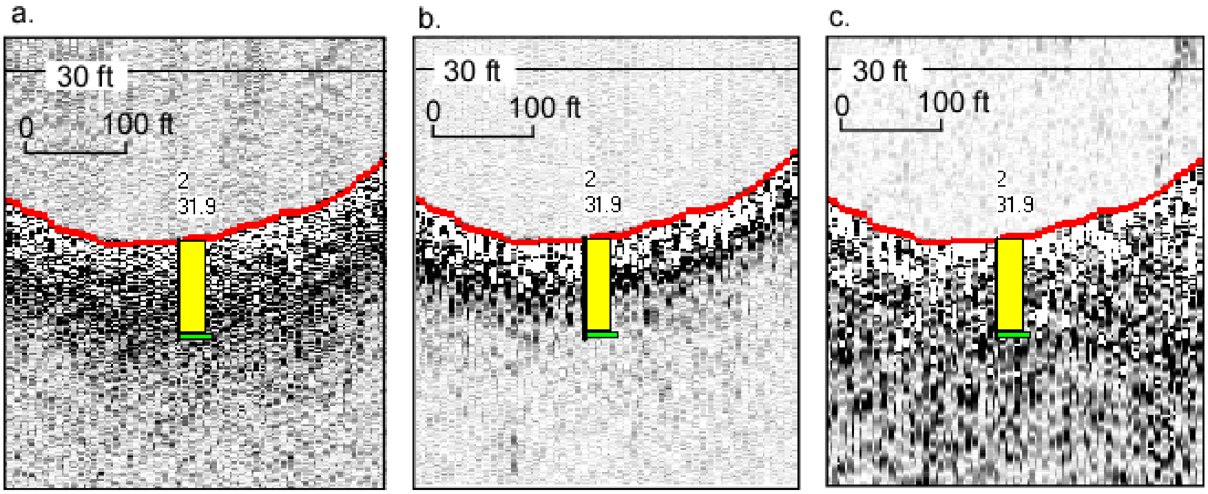


Figure 8. Expanded views of BU Profile 07080102 near Core 2. (a) 50 kHz. (b) 24 (kHz). (c) 12 kHz. Core 2 is projected 31.9 ft to the point of closest approach of the profile. The post-impoundment sediment (yellow) is 5.3 ft thick (1.61 m).

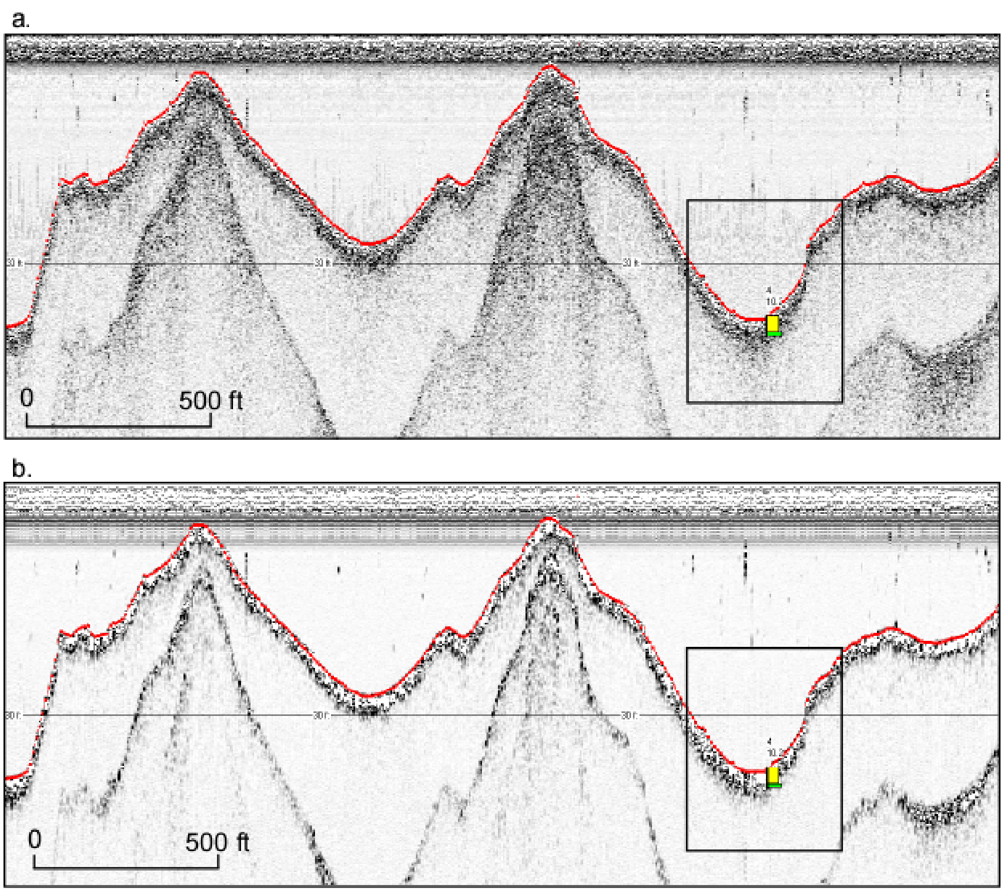


Figure 9. BU Profile 07080103 through Core Site 4. (a) 50 kHz. (b) 24 kHz. The core location was projected 10.2 ft to the point of closest approach to the profile. The yellow bar indicates the location and thickness of post-impoundment sediment found in Core 4, which is 2.1 ft (0.63 m). The green segment indicates the pre-impoundment surface. The boxes surrounding the core location indicate areas shown in expanded views in Figure 10.

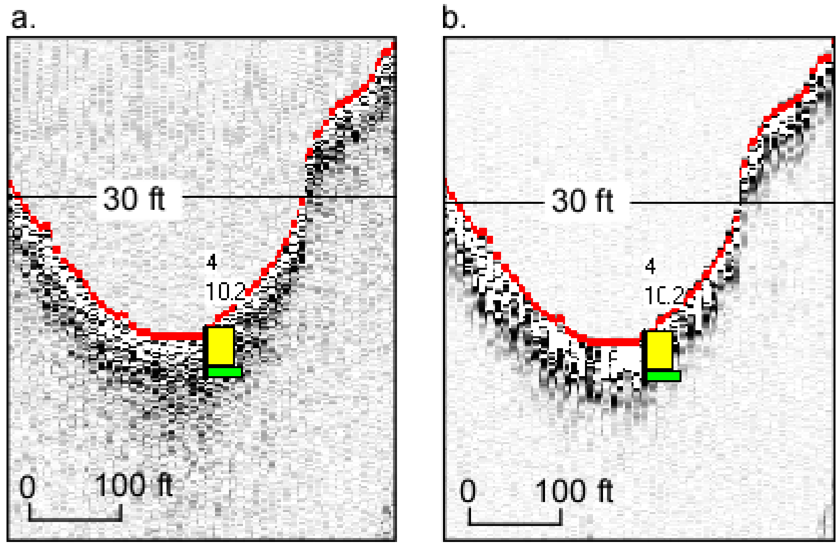


Figure 10. Expanded views of BU Profile 07080103 near Core Site 4. (a) 50 kHz. (b) 24 kHz. The areas of the expanded views are indicated by boxes in Figure 9. The base of the 24 kHz signal coincides with the base of sediment. There was 2.1 ft (0.61 m) of post-impoundment sediment (yellow) found in Core 4.

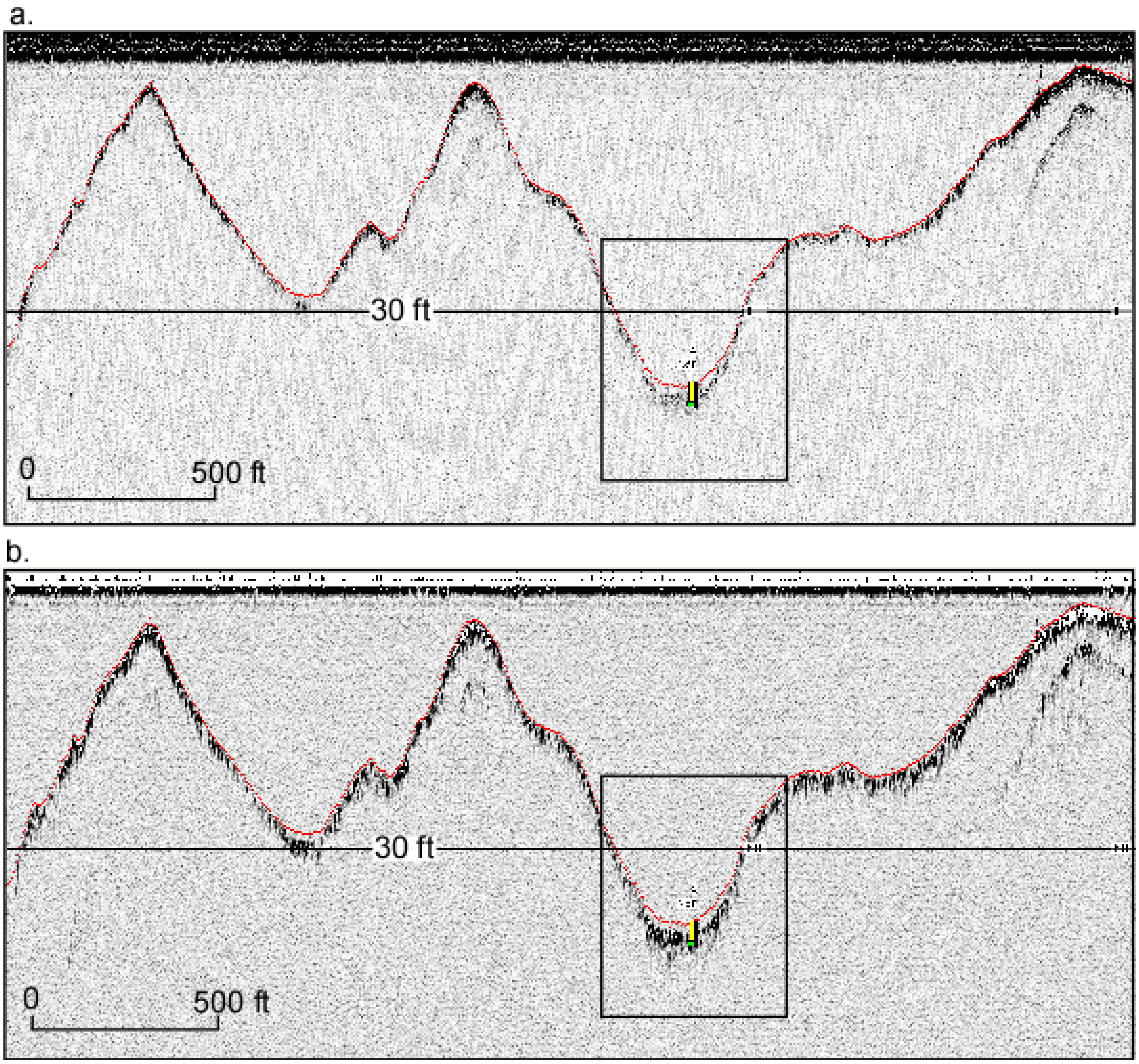


Figure 11. TWDB Profile 07051403 through Core Site 4. (a) 50 kHz). (b) 24 kHz. The core location was projected 15.4 ft to the point of closest approach to the profile. The yellow bar indicates the location and thickness of post-impoundment sediment (2.1 ft) found in Core 4. The green segment indicates the pre-impoundment surface. The boxes surrounding the core location indicate areas shown in expanded views in Figure 10. These images are reversed horizontally to agree with the acquisition direction for BU Profile 07080103, shown in Figure 9. The boxes indicate areas of expanded view shown in Figure 12.

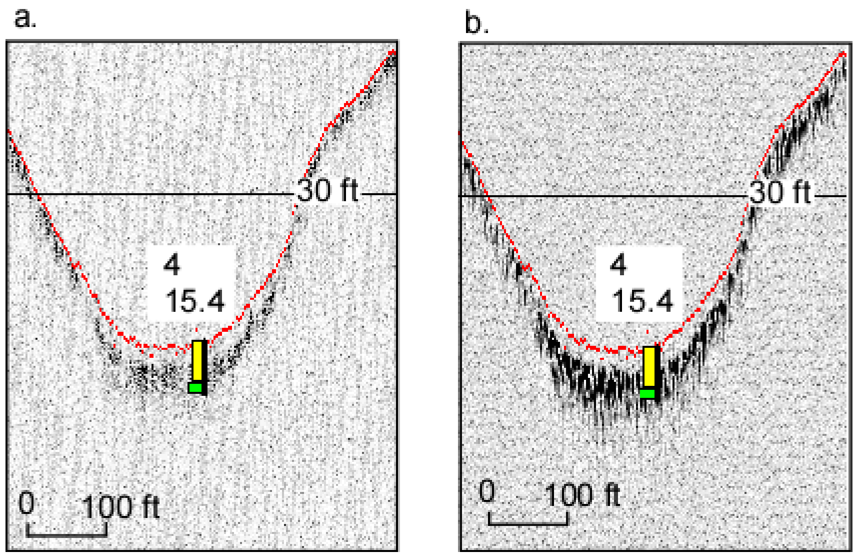


Figure 12. Expanded views of TWDB Profile 07051403 near Core Site 4. (a) 50 kHz). (b) 24 kHz. The areas of the expanded view are indicated with boxes in Figure 11. There was 2.1 ft (0.61 m) of post-impoundment sediment (yellow) found in Core 4.

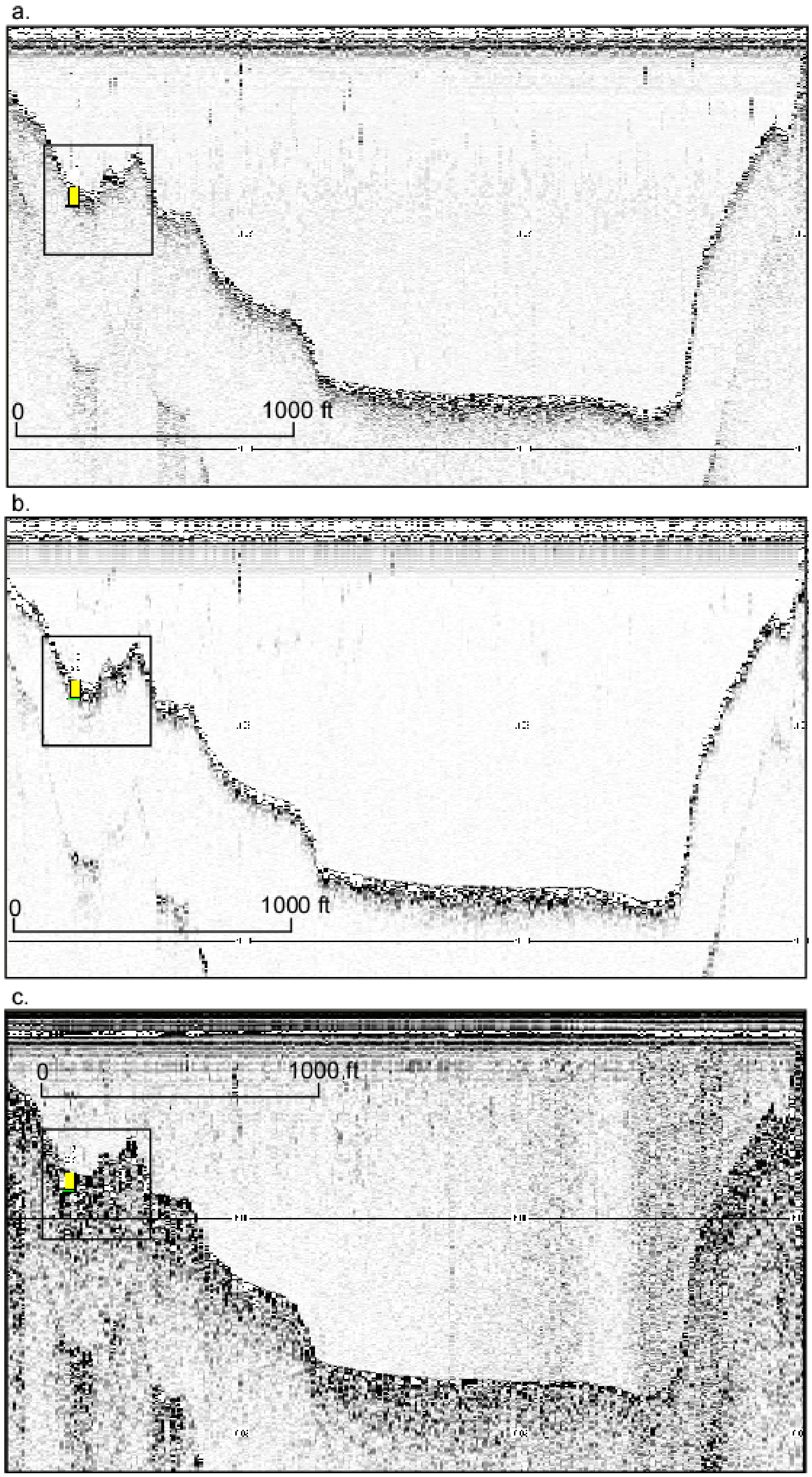


Figure 13. BU Profile 07080105 through Core 5. (a) 50 kHz. (b) 24 kHz. (c) 12 kHz. The yellow bar indicates the location of Core 5 and the thickness of post-impoundment sediment found in the core. The green segment at the base indicated the pre-impoundment. An expanded view of the region near the core in the box is shown in Figure 14.

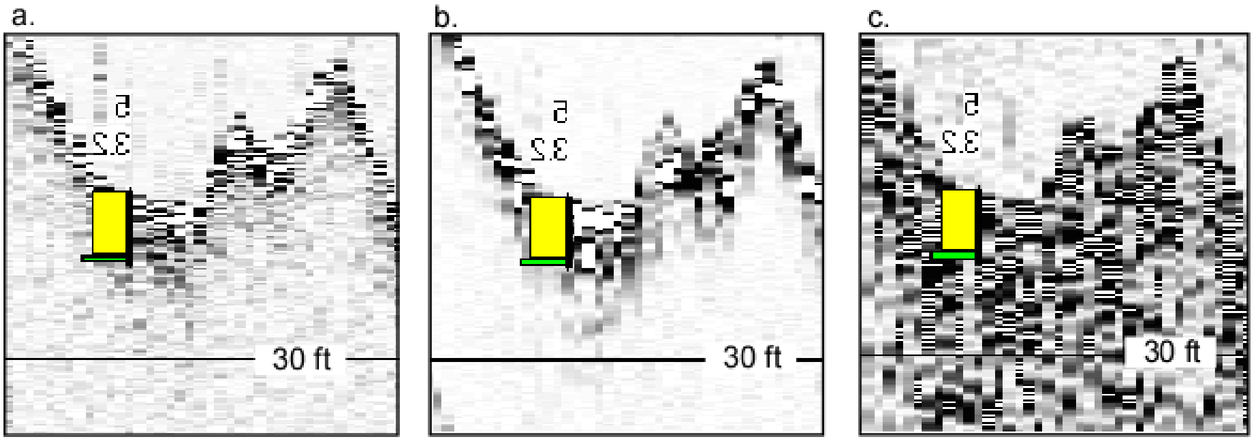
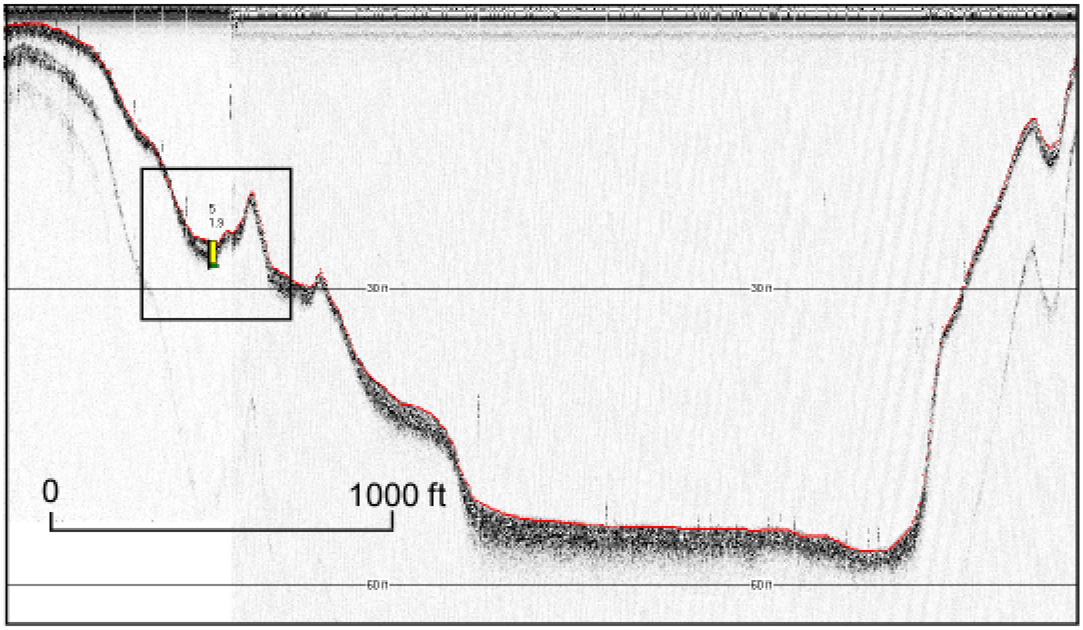


Figure 14. Expanded views of BU Profile 07080105 near Core 5. (a) 50 kHz. (b) 24 kHz. (c) 12 kHz. The images are versed horizontally to match the TWDB profile direction shown in Figure 15. There was 2.5 ft (0.75 m) of post-impoundment sediment (yellow) found in Core 5.

a.



b.

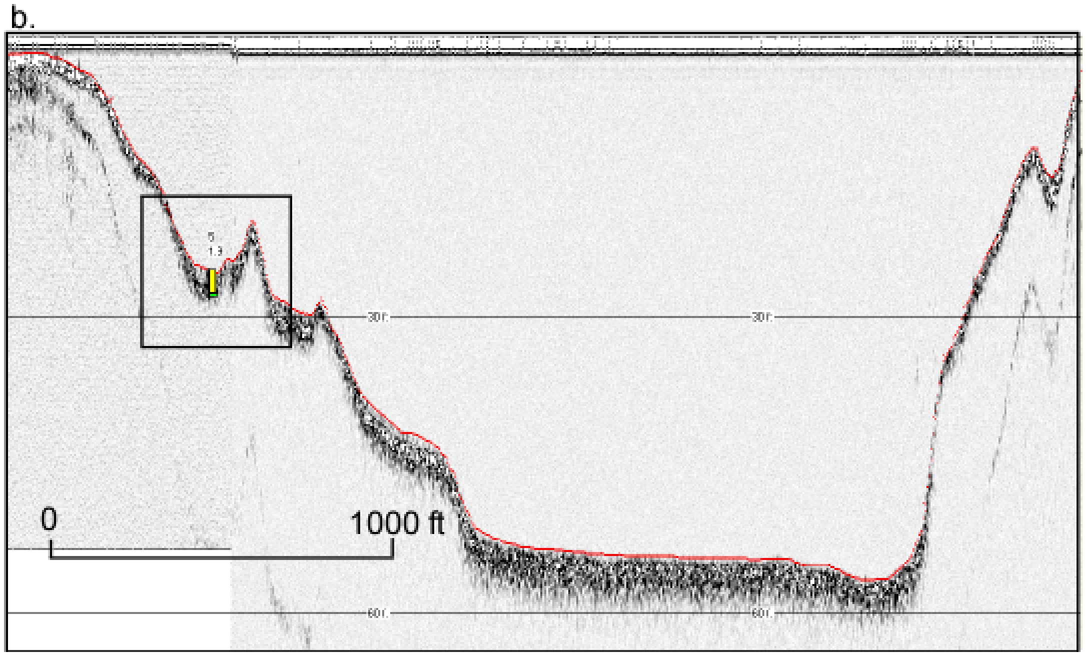


Figure 15. TWDB Profile 07050720 through Core 5. (a) 50 kHz. (b) 24 kHz. The yellow bar marks the location and length of post-impoundment sediment in the core. The green segment at its base indicates the pre-impoundment surface. The location of Core 5 was projected 1.9 ft to the point of closest approach of the profile. Expanded views of the region in the box near the core are shown in Figure 16.

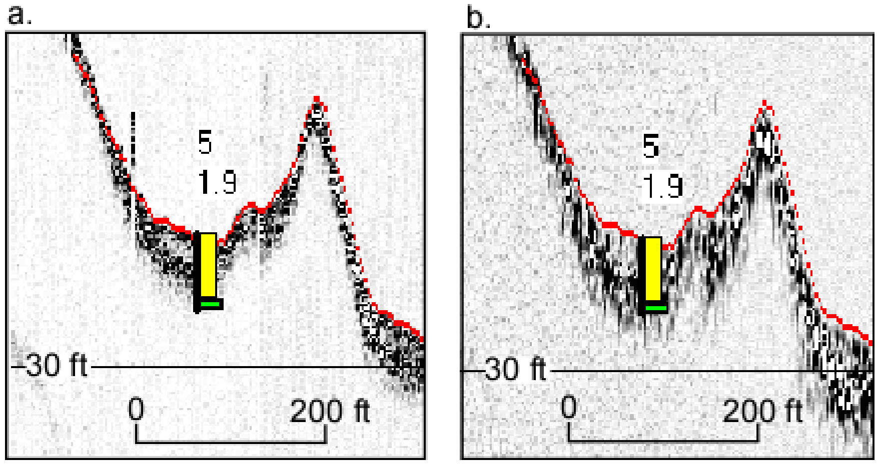
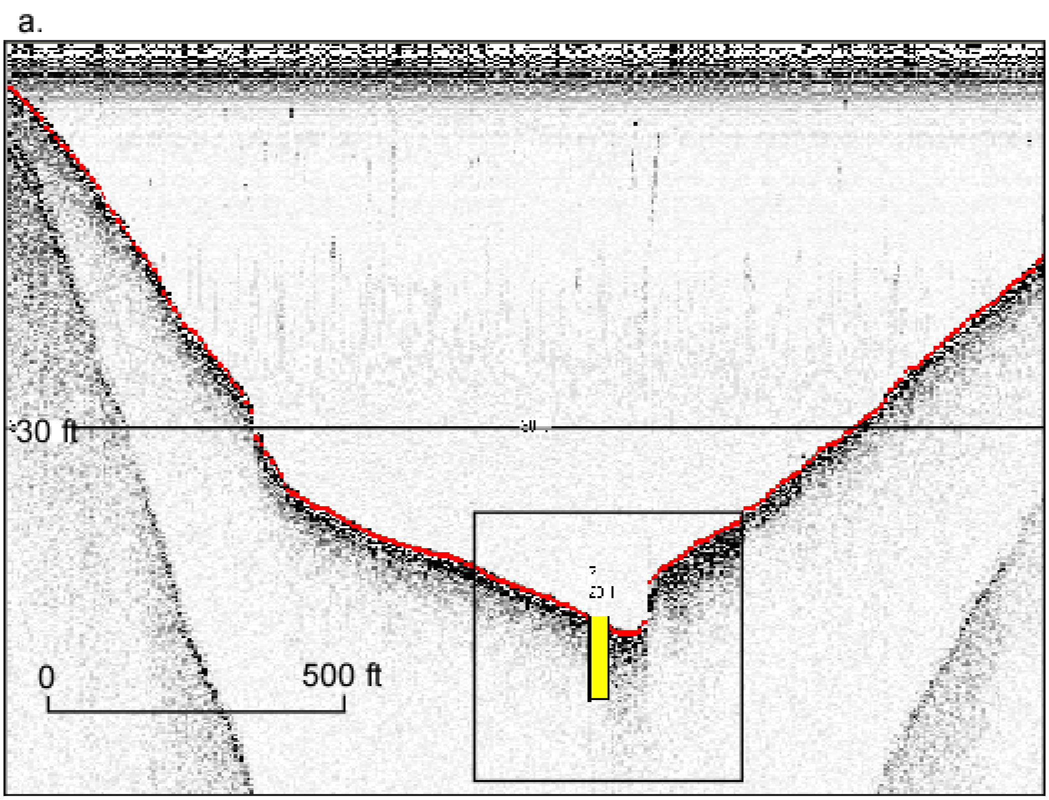


Figure 16. Expanded views of TWDB Profile 07050720 near Core 5. (a) 50 kHz. (b) 24 kHz. The yellow bar marks the location and length of post-impoundment sediment in the core. The green segment at its base indicates the pre-impoundment surface. The location of Core 5 was projected 1.9 ft to the point of closest approach of the profile. These are expanded views of the region near the core along the profile shown in Figure 15. There was 2.5 ft (0.75 m) of post-impoundment sediment (yellow) found in Core 5



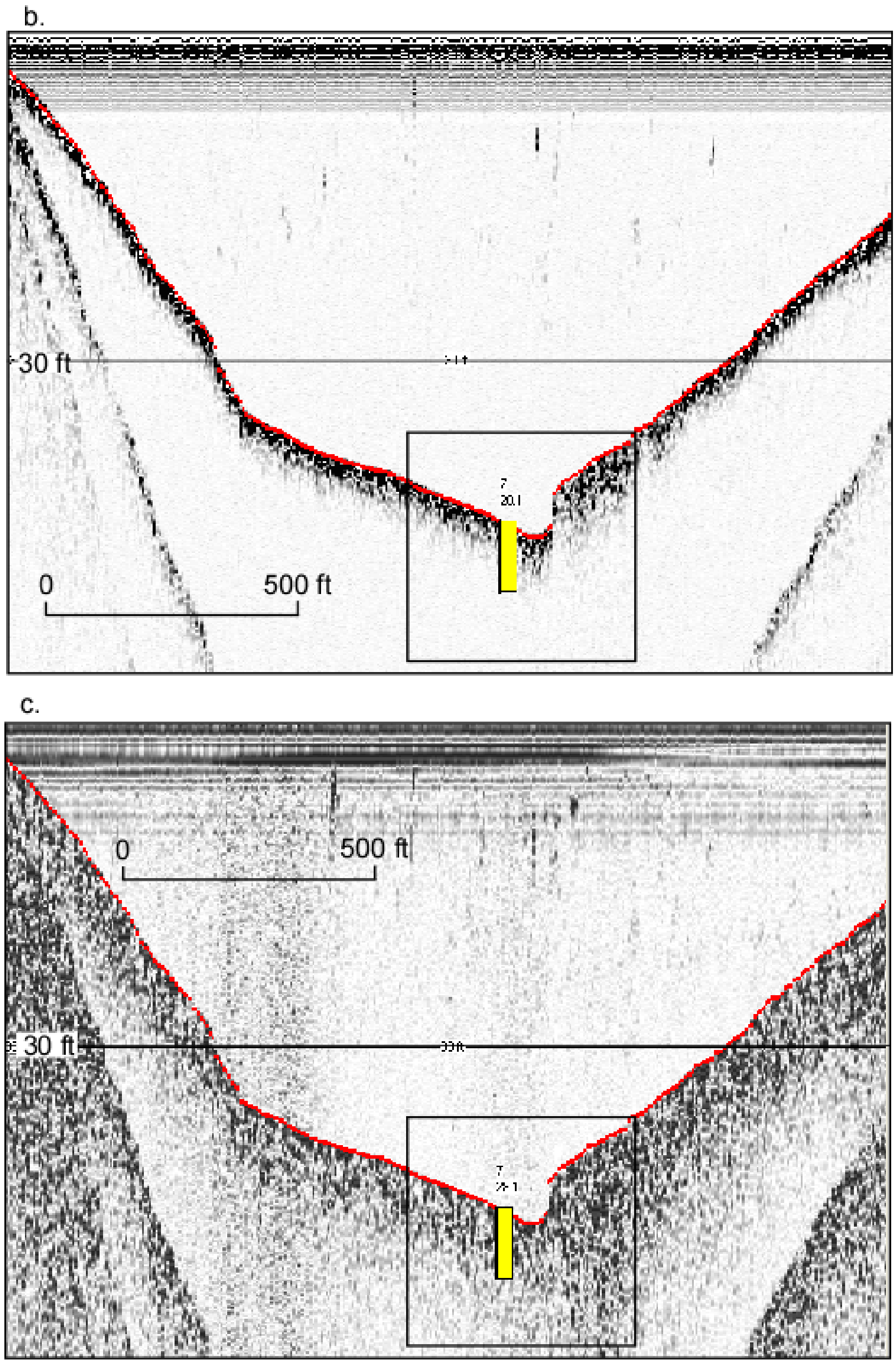


Figure 17. BU Profile 07080107 through Core Site 7. (a) 50 kHz. (b) 24 kHz. (c) 12 kHz. The yellow bar indicates the location and length (6.4 ft or 1.95 m) of Core 7. The location of Core 7 was projected 28.1 ft to the point of closest approach of the profile. Boxes indicate regions of expanded view shown in Figure 18.

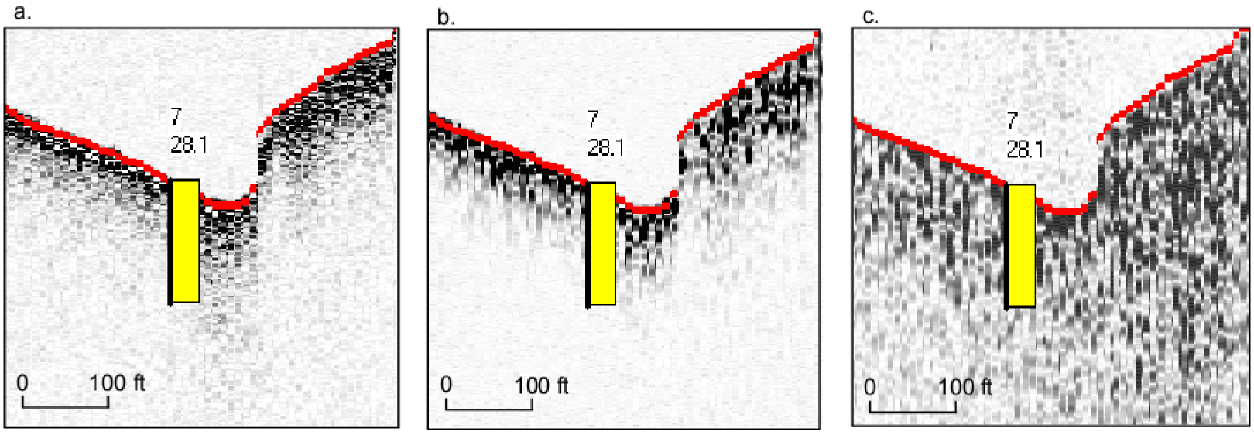


Figure 18. Expanded views of BU Profile 07080107 near Core Site 7. (a) 50 kHz. (b) 24 kHz. (c) 12 kHz. The yellow bar indicates the location and length (6.4 ft or 1.95 m) of Core 7. The location of Core 7 was projected 28.1 ft to the point of closest approach of the profile. The location of the expanded views are indicated by boxes in Figure 17.

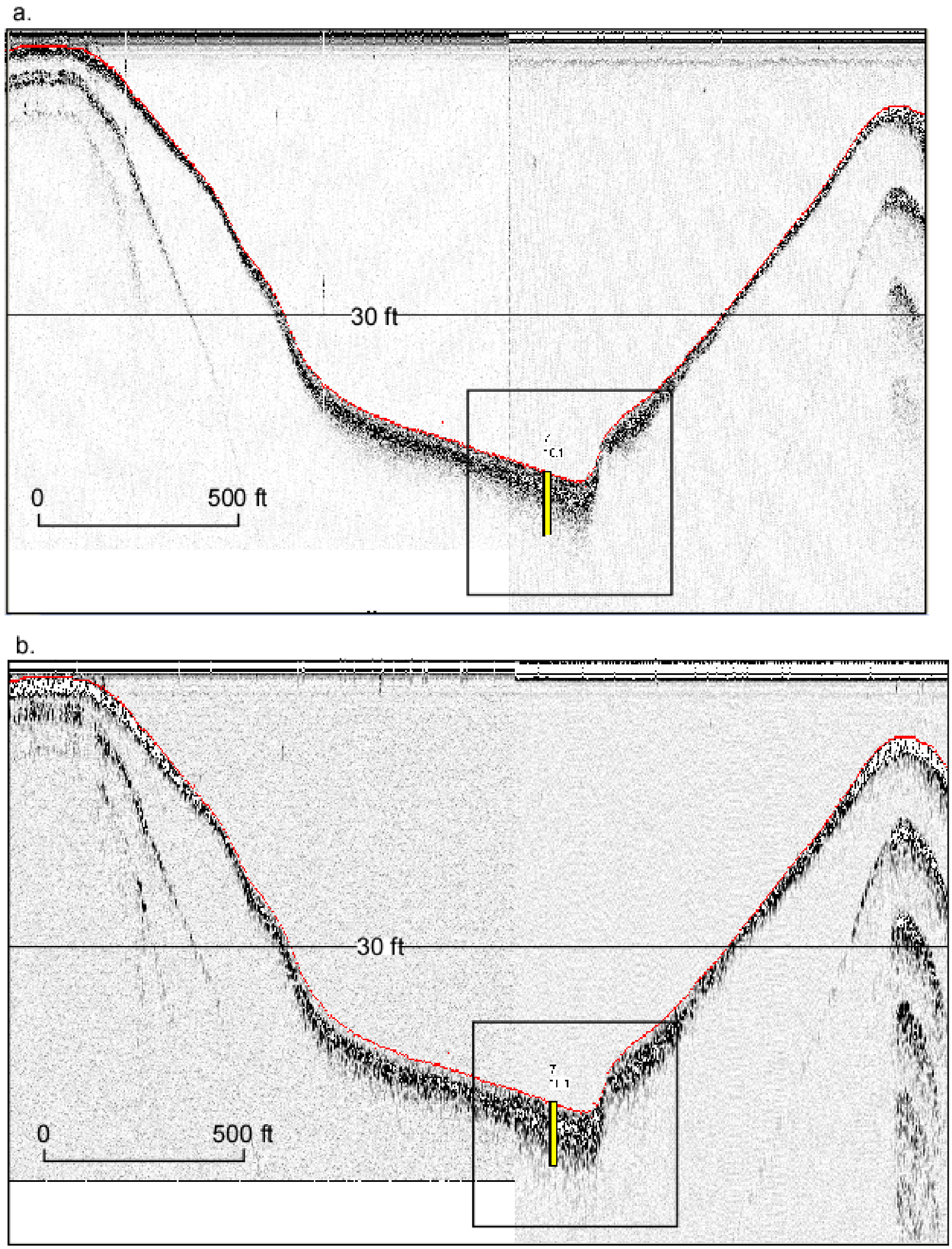


Figure 19. TWDB Profile 07050815 through Core Site 7. (a) 50 kHz. (b) 24 kHz. The yellow bar indicates the location and length (6.4 ft or 1.95 m) of Core 7. The location of Core 7 was projected 10.1 ft to the point of closest approach of the profile. Boxes indicate regions of expanded view shown in Figure 20.

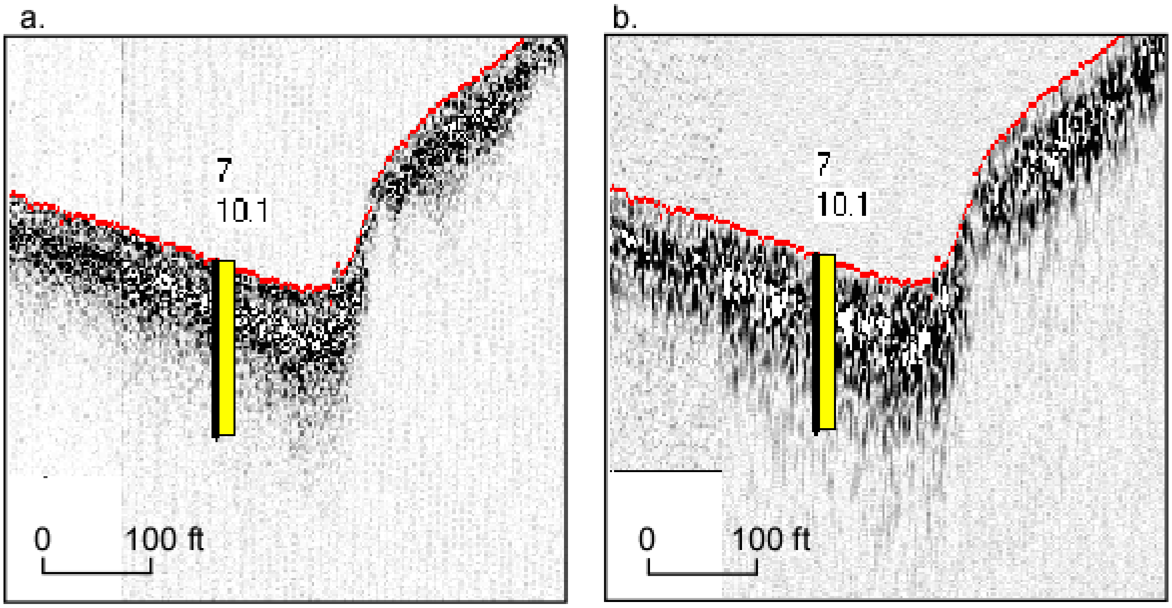


Figure 20. Expanded views of TWDB Profile 07050815 near Core Site 7. (a) 50 kHz. (b) 24 kHz. The areas shown are indicated by boxes in Figure 19. The location of Core 7 was projected 10.1 ft to the point of closest approach on the profile. The yellow bar indicates the location and length (6.4 ft or 1.95 m) of Core 7.

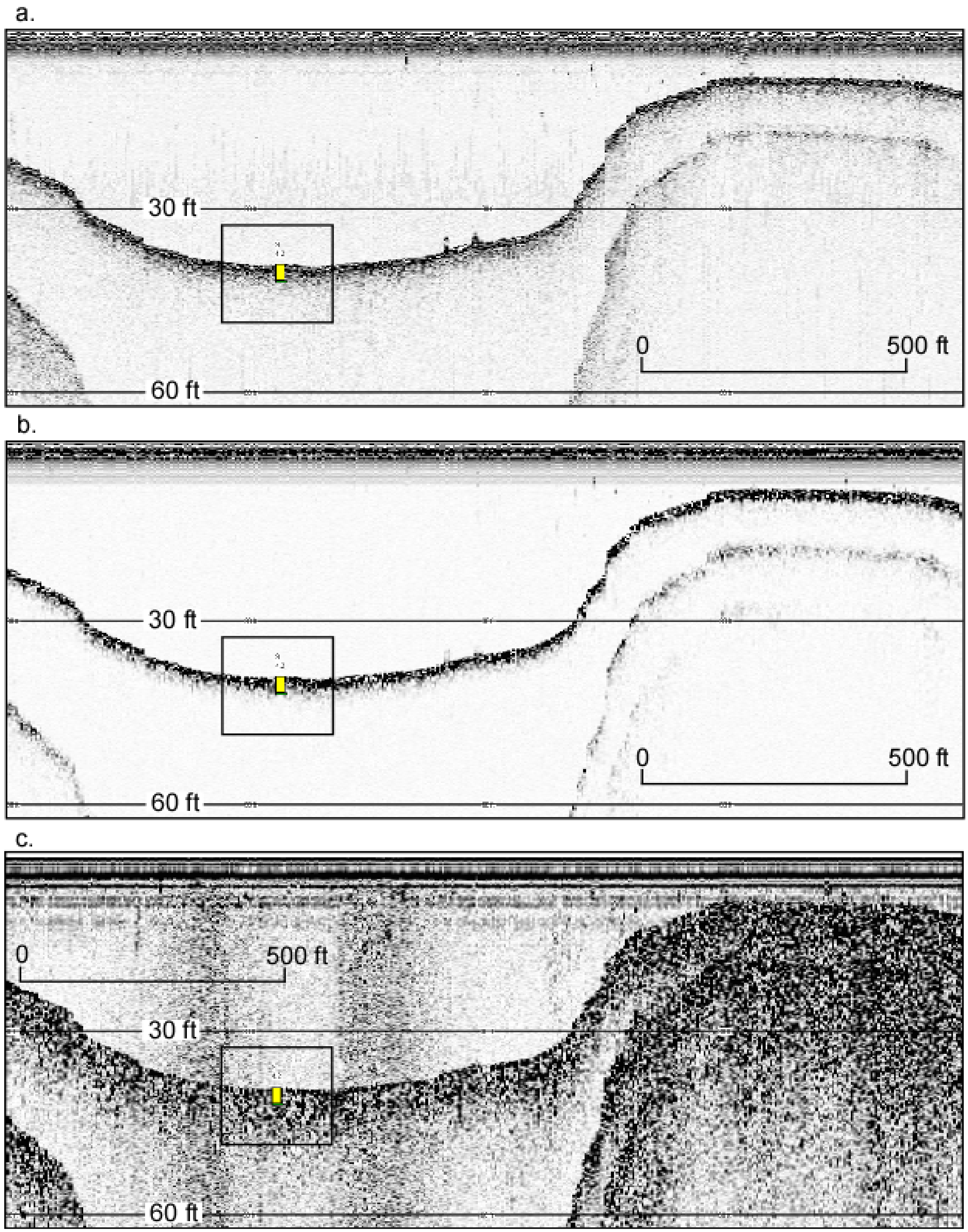


Figure 21. BU Profile 07080109 through Core Site 9. (a) 50 kHz. (b) 24 kHz. (c) 12 kHz. The yellow bar indicates the location and length (2.6 ft or 0.8 m) of Core 9. The location of Core 9 was project 4.2 ft to the point of closest approach of the profile. Expanded views near Core 9 for the area indicated by the boxes are shown in Figure 22.

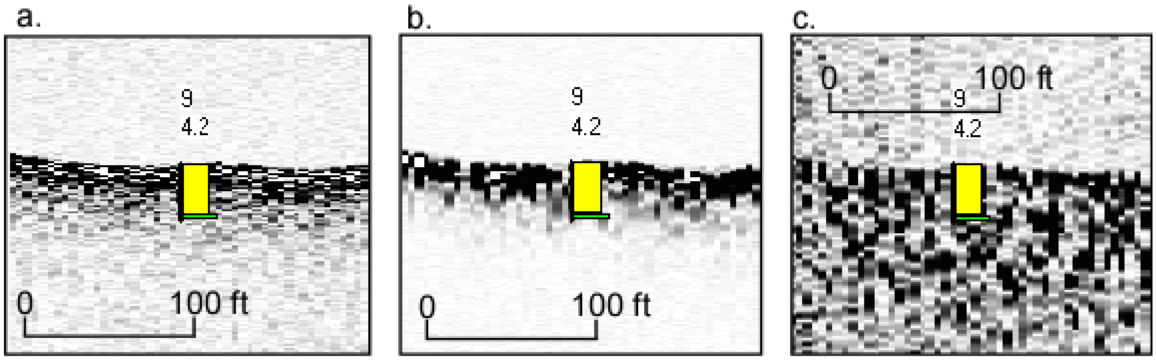


Figure 22. Expanded views of BU Profile 07080109 near Core Site 9. (a) 50 kHz. (b) 24 kHz. (c) 12 kHz. The yellow bar indicates the location and length (2.6 ft) of Core 9. The green segment indicates the pre-impoundment surface. The location of Core 9 was project 4.2 ft to the point of closest approach of the profile. There was 2.6 ft (0.8 m) of post-impoundment sediment found in Core 9. These are expanded views of from the profile shown in Figure 21. The base of sediment is most clearly indicated by the 24 kHz signal.

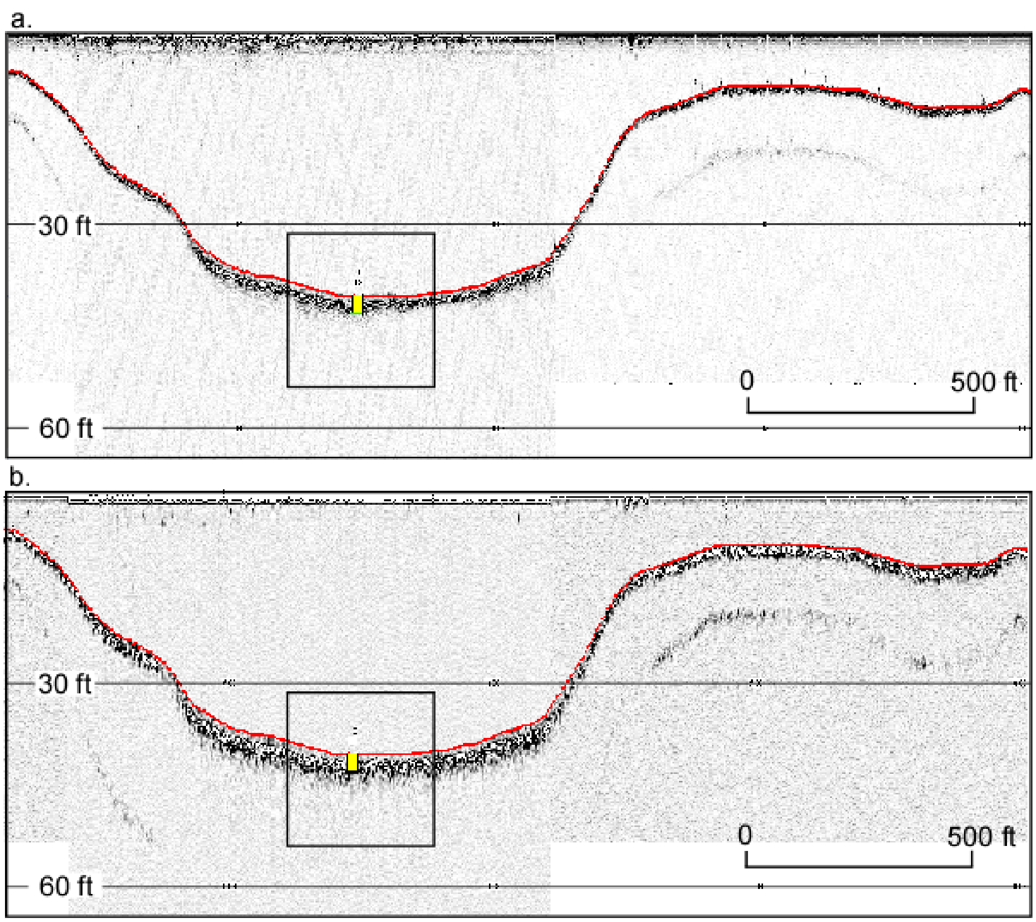


Figure 23. TWDB Profile 07050840 through Core Site 9. (a) 50 kHz. (b) 24 kHz. The images are reversed horizontally for compatibility with of collection direction of BU profile 07080109 shown in Figure 21. The yellow bar indicates the location and length (2.6 ft) of Core 9. The location of Core 9 was project 6.0 ft to the point of closest approach of the profile. Expanded views near Core 9 for the area indicated by the boxes are shown in Figure 24.

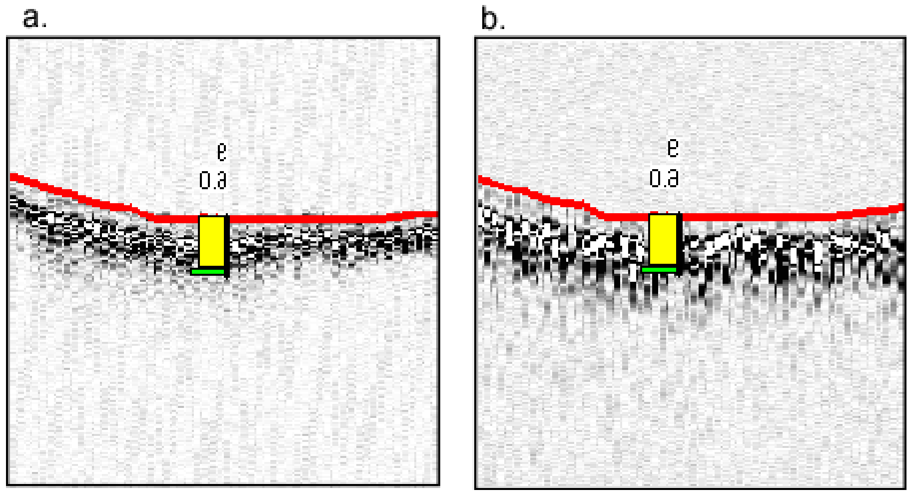


Figure 24. Expanded views of TWDB Profile 07050840 near Core Site 9. (a) 50 kHz. (b) 24 kHz. The yellow bar indicates the location and length (2.6 ft or 0.8 m) of Core 9. The green segment indicates the pre-impoundment surface. The location of Core 9 was project 6.0 ft to the point of closest approach of the profile. These are expanded views of from the profile shown in Figure 23. The base of sediment is most clearly indicated by the 50 kHz signal.

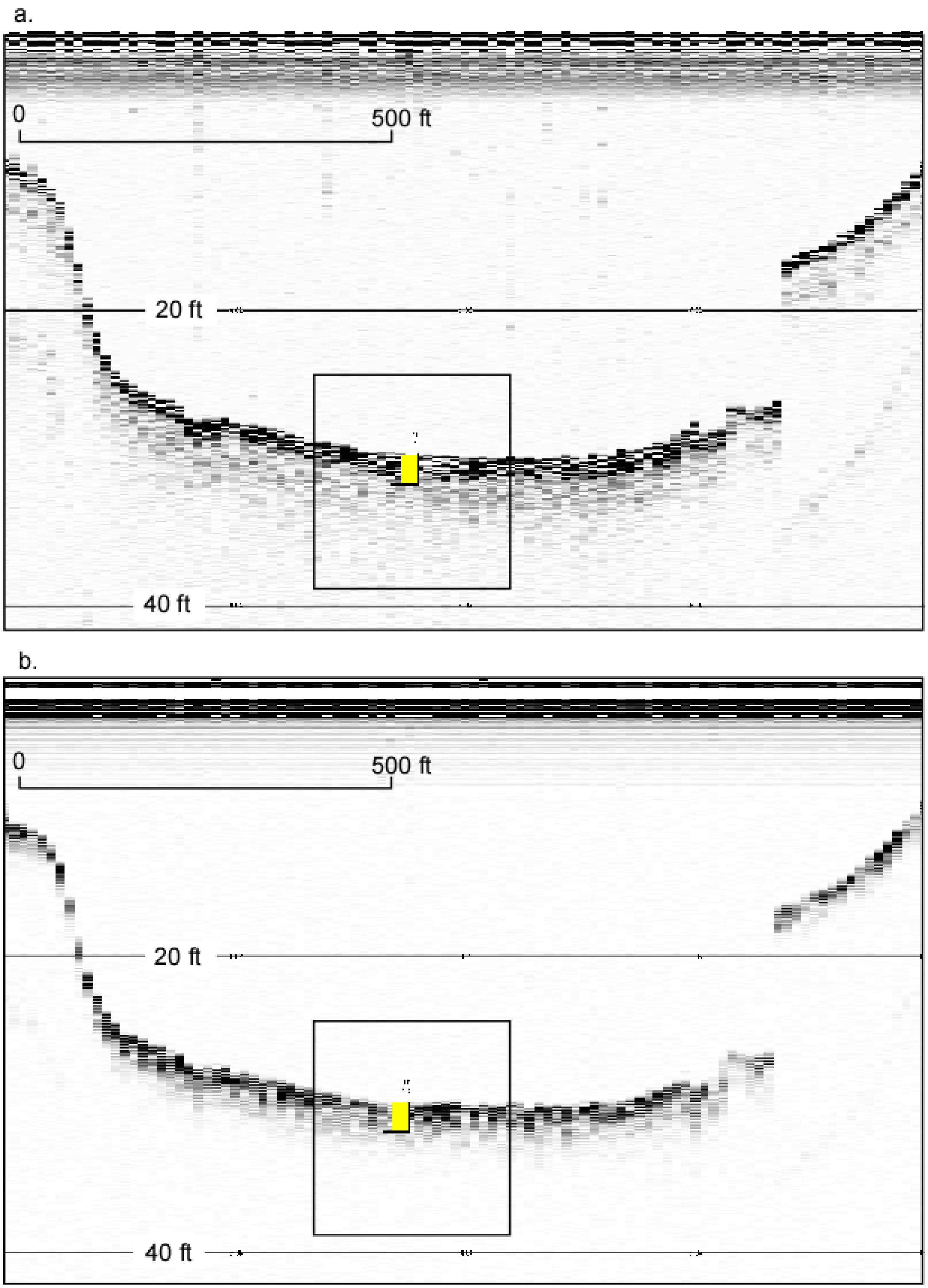


Figure 25. BU Profile 07071021 through Core Site 11. (a) 50 kHz. (b) 24 kHz. The yellow bar indicates the position and thickness of post-impoundment sediment found in the core (2 ft or 0.61 m). The position of Core 11 was projected 2.1 ft to the point of closest approach of the profile. The region near the core enclosed in the box is shown in expanded view in Figure 26.

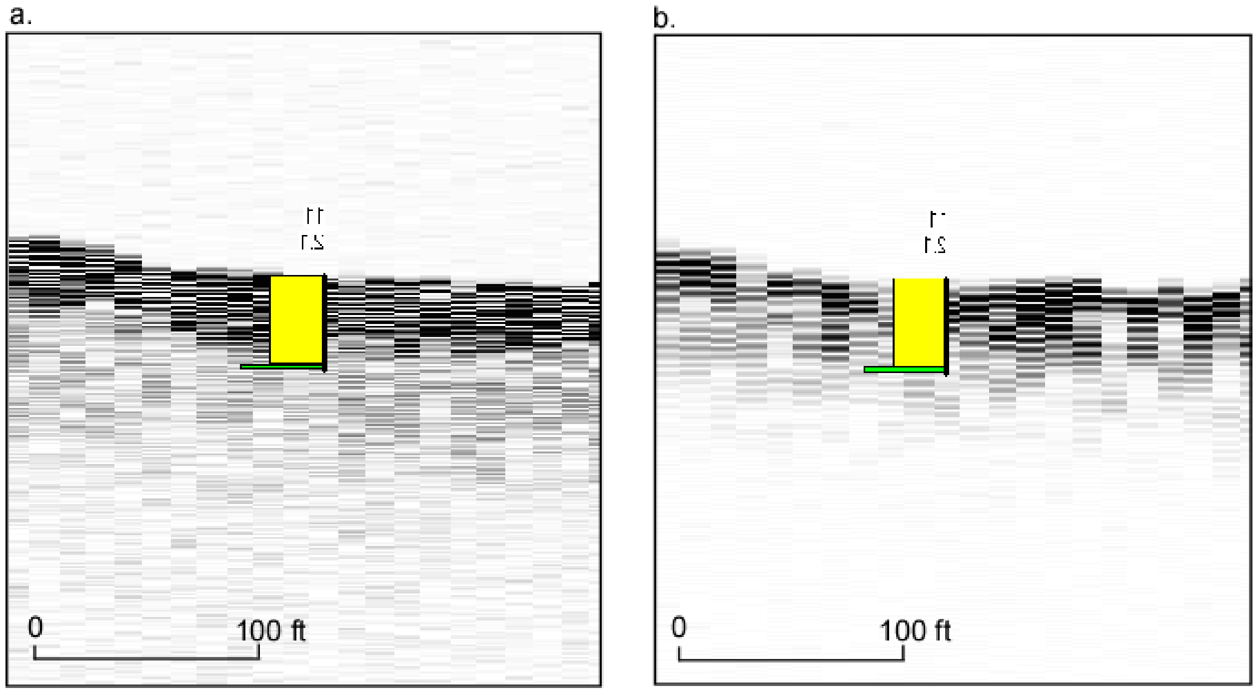


Figure 26. Expanded views of BU Profile 07071021 near Core Site 11. (a) 50 kHz. (b) 24 kHz. The base of post-impoundment fill is associated with the base of strong acoustic returns for both the 50 and 24 kHz signals. The yellow bar indicates the location and length (2.0 ft or 0.61 m) of Core 11. The green segment indicates the pre-impoundment surface. The location of Core11 was project 2.1 ft to the point of closest approach of the profile. These are expanded views of from the profile shown in Figure 25. The images are reversed horizontally to match the collection direction of TWDB Profile 07050915 (Figures 27, and 28). The horizontal resolution of this profile appears unusually poor, because all five signal frequencies were recorded and the profile is unusually short.

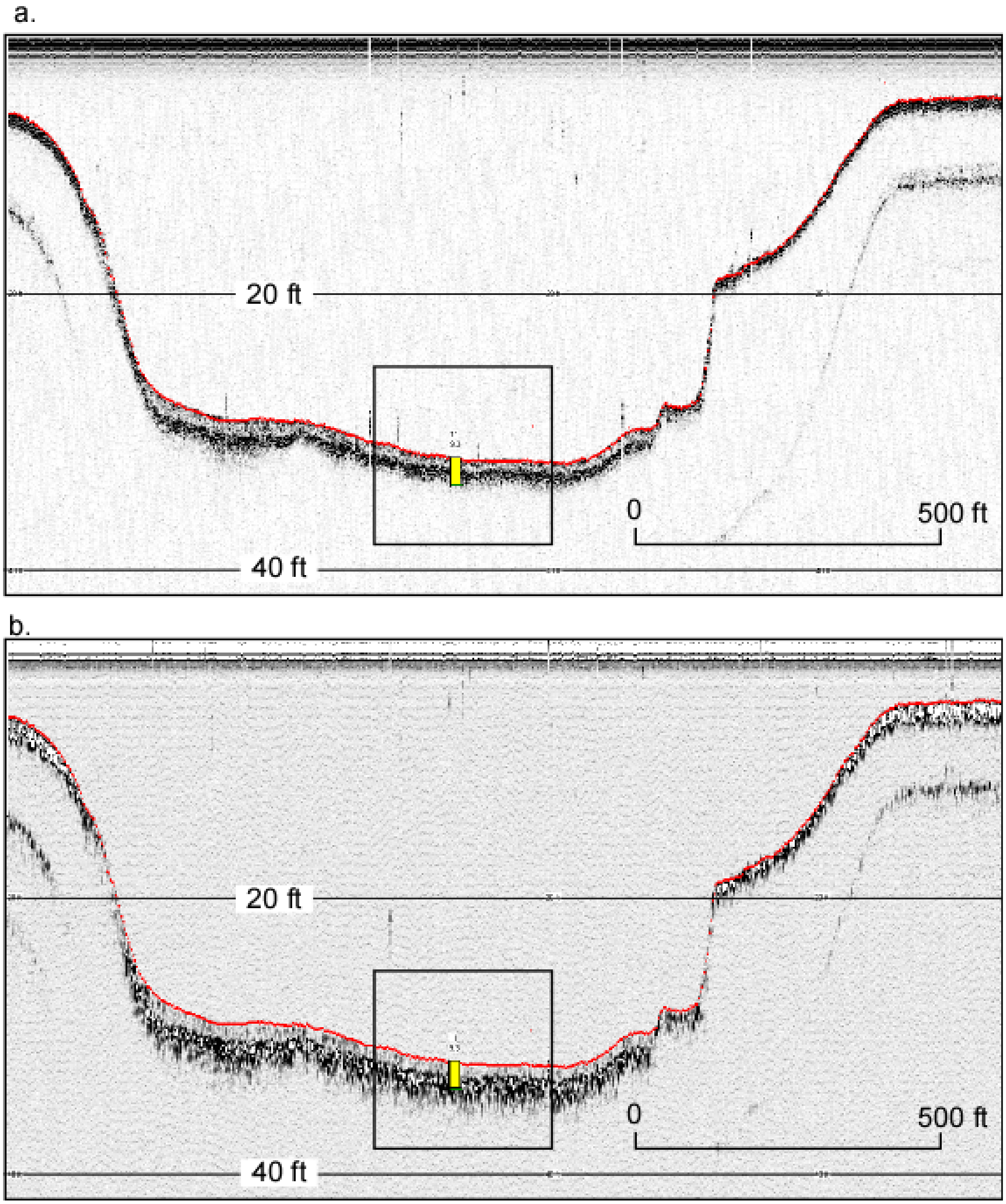


Figure 27. TWDB Profile 07050915 through Core Site 11. (a) 50 kHz. (b) 24 kHz. The yellow bar indicates the position and thickness of post impoundment sediment found in Core 11. The core location was projected 9.3 ft to the point of closest approach to the profile. The regions indicated by boxes are shown in expanded view in Figure 28.

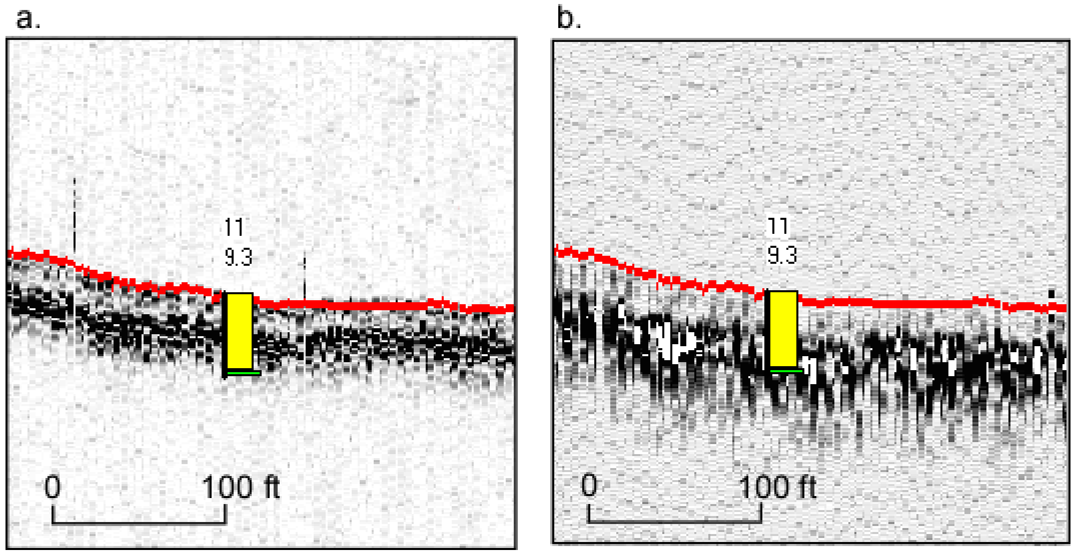


Figure 28. Expanded view of TWDB Profile 07050915 near Core Site 11. (a) 50 kHz. (b) 24 kHz. These are expanded views of from the profile shown in Figure 27. The yellow bar indicates the location and length (2.0 ft or 0.61 m) of Core 11. The base of sediment corresponds to the base of strong returns for the 50 kHz signal.

Coring Results

Of the seven cores collected in Lake LBJ, five reached and sampled the pre-impoundment surface (Table 2). Core analysis results for four of the cores that sampled the pre-impoundment surface are shown in Figures 29 and 30. The longest core, Core 1, collected near the dam (Figure 2), did not sample the pre-impoundment surface. This does not necessary mean that the core did not reach the base of sediment. In some cases the pre-impoundment surface is rock outcrop or gravel that cannot be penetrated by the vibrocore. In the case of Core 1, acoustic data through the core site indicates an apparent sediment thickness of 7.8 ft (2.4 m) compared to a core length of 6.9 ft (2.1 m). Three cores were collected at Core Site 1, with core tube lengths up to 12 ft, in an effort to sample the pre-impoundment material. All were unsuccessful. In each case, highly compacted sediment with high penetration resistance was found at the base of the core, which did not differ compositional from the rest of the core. This indicates that the base of sediment was not reached and that the sediment was too stiff to be penetrated with the vibrocore due to compaction.

Where sampled, the material on pre-impoundment surface was both texturely and compositionally different from the post-impoundment sediment and in some cases contained terrestrial plant roots. Cesium-137 results indicate well defined peaks in Cesium-137 concentration at a depth of 130 cm (4.3 ft) in Core 2, and at 45 cm (1.5 ft) in both Core 4 and Core 5. The pattern of gradual increase in Cesium-137 concentration with depth to a well defined peak, followed by a sharp drop off in concentration is interpreted to reflect changes in regional Cesium-137 fallout rates over time, with the peak corresponding to 1964 ±2 yr. Below the peak, Cesium-137 levels in Cores 2, 4, and 5 decrease to a minimum and then rise slightly in the basal sediments deposited directly on the pre-impoundment surface. Detectable levels of Cesium-137 were also found in the pre-impoundment material. This indicates vertical movement of Cesium-137 into the pre-impoundment material as well as reworking of sediment deposited after the 1954 onset in Cesium-137 deposition. As a result, the 1954 onset in Cesium-137 was not preserved in any of the cores analyzed.

The numerical average of dry mass deposition rates indicates sedimentation rates prior to 1964 were 23% higher than after 1964. Judging from the pattern of thickness observed in all seven cores and the acoustic profiles, the greater thickness of sediment deposition since 1964 at the site of Core 2 is likely characteristic of the deepwater part of the reservoir near the dam. Core 11 shows a decrease in Cesium-137 concentration with depth, which is indicative of previously deposited Cesium-137 bearing sediment being transported to the site, thus inverting the normally increase in Cesium-137 concentration with depth. A numerical average of the observed deposition rate in Cores 2, 4, and 5 since 1964 indicates a long term average rate of 1.7 cm/yr. Assuming this is representative of deposition rates over the entire 6,534 acre surface area of Lake LBJ, this indicates an average volume loss rate of 364.4 acre-ft/yr. Comparing this long term volume loss rate to an initial volume of 134,353 acre-ft, indicates a percentage volume loss rate of 0.27%/yr. At this rate, two surveys collected 10 yr apart that measure the volume to within ±0.135% would be required to constraint the volume loss rate to within 10%. This establishes the minimum accuracy requirement for hydrographic surveys intended to constrain the sedimentation rate in Lake LBJ.

Table 2. Coring results. The locations of the cores are listed in Table 1 and shown Figure 2.

Core Number	Thickness of post-impoundment cored (m)	Pre-impoundment sampled	Deposition rate 1951-1964 (cm/yr)	Deposition rate 1964-2007 (cm/yr)	Deposition rate 1951-1964 ($g/cm^2/yr$)	Deposition rate 1964-2007 ($g/cm^2/yr$)
1	2.1	no	-	-	-	-
2	1.61	yes	2.31	3.02	1.41	1.83
4	0.63	yes	1.54	1.05	1.15	0.67
5	0.75	yes	2.31	1.05	1.72	0.98
7	1.95	no	-	-	-	-
9	0.8	yes	-	-	-	-
11	0.6	yes	-	-	-	-
Averages			**2.05**	**1.71**	**1.43**	**1.16**

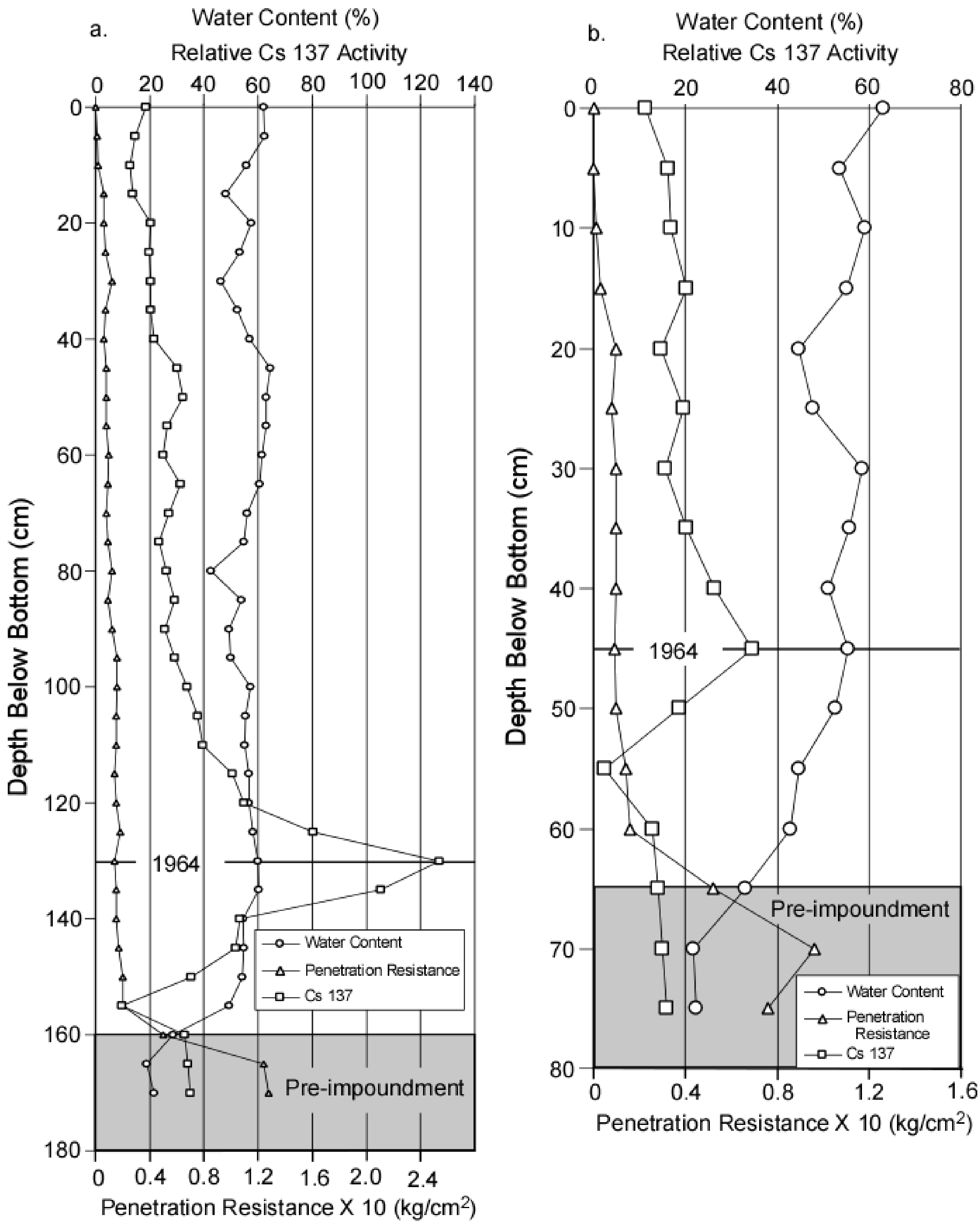


Figure 29. Analysis of Cores 2 and 4. (a) Core 2. (b) Core 4. Water content by weight tends to be high in post-impoundment sediment relative to the pre-impoundment materials. Penetration resistance tends to be low in post-impoundment sediment and high in pre-impoundment materials. The peak in Cesium-137 concentration is associated with the peak deposition rate of Cesium-137 in 1964.

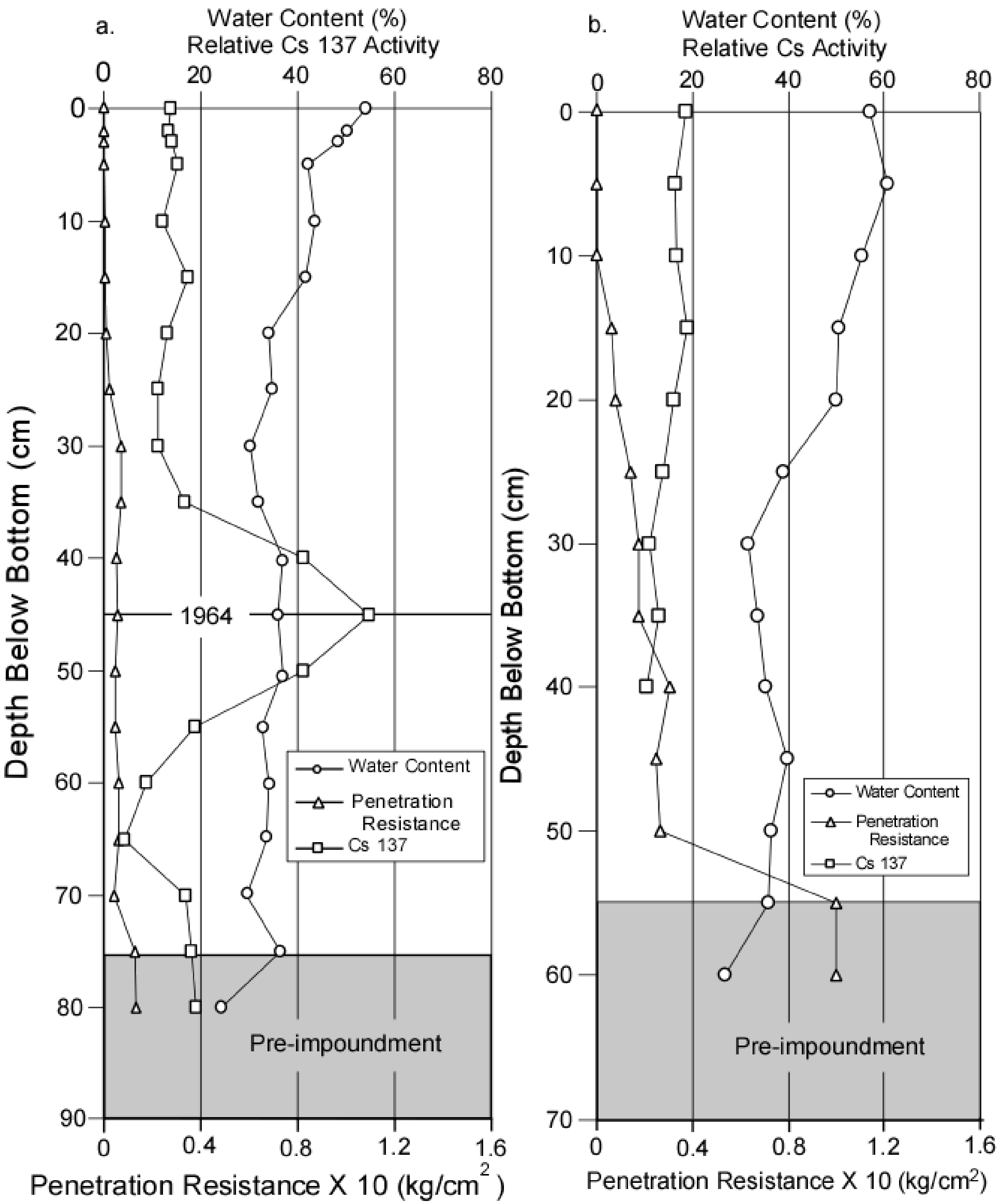


Figure 30. Analysis of Cores 5 and 11. (a) Core 5. (b) Core 11. Water content by weight tends to be high in post-impoundment sediment relative to the pre-impoundment materials. Penetration resistance tends to be low in post-impoundment sediment and high in pre-impoundment materials. The peak in Cesium-137 concentration is associated with the peak deposition rate of Cesium-137 in 1964. Core 11 shows a decrease in Cesium-137 with depth in the core and no peak.

Mapping and Volumetric Results

DepthMap was used to generate water depth maps and to compute water storage volumes at the conservation pool elevation for Lake Marble Falls (Figure 31), Inks Lake (Figure 32), and Lake Buchanan (Figure 33). An effort was made to match the input data used by TWDB in its volume calculations using ArcGIS as closely as possible. The same digitized shorelines were used to bound the reservoir region, as well as the same sounding profiles and interpolated sounding results. Two maps and volumes were computed for each reservoir (Table 3), one based on the sounding profiles alone and the other based on the interpolated soundings. In all cases, interpolation results in smoother water depth maps, by damping unconstrained oscillations in DepthMap surfaces. Because the smooth maps based on interpolated data show greater water depth where the maps based on un-interpolated data show local water depth minima and less water depth where the maps based on un-interpolated data show local maxima, the differences tend to average out. The two types of maps produce nearly the same water volumes. The DepthMap and ArcGIS volumes for the interpolated soundings differ by less than 1% for all three reservoirs. In some cases interpolations results in slightly greater volume and in others slightly less, as a matter of change. The largest difference is for Lake Mable Falls, which is the most riverine and narrowest of the three reservoirs. The smallest difference is for Lake Buchanan, which is the broadest of the three reservoirs, relative to its length. Hence, the difference appears to increase with the area/shoreline-length ratio. This is reasonable, because the two algorithms differ most in the treatment of the regions between control points, which for the interpolated data sets is largest between the interpolated points and the shoreline.

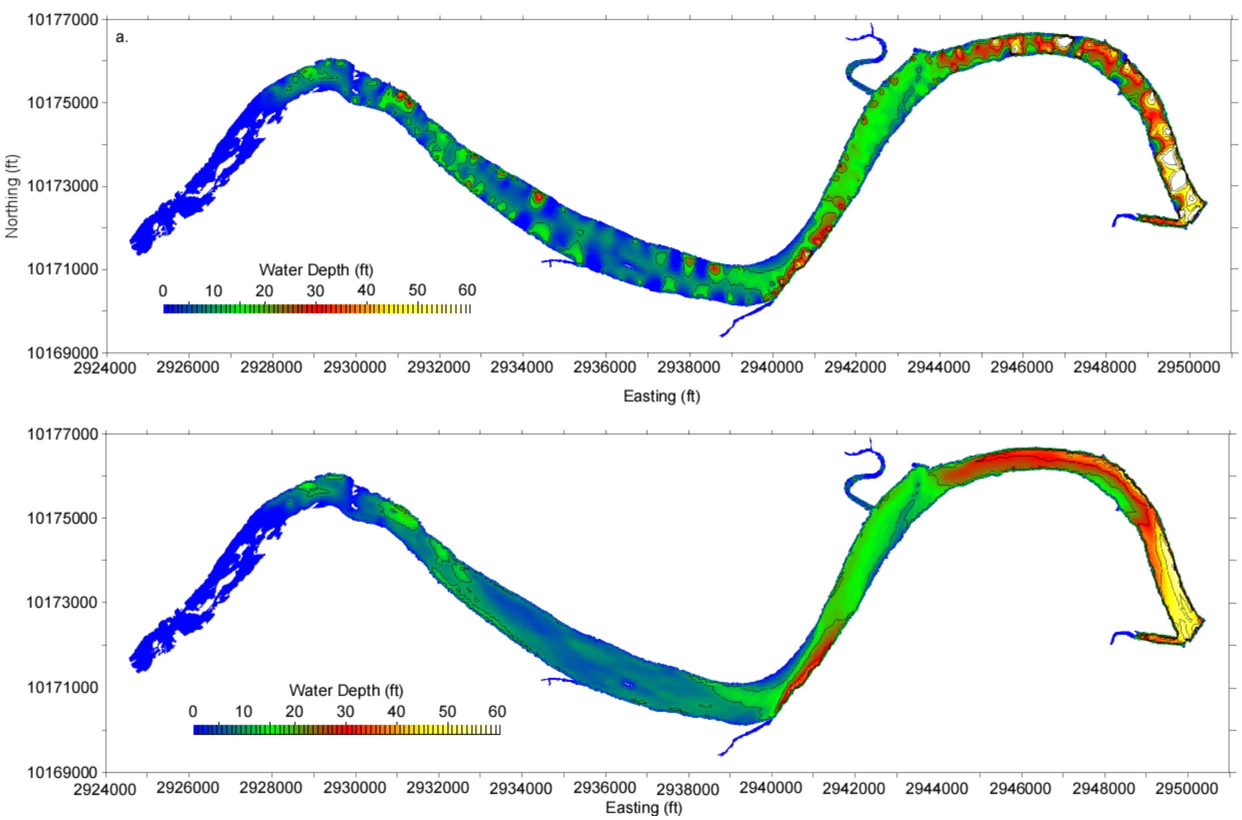


Figure 31. Bathymetric maps of Lake Marble Falls made with DepthMap. (a) Water depth based on TWDB soundings along regular profiles, spaced 500 ft apart. (b) Water depth based on interpolation of TWDB soundings between profile lines, using the TWDB algorithm. Both maps were generated using a tessellation with triangles

with nominal side lengths of 75 ft The shoreline was assigned the conservation pool elevation of 738 ft. Geographic coordinates are given in Texas State Plane, Central zone Coordinates, feet. Volumetric results are reported in Table 3.

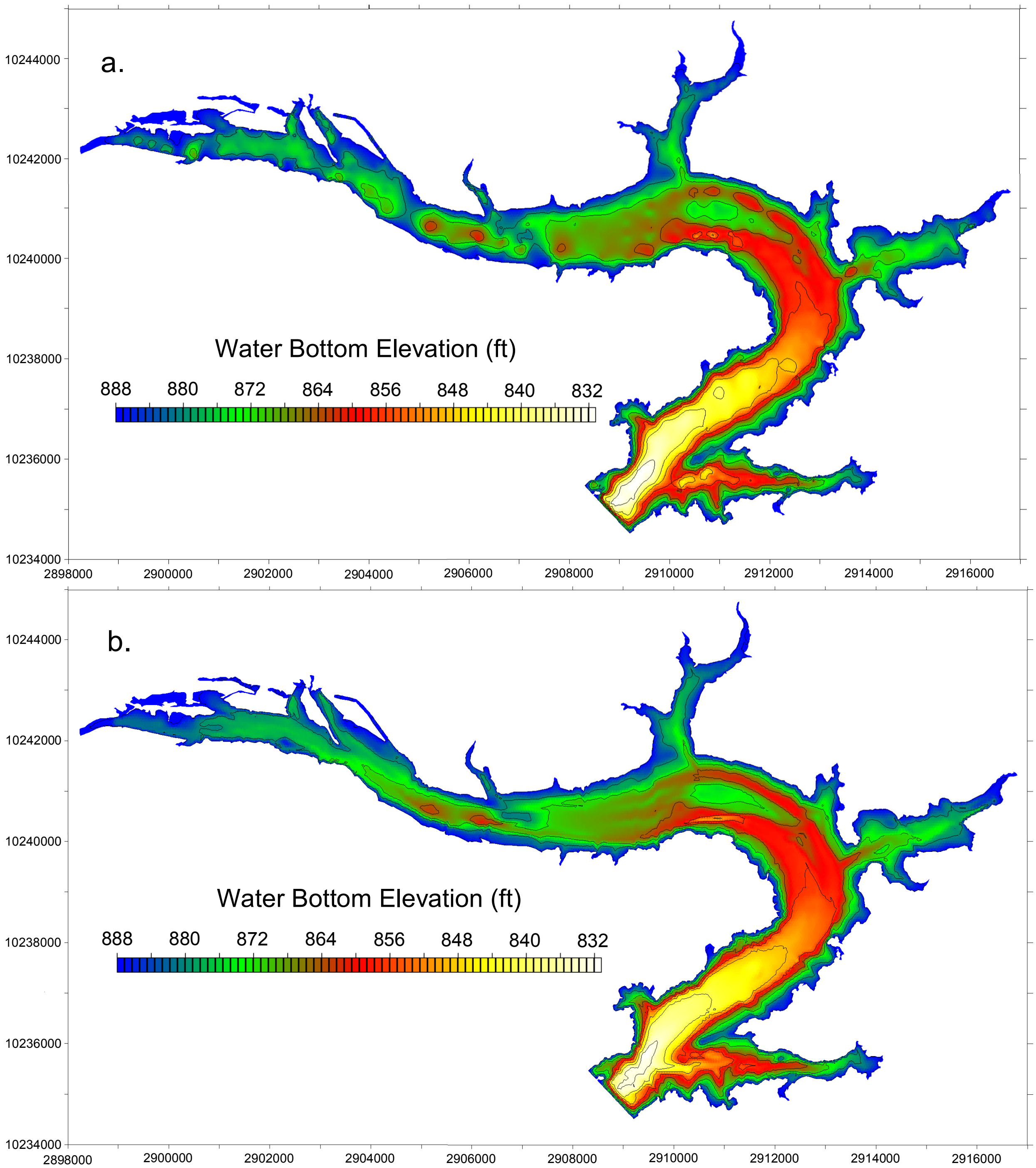
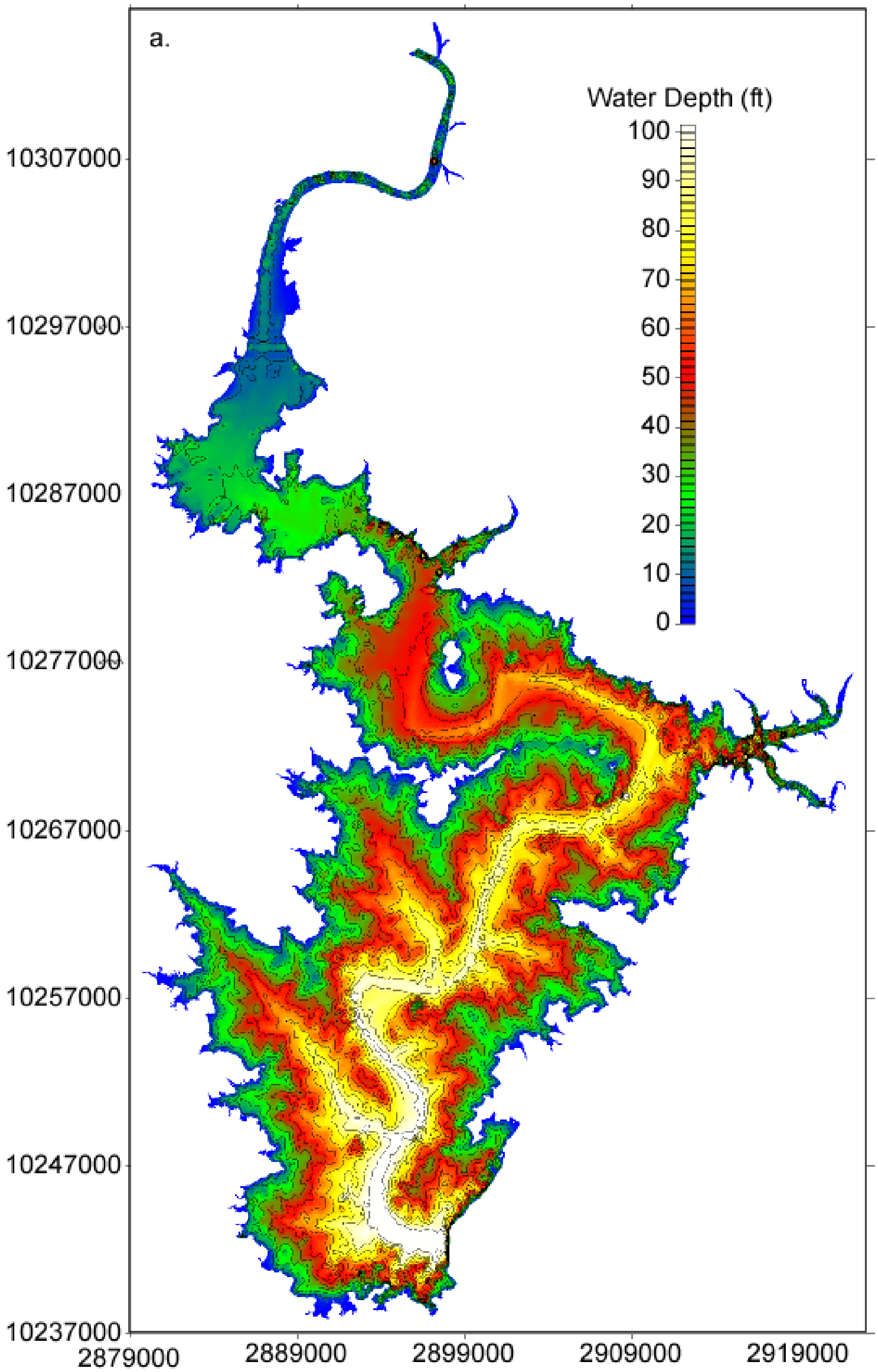


Figure 32. Bathymetric maps of Inks Lake produced by Depthmap. (a) Map based on TWDB depth soundings. (b) Map based on depth soundings plus interpolation using the TWDB interpolation algorithm. Both maps were generated using a tessellation with triangles with nominal side lengths of 50 ft. The shoreline was assigned the conservation pool elevation of 888.22 ft. Geographic coordinates are given in Texas State Plane, Central Zone Coordinates, feet. Volumetric results are reported in Table 3.



a.
Water Depth (ft)
100
90
80
70
60
50
40
30
20
10
0
10307000
10297000
10287000
10277000
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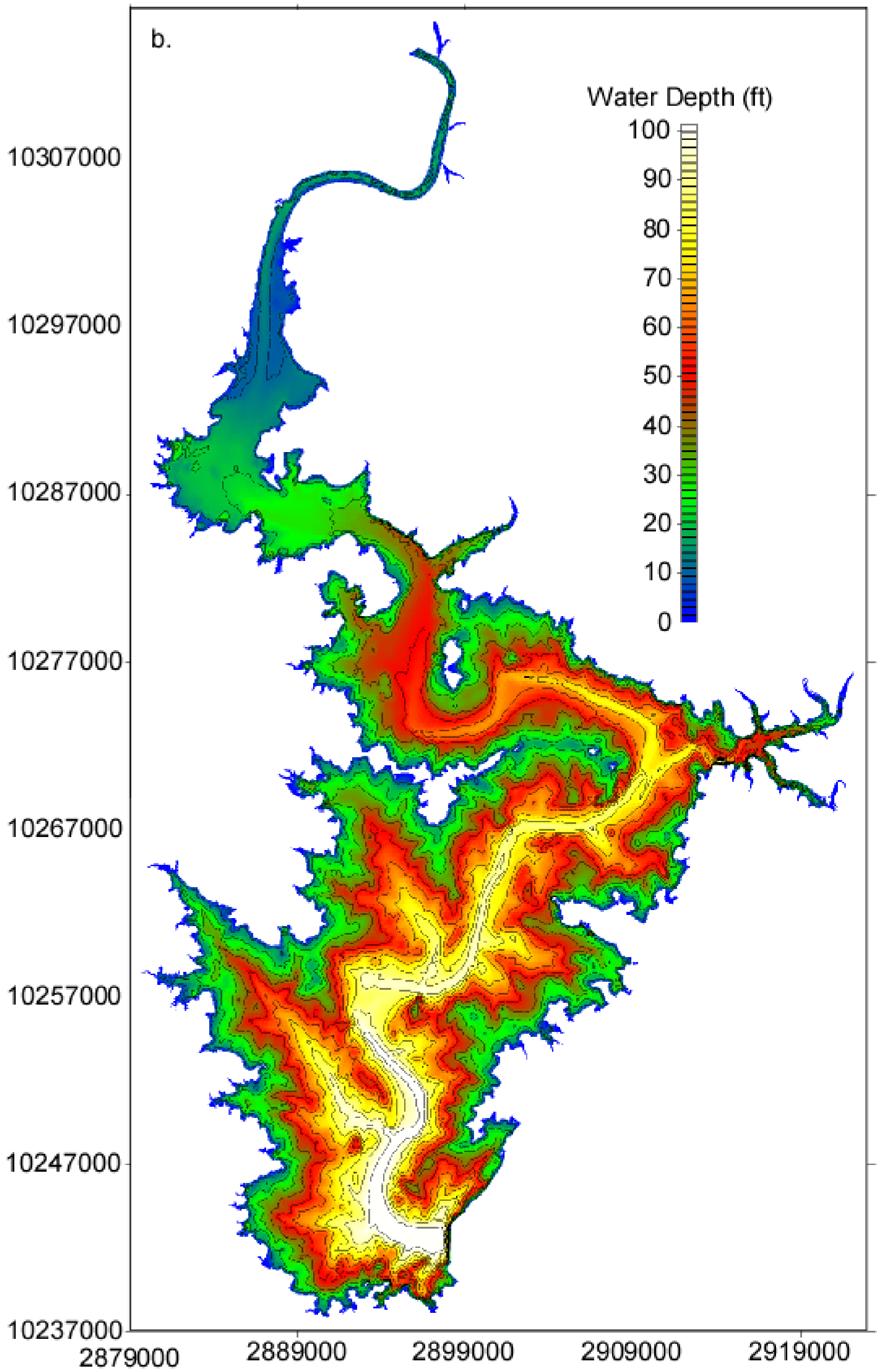


Figure 33. Bathymetric maps of Lake Buchanan produced by DepthMap. (a) Map based on TWDB depth soundings. (b) Map based on depth soundings plus interpolation using the TWDB interpolation algorithm. Both maps were generated using a tessellation with triangles with nominal side lengths of 250 ft. The shoreline was assigned the conservation pool elevation of 1013.48 ft. Geographic coordinates are given in Texas State Plane, Central Zone Coordinates, feet. Volumetric results are reported in Table 3.

Table 3. Volumetric Analyses with DepthMap. Volume calculations for Texas Highland Lakes based on TWDB soundings on profiles spaced 500 ft apart and interpolations of those soundings.

Reservoir	DepthMap Volume based on TWDB Soundings (acre-ft)	DepthMap Volume based on Interpolated Soundings (acre-ft)	ArcGIS Volume based on Interpolated Soundings (acre-ft)	% Difference DepthMap-ArgGIS for Interpolated Soundings
Lake Marble Falls	7604	7,443	7,486	-0.57
Inks Lake	13,810	14,042	14,074	-0.23
Lake Buchanan	733,585	734,581	734,266	0.043

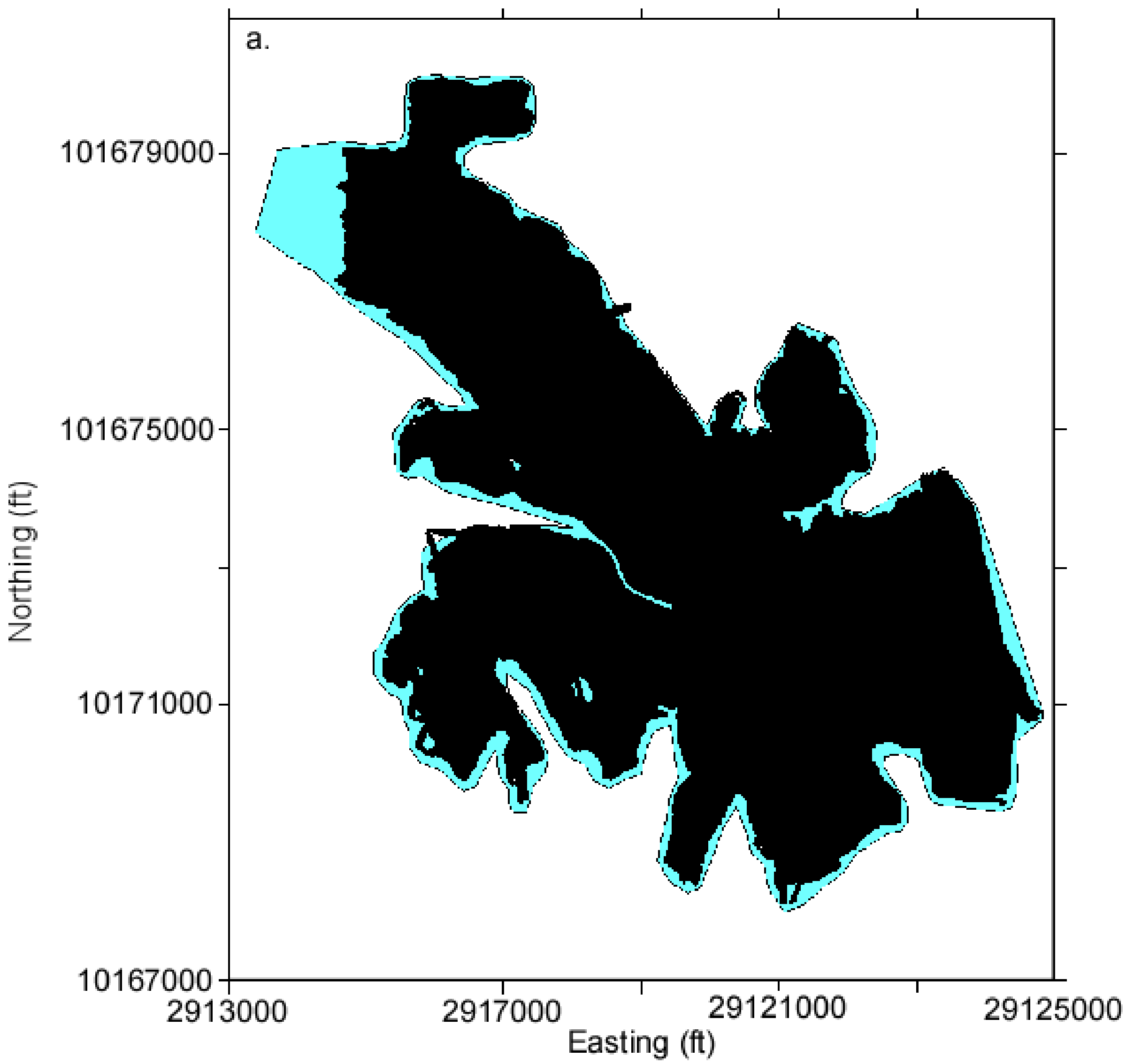
Profiling Spacing Results

To evaluate survey error associated with finite spatial sampling, bathymetric profiles were extracted from the multi-beam data set to simulate hydrographic surveys conducted at 100, 200, 300, 500, 700, 1000, 1500, and 2000 ft. This spans the range of profile spacings used by the U.S. BLM for water reservoir surveys (Ferrari, 2006). To test the random component of the results, two sets of profiles were generated for each profile spacing, with the second set offset from the first one-half of the profile spacing. Water volumes were computed for each set of extracted profiles and compared to the volume for the full multi-beam data set. Assuming the multi-beam data set has vanishingly small error associated with spatial sampling, this analysis yields an estimate of the spatial sampling error versus profile spacing for Lake LBJ. Because TWDB normally interpolates between profile soundings prior to mapping and volume analysis, BU applied its own interpolation algorithm to selected extracted profile sets to test how interpolation influences volume accuracy.

Maps of water depth for the deepwater region of Lake LBJ based on the full multi-beam data set, extracted profiles at 100, 500, and 1500 ft spacings, and an interpolation of the extracted profiles at 500 ft spacing are shown in Figures 34, 35, 36, 37, and 38, respectively. Volume results for all cases are given in Table 4. For extracted profiles spaced 500 ft apart or less, the apparent volume error associated with spatial sampling is less than 1%. However, decreasing the profile spacing below 500 ft does not produce consistent improvement in accuracy. It is likely that at this profile spacing scale, volume error is controlled more by chance profile alignment with bathymetric changes, than with the profile spacing. Profile spacings greater than 500 ft results in volume error of less than 1% to just over 4%. The main difference in the maps for these larger profile spacings is the treatment of the various tributary sections of the reservoir. At the larger profile spacings, few if any profiles are in the tributaries. Hence, the water depth within the tributary arms is largely unconstrained. The interpolations of the extracted profiles produce better looking maps, in that the submerged channel axes are more continuous. However, the volumes based on the interpolations of the extracted profiles are not consistently more accurate than the results from uninterpolated profiles. Judging from the maps based on the interpolated results, this is also likely associated with how the tributaries are treated. The interpolation algorithm used was designed to interpolate between profiles across a single submerged channel. Hence, the algorithm is not designed to treat the intersections of multiple channels that occur where the tributary arms meet the main arm of the reservoir. The interpolation algorithm used in this test is not the same as that used by TWDB. Hence, no conclusion can be drawn about the accuracy of the TWDB interpolation. However, it can be concluded that the interpolation algorithm must be fairly sophisticated to improve the volume calculation beyond that produced by the regular DepthMap TIN surface fitting algorithm.

Table 4. Lake LBJ volume results for simulated profiles extracted from multi-beam data. Maps based on the full multi-beam data set, the extracted 100, 500, and 1500 ft profile spacing, and the interpolated 500 ft extracted profiles are shown in Figures 34, 35, 36, 37, and 38, respectively.

Simulated Profile Spacing	Run 1 Volume (acre-ft)	Run 1 Volume Error (%)	Run 2 Volume (acre-ft)	Run 2 Volume Error (%)
Full Multi-Beam	51,701.5	0.0	51,701.5	0.0
100 ft	51,726.6	0.048	52,020.9	0.062
200 ft	51,646.9	0.106	51,746.4	0.087
300 ft	52,072.8	0.718	51,712.7	0.022
500 ft	51,803.2	0.196	51,703.9	0.005
700 ft	52,247.2	1.06	51,076.0	1.21
1000 ft	51,775.6	0.14	51,277.4	0.82
1500 ft	52,712.5	2.00	49,581.3	4.10
2000 ft	53,141.1	2.78	49,584.5	4.10
500 ft, Plus Interpolation			51,750.6	0.095
1000 ft, Plus Interpolation			51,212.6	0.95
2000 ft, Plus Interpolation			48,304.6	6.57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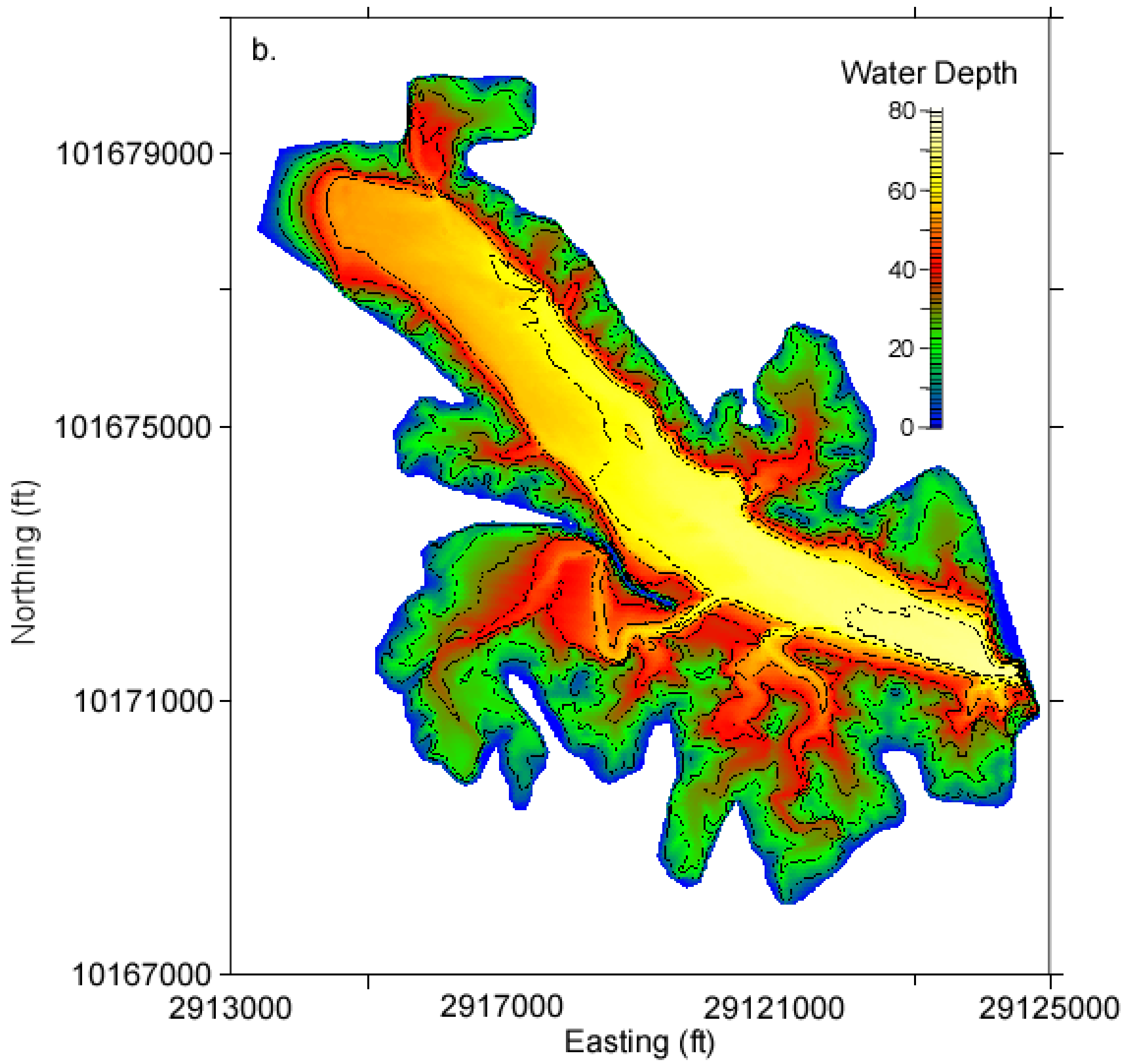
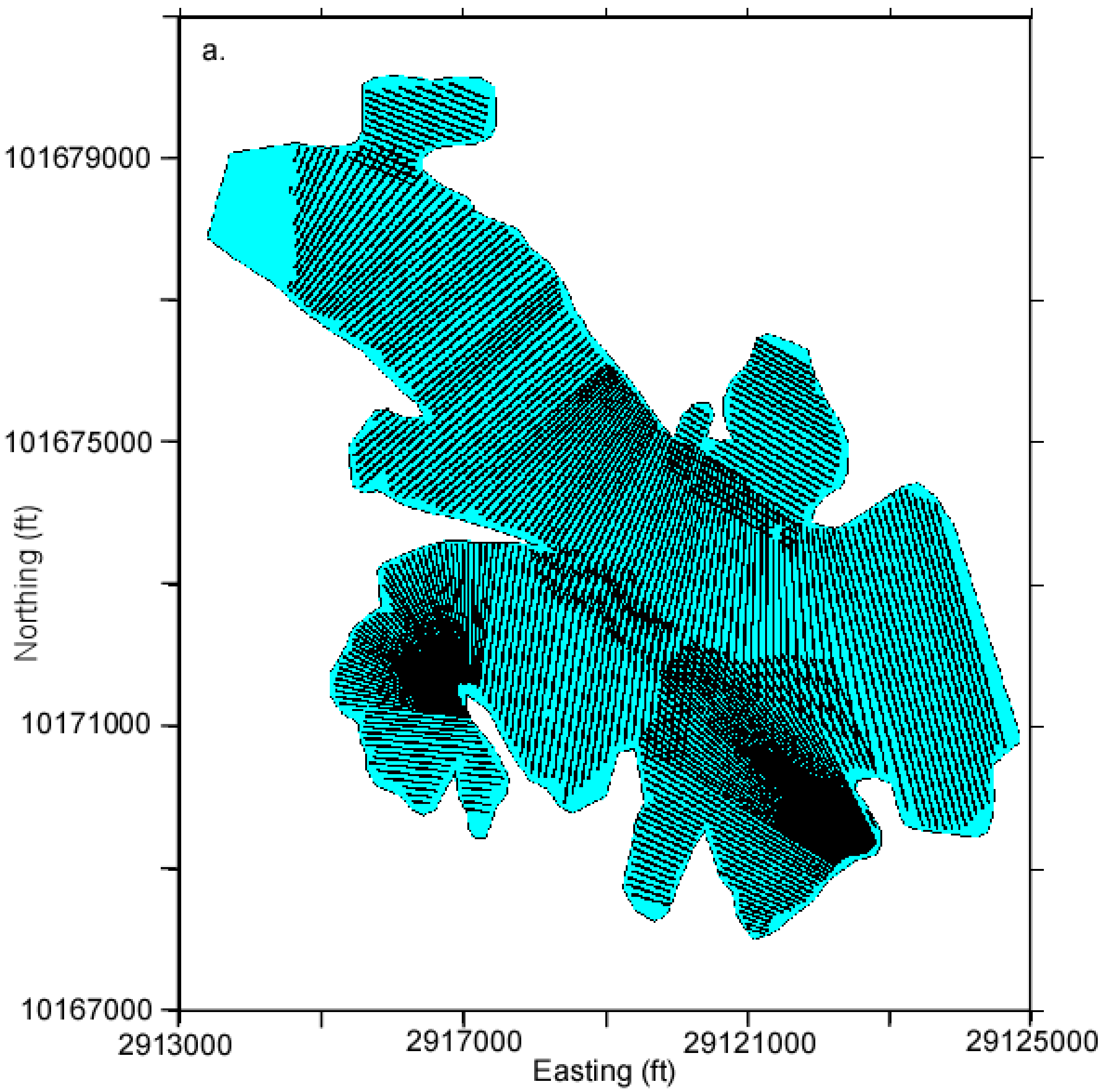


Figure 34. LBJ bathymetry, based on multi-beam data. (a) Distribution of 2.2 million processed multi-beam soundings. Individual multi-beams points are spaced so closely (~10 ft apart) that they appear as a single black mass within the southeastern part of the Lake LBJ. (b) Water depth relative to the conservation pool elevation (825 ft) based on the multi-beam soundings. The water storage volume associated with this map is given in Table 4.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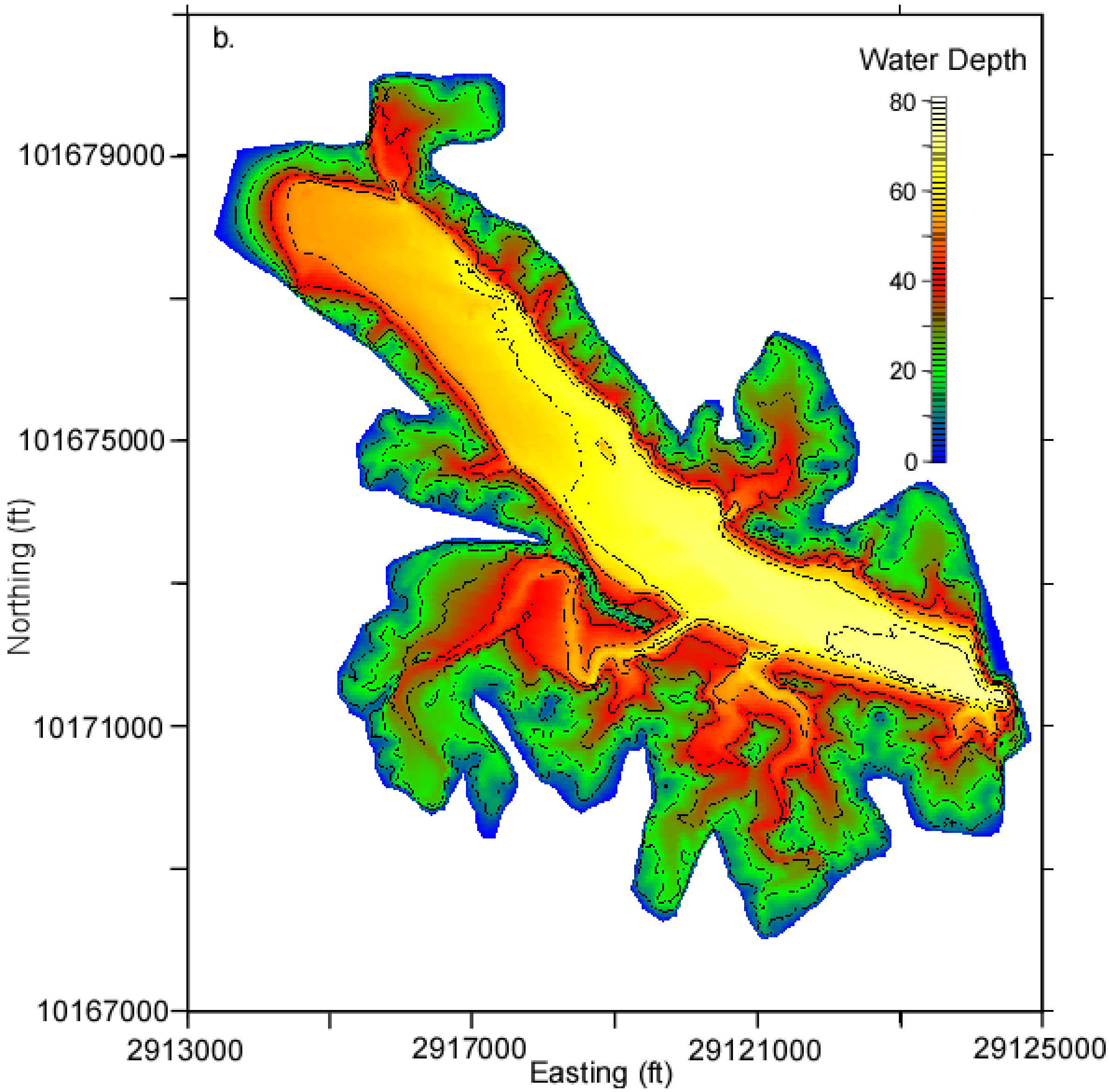
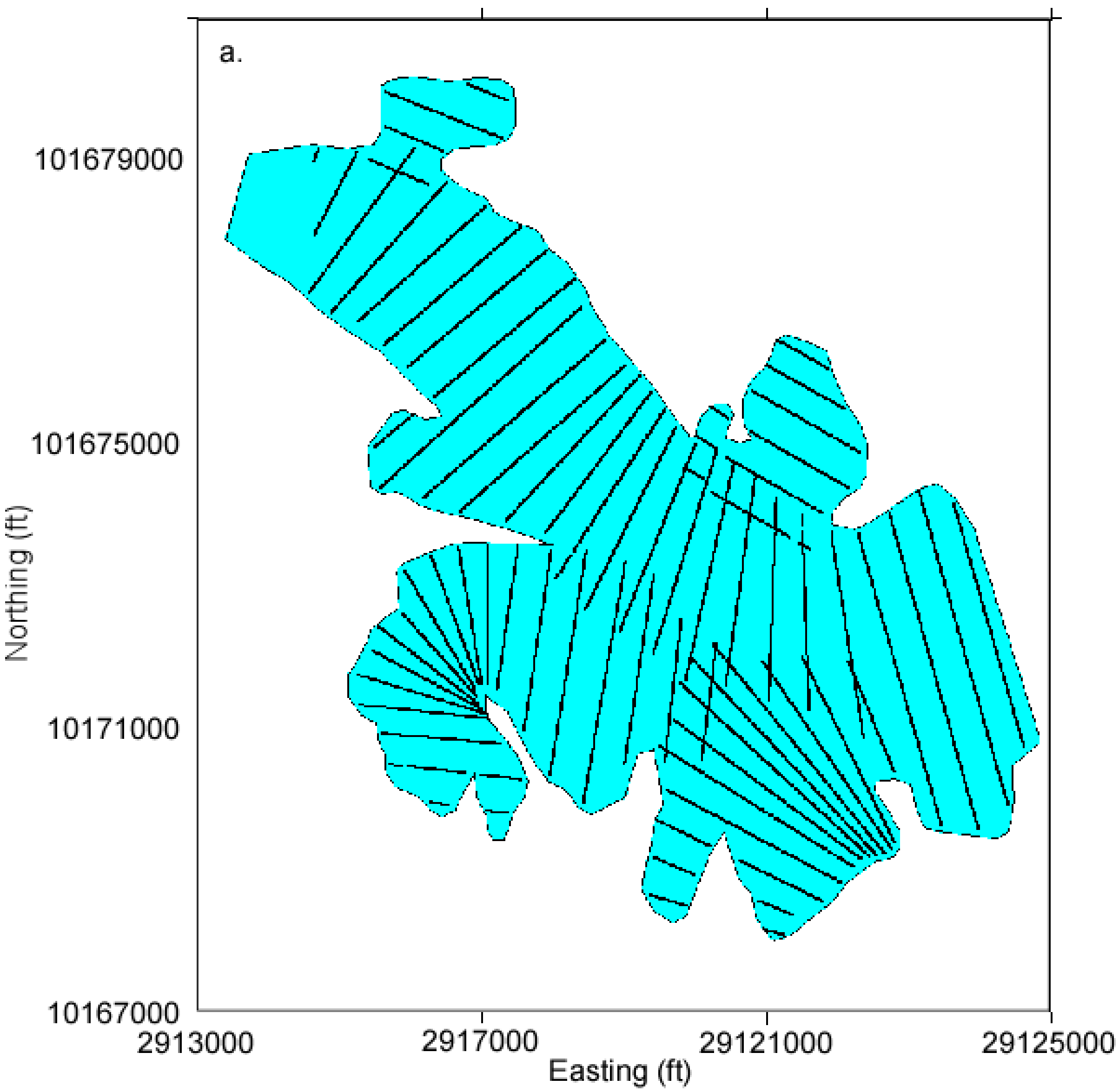


Figure 35. LBJ bathymetry, based on profiles spaced 100 ft apart, extracted from multi-beam data. (a) Distribution of sounding points extracted from the processed multi-beam soundings. Individual multi-beams are spaced so closely (~10 ft apart) along the profiles that they appear as continuous black lines. (b) Water depth relative to the conservation pool elevation (825 ft) based on profiles extracted from the multi-beam soundings. The water storage volume associated with this map is given in Table 4.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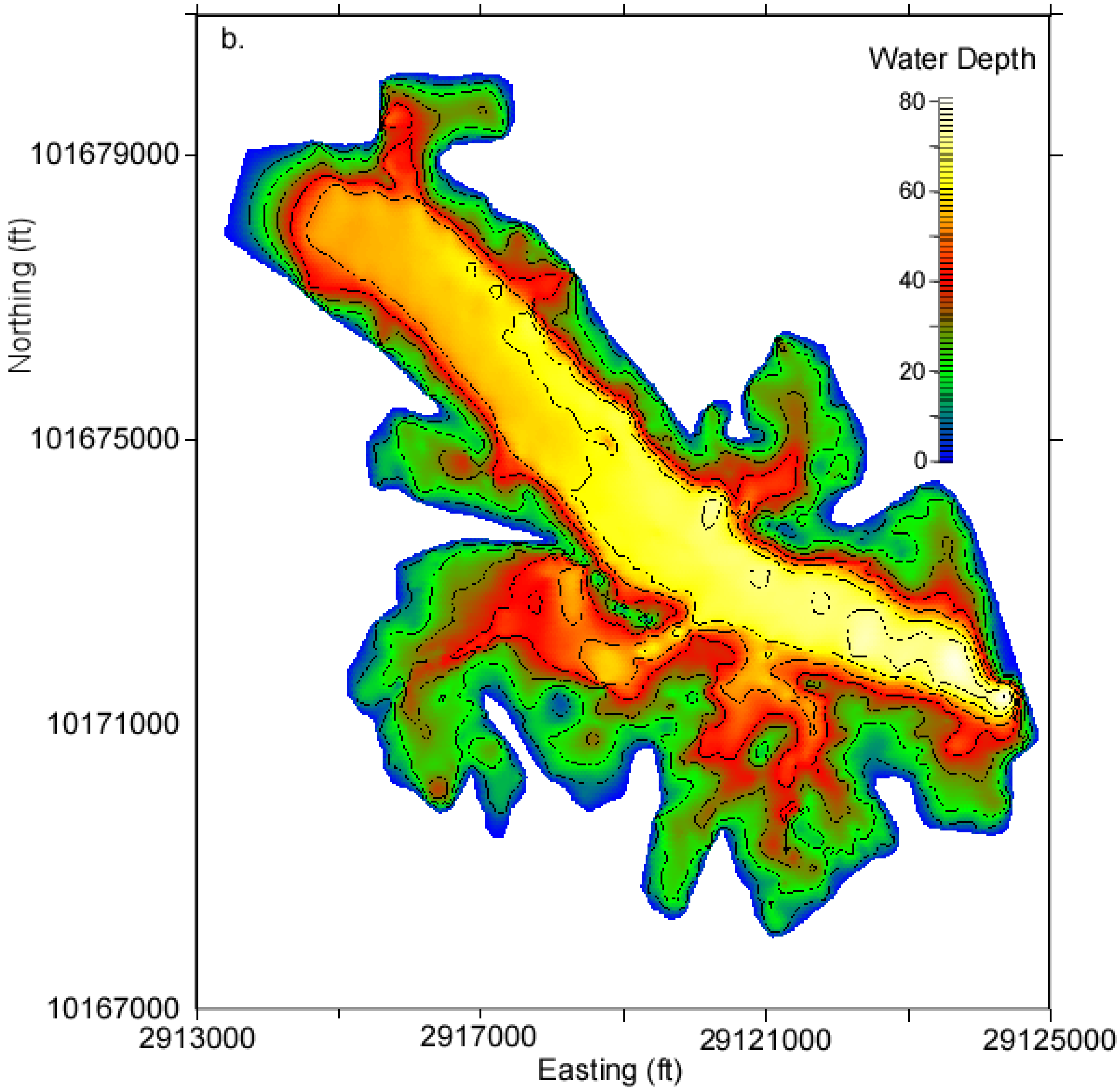
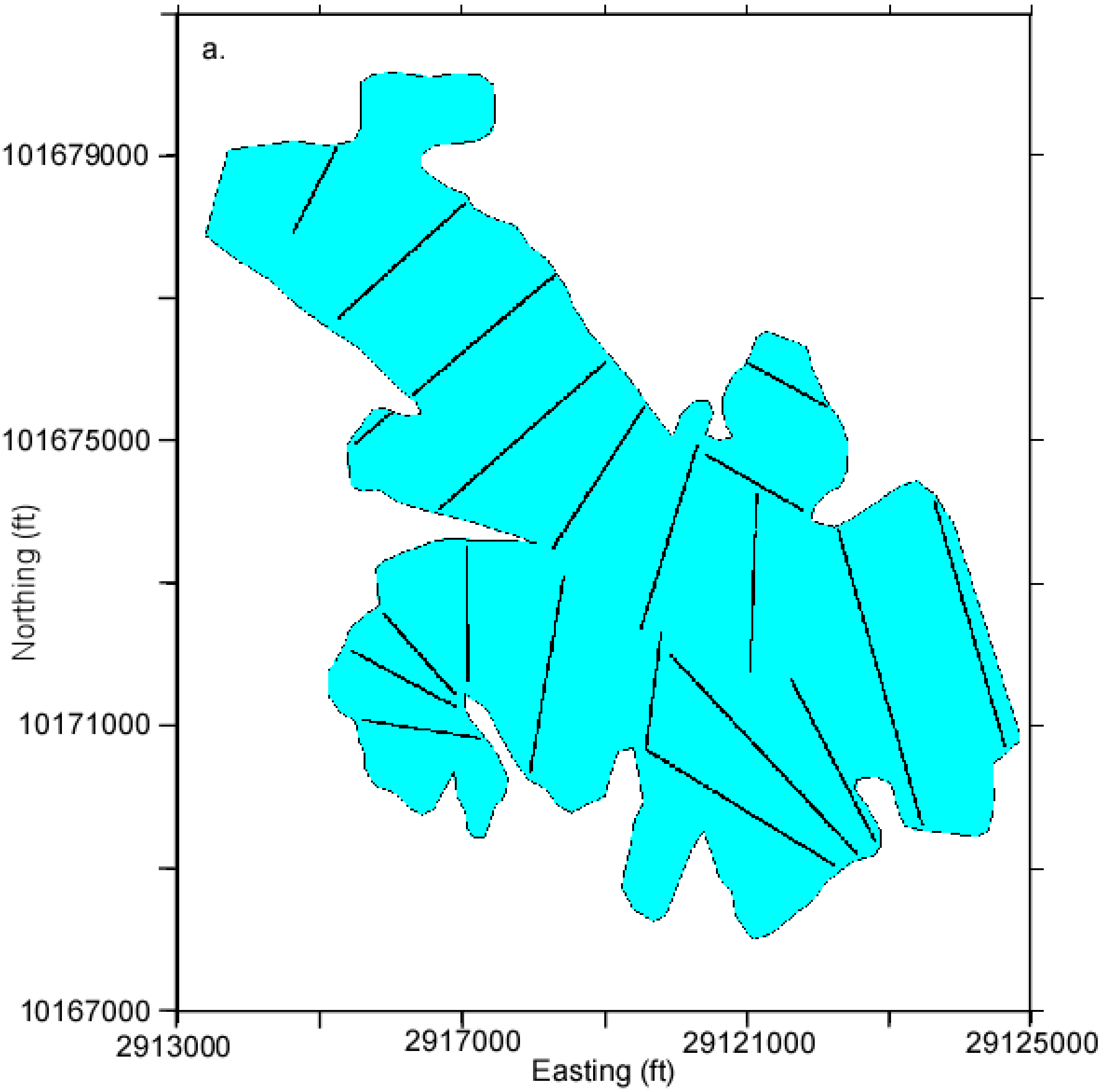


Figure 36. LBJ bathymetry, based on profiles spaced 500 ft apart, extracted from multi-beam data. (a) Distribution of sounding points extracted from the processed multi-beam soundings. (b) Water depth relative to the conservation pool elevation (825 ft) based on profiles extracted from the multi-beam soundings. The water storage volume associated with this map is given in Table 4.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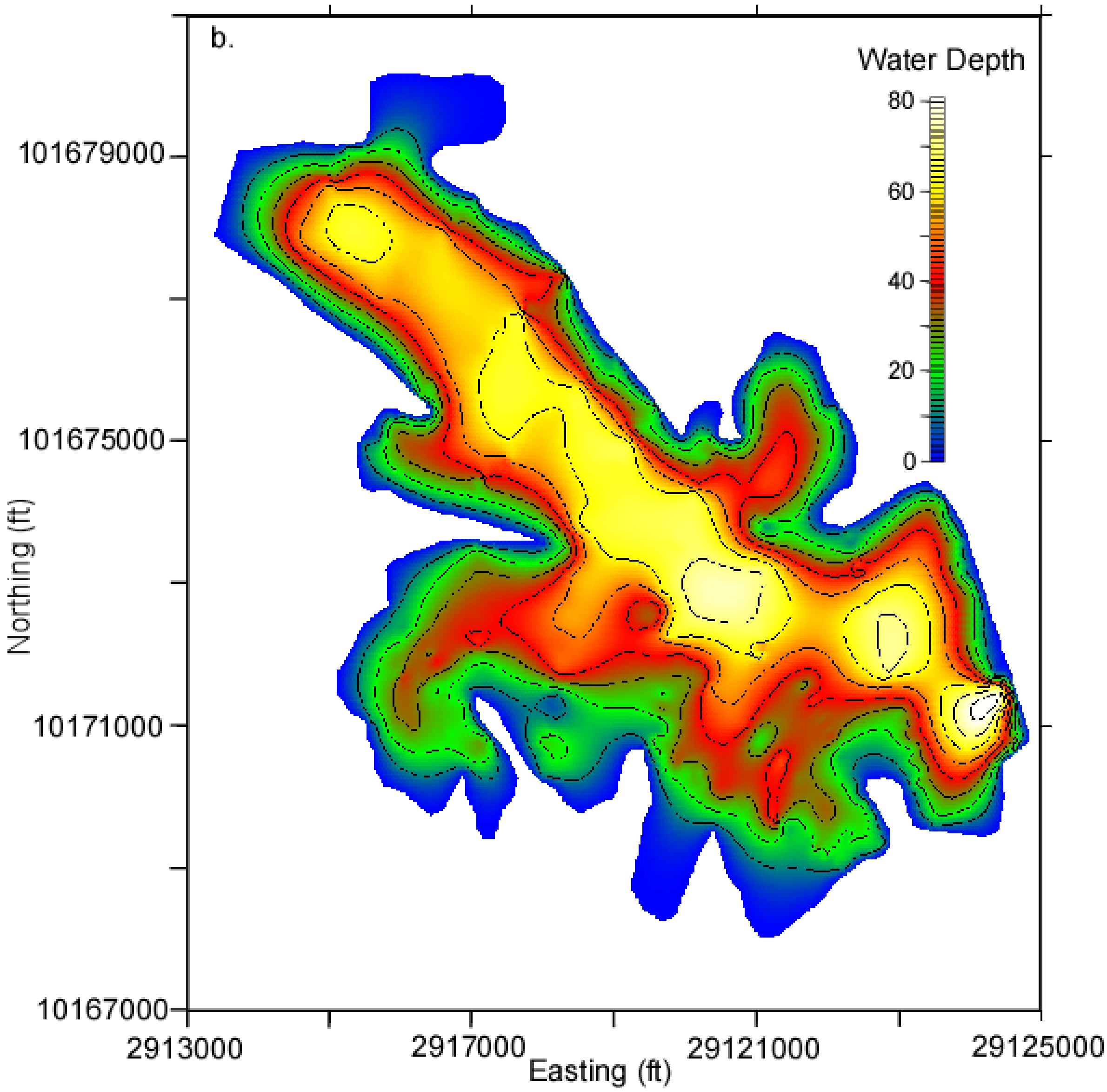
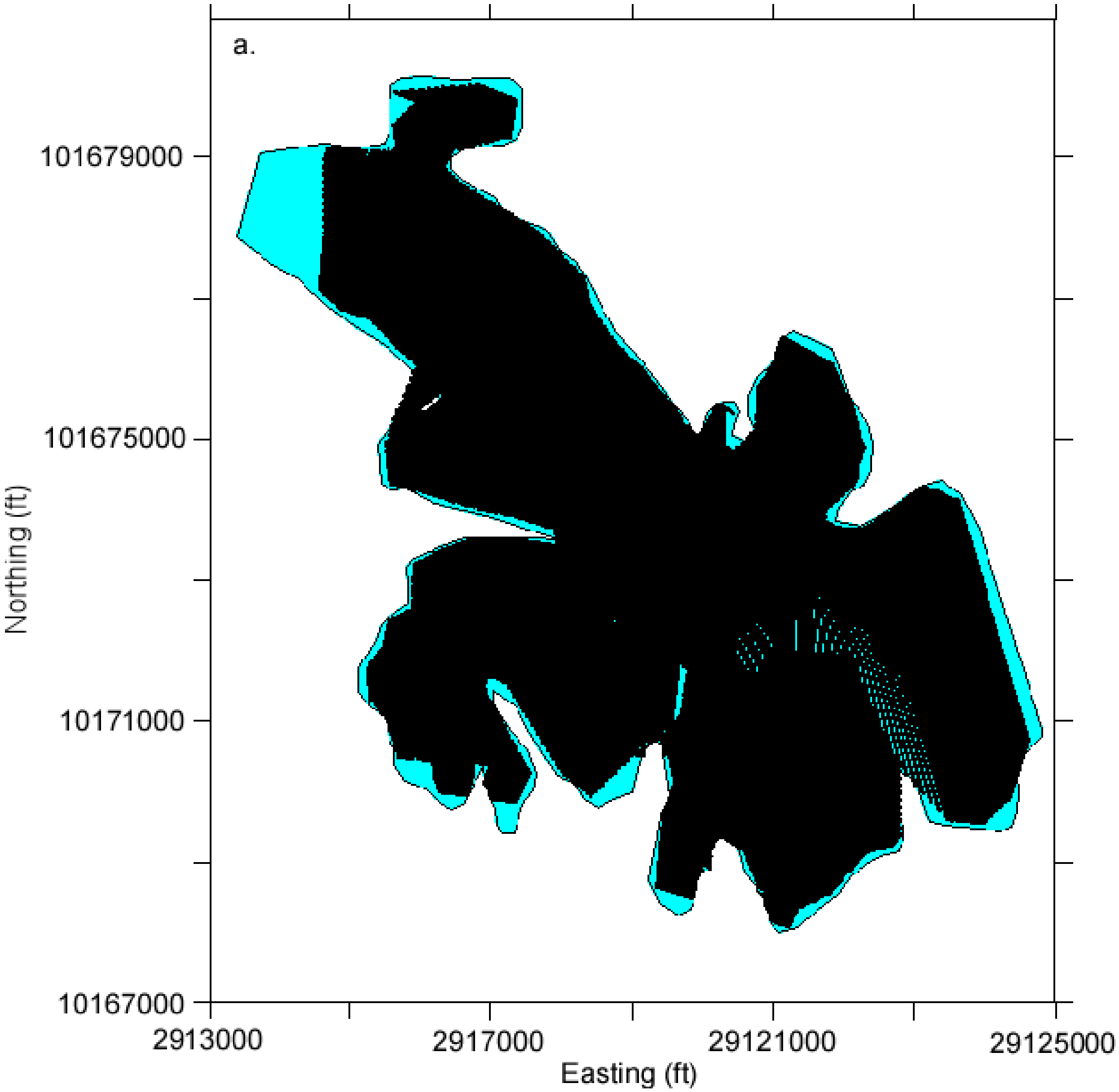


Figure 37. LBJ bathymetry, based on interpolation of profiles spaced 1500 ft apart, extracted from multi-beam data. (a) Distribution of sounding points extracted from the processed multi-beam soundings at 1500 ft profile spacing. (b) Water depth relative to the conservation pool elevation (825 ft) based on profiles extracted from the multi-beam soundings. The water storage volume associated with this map is given in Table 4.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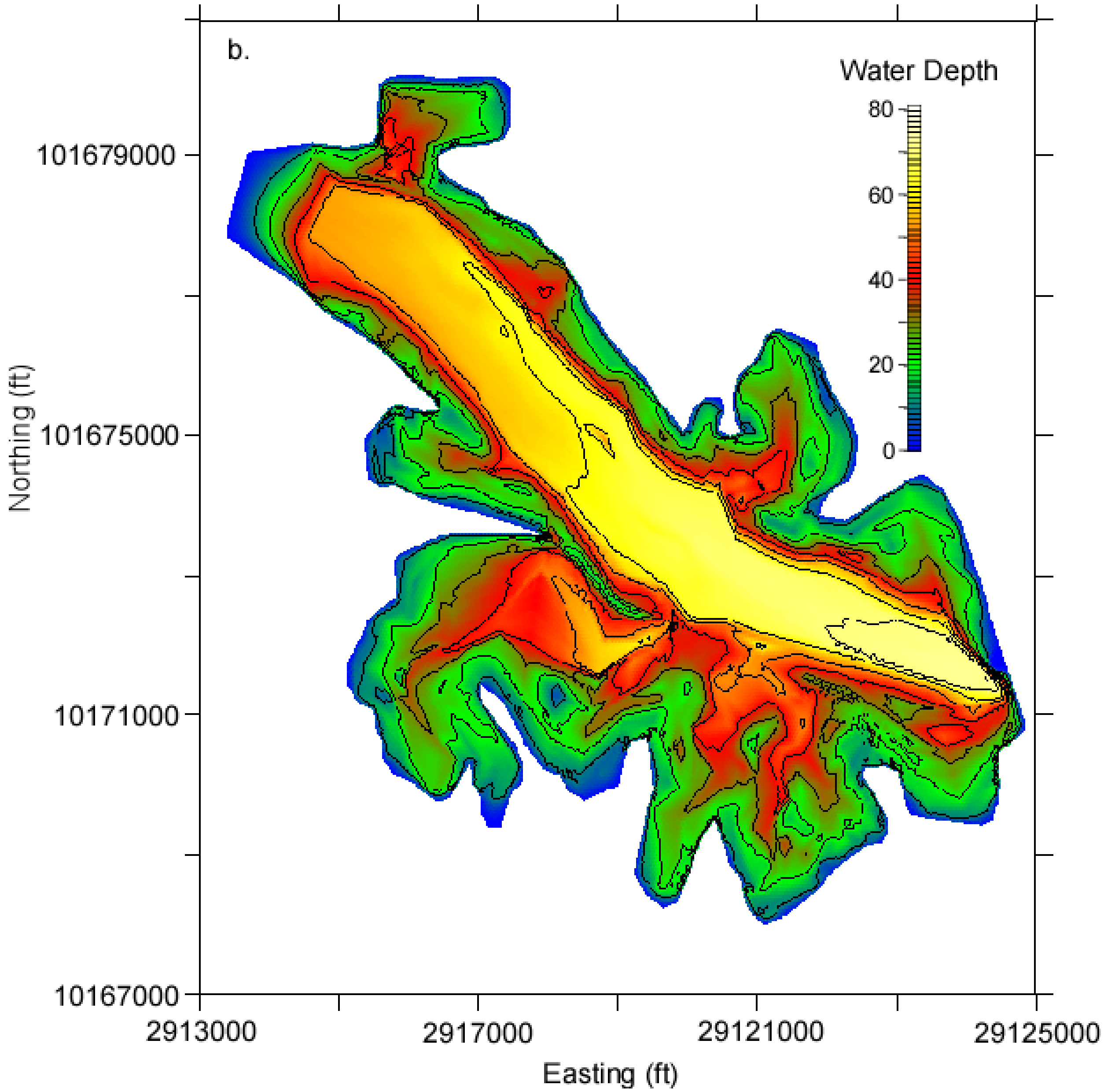

Figure 38. LBJ bathymetry, based on interpolation of profiles spaced 500 ft apart, extracted from multi-beam data. (a) Distribution of sounding points extracted from the processed multi-beam soundings at 500 ft profile spacing and then interpolated between profiles. (b) Water depth relative to the conservation pool elevation (825 ft) based on profiles extracted from the multi-beam soundings and interpolated to fill in the regions between profiles with control points. The water storage volume associated with this map is given in Table 4.

Survey Design Results

In this study a multi-beam data set was collected in the deepwater part of Lake LBJ to test the adequacy of spatial sampling in single-beam hydrographic surveys. This allows quantitative assessment of spatial sampling error for different profile spacing, but is not practical to use as a strategy for routine survey planning. As a potential alternative to collecting a multi-beam data set, BU collected a single-beam profile along the axis of the deepwater part of Lake LBJ to see if comparable information about survey profile spacing could been gleaned from a more easily acquired test data set (Figure 2 and 39). The axial profile, with soundings approximately 5 ft apart, was re-sampled at regular intervals in the orthogonal direction. The cross-section areas of the resampled cross-sections were then compared to the cross-section area of the full resolution profile as a test of the spatial sampling error versus resample spacing (Figure 40). From this analysis, the 500 ft standard profile spacing used by TWDB is predicted to yield 0.5% ±0.33% spatial sampling error (Figure 40). This means that depending on the chance alignment of the profile grid with bathymetric features, the volume error due to limited spatial sampling could be as little as 0.17% or as much as 0.83%. Decreasing the profile spacing to 100 ft is predicted to reduce the spatial sampling error to 0.21% ±0.1%. Increasing the profile spacing to 1000 ft is predicted to increase the spatial sampling error to 0.67% ±0.6%. The large overlap in the 95% confidence intervals about the predicted spatial sampling errors indicates that, depending on chance alignment with bathymetric features, closer profile spacing may increase or decrease the volume accuracy.

The accuracy predictions were tested by comparison with the results from the extracted profiles discussion in the last section ((Table 4). The comparison shows that the spatial sampling error for the extracted profiles tracks the 95% confidence interval for the predicted error closely for profile spacings up to 1000 ft. For 1500 ft and 2000 ft spacings the error determined from the multi-beam data is, in some cases, a factor of 2 greater than the predicted upper error limit.

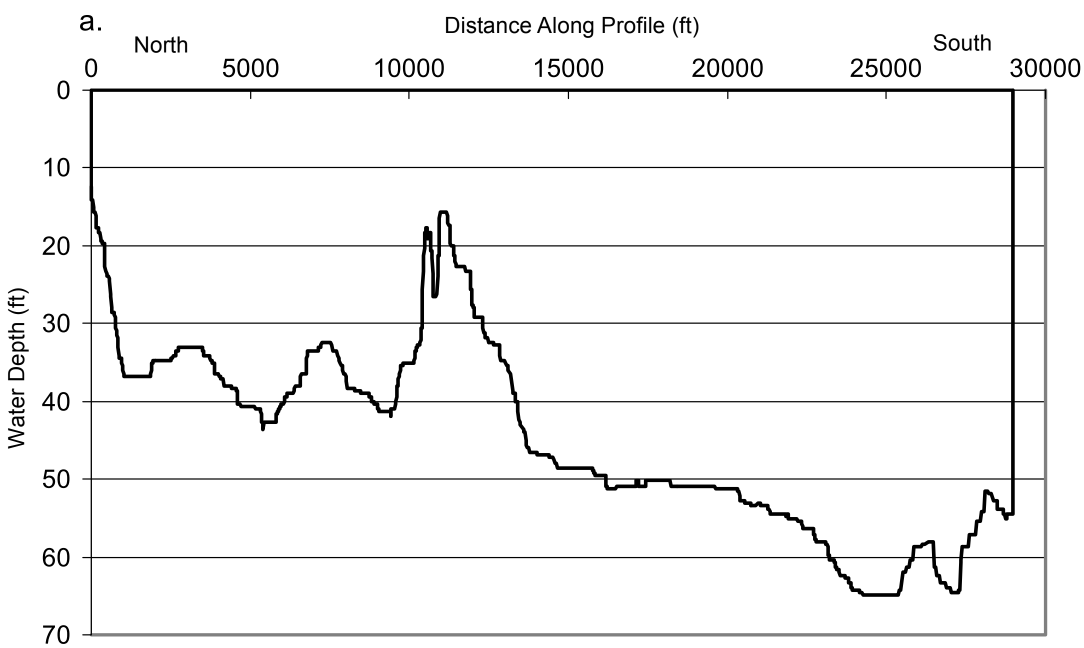

Figure 39. Water depth along an axial profile through Lake LBJ. The track line of the profile is shown in Figure 2.

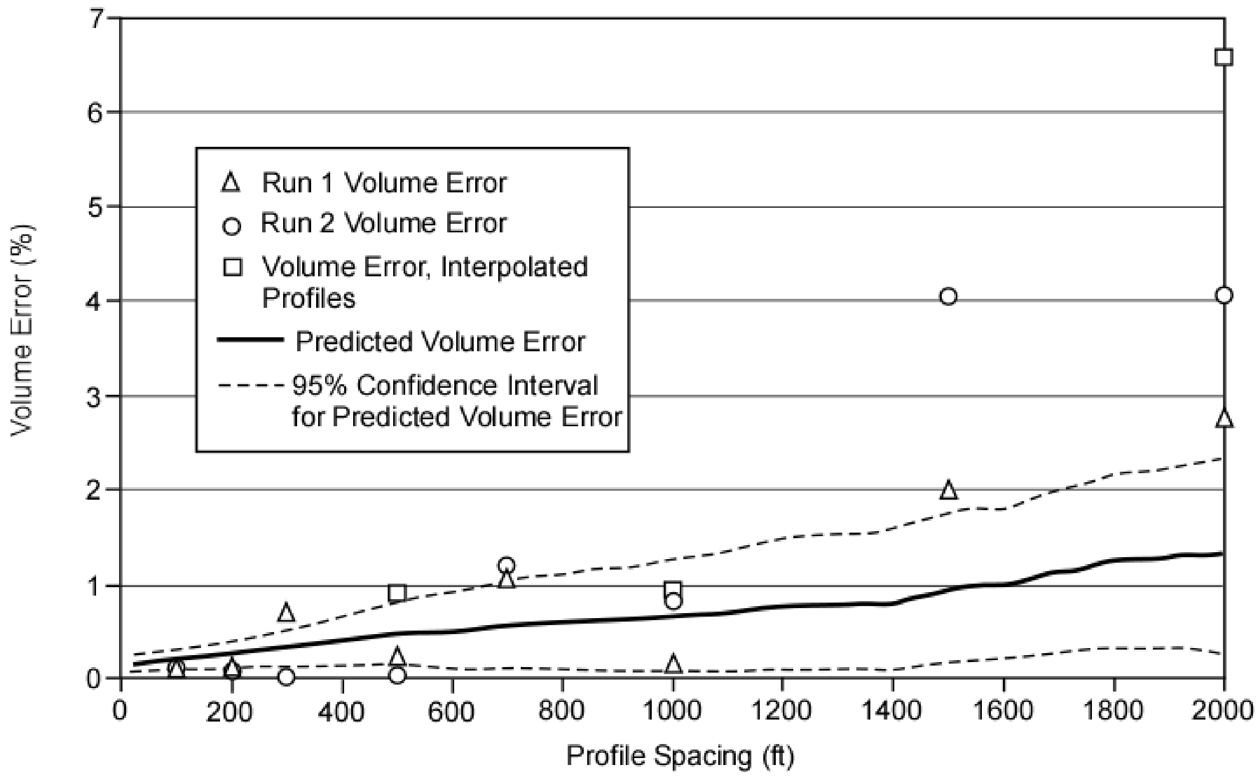

Figure 40. Estimated volume error in a reservoir survey versus profile spacing. The estimate is made by computing the area bound by the axial profile for a range of resample spacings versus the area bound by the profile at full resolution. Points marked by triangles, circles, and squares correspond to volume error results for profile sets extracted from the multi-beam data set given in Table 4.

Discussion

In this study three main sources of error in hydrographic surveys were considered: (1) error associated with the point soundings of sediment thickness, (2) error associated with surface modeling and volume computation, and (3) error associated with limited spatial sampling. An attempt was made to isolate and quantify each of these potential sources of error. Sources of systematic error in point measurements of water depth are well understood and avoidable (USACE, 2001). Error in point measurements of sediment thickness using acoustic sub-bottom profilers is less well understood. To test the accuracy and repeatability of sediment thickness measurements in this study, comparisons were made between profiles collected by TWDB using a standard 3-frequency SDI survey system and by BU using an experimental system with a higher time sample rate and two additional frequencies. Acoustic profiles collected with the two profiling systems were also compared to sediment thicknesses in cores collected along the acoustic profiles. The comparisons show that for sediment thicknesses of 8 ft and less, either system could be used to map the sediment thickness. The error of acoustically measured sediment thickness is in the range of a few inches and is generally less than 10% of the sediment thickness. For sediment thicknesses of 12 ft or more, the lowest frequency available on the TWDB system (24 kHz) does not penetrate to the base of sediment. This would lead to an underestimate of the sediment thickness.

The comparison between the base of sediment documented by coring and the acoustic records indicates that the acoustic character of the base of sediment changes significantly over the length of Lake LBJ. In some cases the base of sediment correlates with the base of acoustic returns of the 50 kHz signal. In other cases the base of returns of the 24 kHz signal corresponds closely with the base of sediment. Failure to recognize the changing character of the base of sediment would result in error in the sediment volume. This can be best avoided by collecting co-located acoustic profiles and sediment cores throughout the reservoir. For a reservoir of the size and complexity of Lake LBJ, six or more cores are needed to identify changes in the acoustic character of the base of sediment.

The second potential source of survey error treated is associated with the surface modeling algorithm used to generate a continuous surface from discrete control points. The challenge in surface modeling is to generate a reasonably shaped surface between control points. The TWDB approach is to linearly interpolate between profiles and between the profiles and the shore. A TIN model is then generated by using the resulting interpolated points as corner nodes of triangles. This honors the linear interpolation exactly. BU fits nearly equilateral triangles to the profile and shore control points and forces the resulting surface to be as smooth as possible between control points. Both of these approaches are reasonable. Neither approach will likely be better in all cases. In this study a comparison was made of the volumes produced using the two approaches as a way to quantify the level of uncertainty in volume associated with the choice of surface modeling algorithm. The results for Lake Marble Falls, Inks Lake, and Lake Buchanan, indicate that the different surface modeling algorithms produce less than 1% difference in volume. The differences were largest for long and narrow Lake Marble Falls, with a high shoreline to area ratio. In this case the method of interpolating between the sounding points and shore is more important than for less elongate reservoirs. The current approach used by the TWDB has the advantage of scalability over the approach used by BU and is better suited for mapping large reservoirs with highly resolved shorelines and islands. The potential advantage of the approach used by BU is that it produces reasonably accurate maps and volumes with little human input. In either case, when computing sedimentation rates from the change in water volume from one survey to the next, the same algorithm should be used for both surveys.

Error due to limited spatial sampling was assessed by comparing volumes produced by profiles extracted from the multi-beam data set at different spacings, with the volume produced from the full multi-beam survey. The results show that there is a good deal of scatter in the volume accuracy for a given profile spacing, depending on the chance alignment with bathymetric features. As a result, decreasing the profile spacing improves the chance of increased volume accuracy. However, due the random component in the sampling, the difference between volumes determined from surveys along lines versus the full multi-beam data set does not decrease monotonically with decreasing line spacing. Hence, decreasing the profile spacing from the 500 ft TWDB standard to 300 or 100 ft, may or may not improve the accuracy of the final volume estimate in a particular reservoir. In contrast, increasing the profile spacing beyond 500 ft in all but one example resulted in a significant increase in volume error. This suggests that for reservoirs like Lake LBJ, with significant water bottom variation and many tributary arms, 500 ft profile spacing is a practical choice. The maximum error for all runs of 500 ft spacing or less was 0.71% error for one of the 300 ft profile spacing. This is close to the 0.83% maximum error for the 500 ft spacing estimated from the axial profile.

The estimated rate of fill for Lake LBJ was found to be 0.27%/yr from Cesium-137 analysis of core samples. If 0.83% is assumed to be the maximum spatial sampling error associated with profiles spaced at 500 ft in Lake LBJ, and this is the only source of error, a 61 yr period between surveys would be required to guarantee constraining the rate of fill to within 10%. For example, at a rate of fill of 0.27%/yr and a survey accuracy of +/-0.83%, one would need to wait until the year 2068 to repeat a survey of Lake LBJ conducted in 2007 to guarantee measuring the volume change to within 10%. The logic of this estimate is as follows. At a rate of fill of 0.27%/yr for 61 yr, one would expect a per cent volume loss of 0.27%/yr x 61 yr = 16.5%. An error of 10% of 16.5% is 1.65% of the total volume of the reservoir. The difference between two surveys, each with a potential error of +/-0.83, could be in error by as much as 1.66%.

Cesium-137 analysis of core samples also provided an estimate of the change in depositions rates during impoundment. Potential Cesium-137 markers occur at the onset of deposition in 1954, a minor peak in deposition in 1958, and the all time peak in deposition in 1964. Along with the independently identified pre-impoundment surface and the date of the core sample, Cesium-137 dates potentially break the sediment column into four time intervals. However, in cores collected in this study, the 1954 and 1958 Cesium-137 time lines were not observed. Hence, the analysis was restricted to just the intervals from impoundment in 1951 to the peak in Cesium-137 deposition in 1964 and from 1964 to the core collection date in 2007. Of the four cores analyzed, core 11, collected in the backwater region showed signs of reworked sediment deposition. Cores 4 and 5, collected in the mid-lake region, showed higher rates of deposition between impoundment and 1964 than between 1964 and 2007. Core 2, collected nearer the dam showed a higher deposition rate post-1964 than pre-1964. Hence, it is difficult to draw conclusions about the differences in the overall deposition rate through time from the core data.

The main reason for this difficulty is that sedimentation in reservoirs is not uniform in time or space. During initial deposition, sediment laden storm water tends to flow along the submerged river channel and to bypass the adjacent submerged floodplain. This continues until the submerge river axis fills with sediment to the point that it no longer contains the volume of turbid storm flows. Once the submerged channel is filled with sediment, further sedimentation is normally more uniform. This means that early deposition rates can be underestimated based on core samples from submerged floodplains. An example of this sediment focusing was found by BU in the study of Lake Aquilla, Texas (Dunbar and Allen, 2003). In Lake Aquila two cores were collected along a single profile across the main arm of the reservoir. One core was collected in the submerged river channel and the other on the submerged floodplain, 200 ft away. The post-impounded sediment layer after 20 years of deposition was found to be 40 cm thick in the channel and only 5 cm thick on the adjacent floodplain. Hence, the apparent deposition rate can differ by a factor of 8 in cores only 200 ft apart, depending on the placement of the cores. Once the submerged river channel is filled with sediment, further sedimentation is more uniformly distributed. Forth this reason, in this study of Lake LBJ, BU relied on average deposition rates since 1964 from three cores collected on the submerged floodplain to estimate the long-term rate of fill.

This study also produced a test of a proposed method for predicting the spatial sampling error versus profile spacing for a given reservoir. The method is based on the analysis of one or more axial profiles, trending orthogonal to the intended survey profile direction. Comparison with volume error for profiles extracted from the multi-beam data indicates the method did a reasonable job of predicting the range of volume error for profile spacing up to 1000 ft. For profile spacing beyond 1000 ft the method under predicted the volume error significantly. The break down in the predictions at larger profile spacings likely stems from inadequate sampling within the tributary arms of the reservoir. The prediction error was based on data from the main arm, and did not account for the fact at large profile spacing, few if any profiles would be placed in the tributaries. This problem could be solved by collecting additional axial profiles along the axes of major tributary arms of the reservoir, but at the cost of more pre-survey testing time.

Conclusions and Recommendations

Five conclusions can be drawn from the BU part of the study of hydrographic survey methods. (1) Both the standard three-frequency and experimental five-frequency SDI profiling systems produced sediment thickness measurements accurate to within 10% for sediment thicknesses of 8 ft or less. Regions in which the sediment thickness appeared to be 12 ft thick were observed in Lake LBJ. To map sediment thicknesses greater than 8 ft, signal frequencies lower than 24 kHz are required. The addition of one or two lower frequencies (e.g. 12 and 4 kHz) to the TWDB system would solve this problem. (2) The two surface modeling approaches used by TWDB and BU produced volume estimates that agreed to well within 1%. However, the TWDB approach of linear interpolation followed by TIN generation by ArcGIS, scales better than the BU approach. The TWDB approach is better suited to making maps of large reservoirs with accurately rendered shorelines. It is possible that a blend of the two approaches could be developed that would have the benefits of both approaches without their respective drawbacks. (3) The test of spatial sampling error versus profile spacing indicated that the standard 500 ft spacing used by TWDB is a good choice for reservoirs like Lake LBJ. Decreasing the spacing substantially would not guarantee better volume estimates and increasing the spacing significantly would likely increase volume error. (4) The results also indicate that estimating the sedimentation rate based on the apparent change in water storage capacity between two surveys separated by 10 yr or less, likely results in errors well above 10%. One solution is to use acoustical measurements of sediment thickness to compute the sediment volume, independent of prior surveys, as is current TWDB practice. It also may be possible to conduct complete or partial surveys with the multi-beam technology and thus improve the accuracy of the water volume estimate. (5) For reservoirs where there is doubt about the adequacy of the standard 500 ft profile spacing, the proposed method of predicting spatial sampling error versus profile spacing appears to produce reasonable bounds on volume error for profile spacing of 1000 ft or less.

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