BUREAU OF RECLAMATION

Technical Report No. ENV-2023-086

Reservoir Survey Cost Estimating – Version 2

Denver Office

Asset Management Division

U.S. Department of the Interior Aug 2023

Mission Statements

The U.S. Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; honors its trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated Island Communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Cover photo: Triangulated surface of Santa Cruz Reservoir (NM) built from boat deployed multibeam echosounder data (Reclamation).

Reservoir Survey Cost Estimating

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Technical Service Center

Denver, Colorado

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Acronyms and Abbreviations

ACAP	area and capacity
ADCP	Acoustic Doppler Current Profiler
BORGIS	Bureau Of Reclamation Geographical Information System, online database
DEM	Digital Elevation Model
ES-1	Executive Summary, Table 1
GIS	Geographical Information System
GPS	Global Positioning System
HYPACK	Software used for bathymetric surveying and data processing
iWBMSh	Wide Band Multibeam Sonar, manufactured by Norbit
LAS	LASer, a format for delivering lidar data
MB1	MultiBeam sonar model 1, manufactured by Odom
MBES	Multibeam Echo Sounder
mi	miles
mph	miles per hour
NAVD88	North American Vertical Datum of 1988
NGS	National Geodetic Survey
RISE	Reclamation Information Sharing Environment
RPVD	Reclamation Project Vertical Datum
RSI	Reservoir Survey Index
S&T	Science and Technology research program
SRH	Sedimentation and River Hydraulics
TSC	Technical Service Center, Reclamation, Denver
UAS	unmanned aerial system
USACE	United States Army Corps of Engineers
USGS	U.S. Geological Survey

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Introduction

Periodic surveys of the Bureau of Reclamation's (Reclamation) reservoirs are needed to maintain proper water operations and to estimate when the dam and reservoir facilities may be impacted by sediment (Randle and Larsen 2021). Within Reclamation, reservoir surveys are performed to produce updated area and capacity (ACAP) tables. These surveys identify trends in sediment accumulation and resulting loss of capacity since the previous survey. Reservoir surveys can also be used to assist maintenance activities, sediment management efforts, inform infrastructure inspections, provide data for estimating the reservoir's economic life, resolve storage capacity conflicts, and other concerns within the reservoir inundation area (Ferrari, 2006).

Recently the Reclamation Manual was updated to include a directive and standard to coordinate, schedule, and budget for Reclamation's costs in the development of reservoir sedimentation plans to periodically update reservoir surface areas and storage capacities (Reclamation Manual, FAC02-01, modified April 20, 2022). FAC02-01 only pertains to storage reservoirs at high and significant hazard potential facilities, of which there are currently 240 in Reclamation's reservoir asset inventory (Reclamation's Asset Management Division's Asset Registry accessed July 11, 2023). Given this new directive, there is a need to develop procedures to estimate costs of reservoir surveys for both individual reservoirs and the entirety of Reclamation's inventory. This is version 2 of a reservoir survey cost estimating best practice report, which supersedes the original version (November 2021). Several improvements have been made in this version. Chief among them is improved values for reservoir area and perimeter used in the rapid cost estimating spreadsheet.

Survey method, water depth and reservoir shape influence the efficiency at which a reservoir can be surveyed and therefore the cost. Typically, topographic data are merged with bathymetric data to form a continuous digital terrain model with enough data to represent the irregular shape of the reservoir. Prior to the 1990s, reservoir surveys were accomplished by surveying established range lines, using either a single beam transducer or manual methods such as lead lines, sounding poles, or levels and transits (USACE, 2013). Past range line or single beam cross-section surveys typically represented 1% to 10% of the reservoir surface when spaced 100 to 200 ft apart (USACE, 2013). More recently, multibeam echo sounders (MBES) equipped with Global Positioning Systems (GPS) have been used for underwater portions of the reservoir survey. Lidar or photogrammetry is typically used for the above-water portions to achieve a more complete, accurate, and cost-efficient reservoir survey. When using a multibeam sonar system, individual beams emanate from the transducer face at various angles, forming a swath. The swath width across the reservoir bottom is a function of depth and swath angle. As a result, a wider swath can be obtained in deeper water than shallow water. The number of beams and the swath angle vary among MBES manufacturers and systems.

In some cases, particularly for small reservoirs or other facilities where a full-size boat is impractical, an acoustic Doppler current profiler (ADCP) or single beam depth sounder can be deployed from various types of vessels, including a raft or remote-controlled boat. This document focuses on determining the cost estimates of multibeam echo sounder (MBES) surveys on Reclamation's reservoirs, supplemented by ADCP or single beam where needed. Additional information is provided on LIDAR or photogrammetry data collection for above water areas, with some example costs from recent efforts.

A bathymetric reservoir survey can involve several different bottom coverage scenarios: reconnaissance, partial coverage, or full coverage. The lowest level of coverage would be a reconnaissance survey (Ferrari, 2006). A reconnaissance survey measures a longitudinal profile along the reservoir centerline or original channel if it can be identified. These surveys may also include several passes along the dam. A reconnaissance survey can sometimes be used as a reservoir sediment monitoring tool to determine when a larger survey effort is needed to update ACAP tables. Reconnaissance surveys are most practical at large storage reservoirs that would otherwise take a significant effort to survey.

On occasion, there is a need to collect a partial survey, where only a portion of a reservoir is surveyed for a specific purpose, such as evaluating bed elevation at or near a marina, critical habitat areas, dam intake, or outlet structure.

A full coverage survey refers to a bathymetric survey where 100% of the reservoir bottom, accessible by a sonar-equipped boat, is surveyed with overlapping swaths of a multibeam sonar, leaving no un-surveyed portions of the bed. A full coverage survey can become time consuming and costly in shallow reservoirs or shallow portions of a reservoir. This is due to the narrow swath width of the MBES in vary shallow water.

When collecting bathymetry for the purpose of updating an area-capacity (ACAP) table, it is not always necessary to perform a full coverage survey. An ACAP-level survey requires professional judgment to establish a plan that collect sufficient bathymetry to represent the entire extent of the irregularly shaped reservoir, that is accessible by a sonar-equipped boat, collecting data over perhaps 60% to 80% of the reservoir bottom (Figure 1). The gaps between the surveyed swaths of data are interpolated when the digital elevation model (DEM) is built.

Most surveys to quantify sedimentation impacts on water storage capacity will perform an ACAP level survey, with overlapping sweeps of the multi-beam footprint in the deepest water and at the dam face (Figure 1). This portion of the reservoir typically has the greatest variability in reservoir bottom elevations due to the lack of significant sediment deposition burying bottom features. Overlapping survey coverage with the multi-beam depth sounder is often desired in these areas to avoid the uncertainty associated with interpolation of bathymetric data between survey sweeps and to provide greater detail near and at the dam. The middle portion of the reservoir is often mapped by surveying longitudinal lines parallel to the shoreline. Depending on the bathymetric variability and depth, a coverage of approximately 50% - 70% may be appropriate in the middle portion of the reservoir where variability in bottom elevation may decrease relative to the deepest area nearest the dam. In the upper reservoir, or delta area, depth is often shallow, resulting in a narrow swath width, and variability in bottom elevations is typically minimal. For these reasons a lesser coverage (35% - 50%) is generally suitable, as linear interpolation between surveyed swaths will normally provide a reasonable representation of the flat reservoir bottom (Figure 1). The delta portion of the reservoir is often surveyed with cross sections so delta channels, if they exist, can be identified and surveyed in greater detail if warranted. Surveying bathymetry in the described manner balances survey time (cost) with sufficient coverage to represent the topographic relief of the reservoir for ACAP computations.

Airborne lidar or photogrammetry is often used to capture the above water portion of the reservoir, as above water topography is needed up to the elevation of the dam crest to provide a comprehensive analysis of reservoir area and capacity. In addition, surveys of the upstream delta can document the upstream sedimentation volume, which often cannot be reached with vessel-based sonar due to very shallow water. Some smaller storage reservoirs are drawn down for maintenance and can be surveyed with airborne lidar or photogrammetry. If possible, it is best to obtain overlapping bathymetric and lidar data to eliminate the need to interpolate between the datasets. Therefore, airborne survey methods should be performed when the reservoir water level is low (drawn down for maintenance, end of irrigation season, or during severe drought periods) while the bathymetric survey should be performed when the reservoir water level is high.

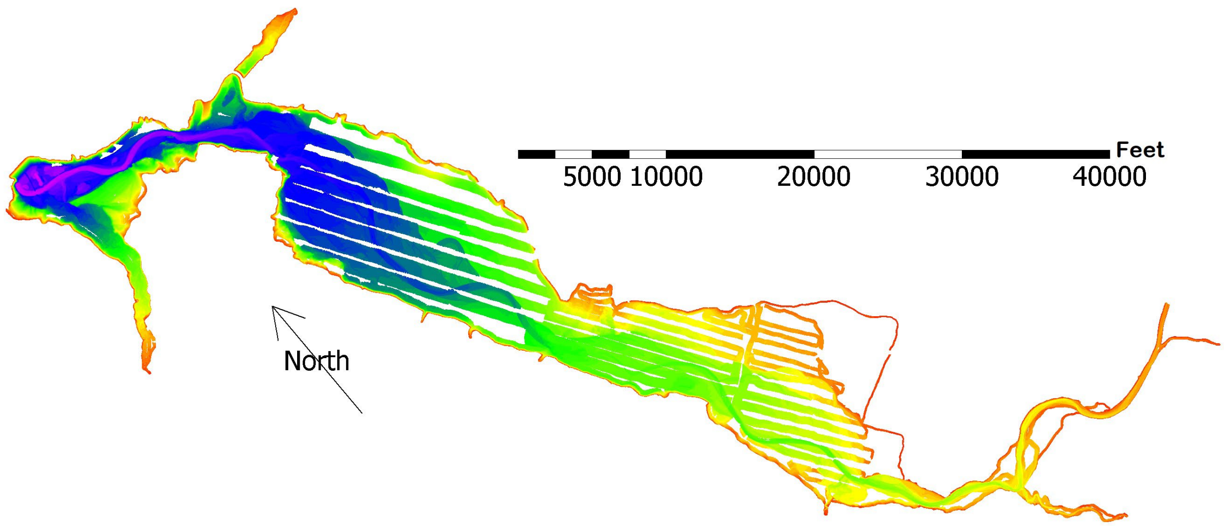

Figure 1. Reservoir survey data for Palisades Reservoir collected in June 2022. This is an example of a typical level of coverage for a bathymetric survey for updating an ACAP table, where full coverage was collected near the dam and approximately 70% coverage in the other portions of the reservoir. The cool colors (purple and blue) represent deeper water. Red represents the shallowest water. Note that the deepest areas near the dam (left side of image) have overlapping data while the middle and upper areas of the reservoir contain gaps between sonar swaths.

Purpose

This document provides guidance for the development of cost estimates for reservoir surveys performed by the Sedimentation and River Hydraulics Group (SRH) at the Technical Service Center (TSC) for Reclamation. There are two methods for obtaining developing a cost estimate: 1) a planning level (rapid) spreadsheet for multi-year budget planning of all future reservoir surveys in each region's asset class (-30% to +50% error), and 2) an implementation cost estimate with high accuracy that incorporates more detailed information and current reservoir conditions.

There are also two methods provided to determine the estimated days spent on the water, which is needed to estimate the cost to survey the reservoir. On-water survey time estimating method #1 includes greater detail and time investment (Appendix 1). The on-water survey time estimating method #2 requires less time to develop (Appendix 2). Both on-water time estimating methods have been tested on several reservoir surveys and return comparable estimated project costs. Either of the on-water methods can be used to estimate the number of days to perform a reservoir survey.

A secondary component of this report includes a master spreadsheet that provides an estimated planning level (rapid) cost for each high and significant hazard potential reservoir in Reclamation's inventory. This spreadsheet was developed using several known quantities and is only intended for an approximation. To compensate for model errors generated from the wide variability in factors that need to be considered for estimating reservoir survey costs, project-specific and professional knowledge should be used in conjunction with the estimate.

Primary Reservoir Survey Cost Estimation for Implementation of Service Agreements

The overall cost estimation begins with understanding the purpose of the survey and important details about the reservoir operations (e.g., anticipated water surface elevations throughout the year) and local conditions (reservoir access, fueling options, overnight boat slips, etc.). A client questionnaire is attached to this report (Appendix 3). This questionnaire can be given to the client to provide key information so that objectives are clear and an accurate cost estimate can be achieved.

Once the questionnaire has been filled out, a cost estimate can be generated by evaluating the amount of work in the three major task areas; pre-survey office costs, field costs, and post-survey office costs. In this document, the estimated on-water time is the time the sonar is turned on and collecting data, not necessarily the amount of time the boat is in the water. Each task and sub-task should be examined to determine if it is applicable to the specific survey, with appropriate labor and non-labor charges applied. A Project Management Plan template has also been created using this outline as a guide and includes ranges of typical staff day estimates for each task. The outline presented below provides a list of topics to help develop a reservoir survey cost estimate. The person leading the reservoir survey should consider each topic to provide an accurate cost estimate. This list may not be complete and there may be other site-specific considerations that affect total cost.

Reservoir surveys performed by Reclamation's TSC typically include 2 people on the boat - a helmsman and a person to operate and monitor the sonar data collection and software. For surveys taking more than 1 or 2 days, a third person often accompanies the crew. The third person can be utilized in a number of ways to allow greater time spent on the water by the boat crew and to decrease data processing time required once the survey is complete.

Estimating Pre-Survey Office Work: Preliminary Evaluation of Survey

1. Define the purpose and need of the survey to determine the scope of work to be performed.
2. Identify what type of bathymetric survey will be needed (See Appendix 3)
3. Determine the appropriate sonar system(s) that will be used (multi-beam, ADCP, single beam). Consider if one or multiple boats will be used.
4. Identify personnel
    a. How many budgeted personnel will participate in the survey? See step 2a below.
    b. If a person will remain on shore, how much time will that person be able to spend on data processing? This person may have other tasks that prevent full-time processing, including:
        i. Shuttling personnel, equipment, fuel, or trailers
        ii. Setting up and breaking down the GPS base station
        iii. Performing ground surveys outside of the normal control point surveys typically required
        iv. Making and overseeing repairs (truck, trailer, equipment, etc.)
5. Determine schedule: Hydrology and reservoir operations will largely determine survey dates, assuming the survey is to take advantage of high-water elevations.
6. A shoreline survey should always be assumed necessary for the purpose of cost estimating.
7. Identify availability of above-water data that will be needed to supplement bathymetric data and estimate time and cost required to acquire and convert to a consistent spatial reference that matches that of the facility. Alternatively, estimate the time needed to implement a contract for acquiring above water data, including writing specifications, processing the contract, and a quality control check of the products. There is a 15% fee to use Denver acquisitions for administering the contract.
8. Review prior surveys to inform spatial extent of new survey and determine if it will be necessary to digitally scan and rectify prior data, in a known projection, to allow for comparison with the new survey data. Multiple reports of previous surveys may exist and need to be examined and their data incorporated into an upcoming report. This will add time for final reporting, particularly if these reports are not readily available.
9. Enter project planning data in bathymetric data collection software including obtaining and loading of background images and creating survey lines, hardware settings, project geodesy, etc.
10. Include time to pack for trip; this typically includes two people for 4-8 hours.

Estimating Field Portion of the Survey

1. **On-water data collection**
   a. Estimate on-water survey time.
      i. Use the on-water time estimating method #1 or #2 – shown in Appendix #1 and #2.
      ii. This estimate should not assume more than 6-7 hours on the water each day due to the factors listed immediately below (1-b). It is likely that there may only be 6-7 hours/day of on-water survey time available, out of a 10-12-hour workday, due to travel time, GPS base set-up/breakdown, boat rigging/derigging, refueling, and other tasks.
   b. Estimate non-survey time in the field.
      i. Set-up and tear-down time for sonar and boat.
      ii. Drive time getting to and from the reservoir.
      iii. Fueling the boat - is it available on the reservoir?
      iv. Mooring the boat – having to launch and recover the boat each day requires rigging and derigging the sonar and other equipment and adds about two hours to the day.
      v. GPS base station set-up time, including driving – this may reduce reservoir survey time unless there's a third person on the trip.
      vi. Collecting multiple sound velocity profiles each day is required, as are calibration and performance tests.
      vii. A calibration patch test needs to be collected, as well as a performance test. The patch test may need to be repeated if equipment strikes the bottom.
      viii. Collecting water surface elevations multiple times a day to compare to local gage record.
      ix. Ground surveying as needed: data gap areas in the topographic (above water) data, collecting data for verifying/validating topographic data.
2. **Ground control survey**
   a. Typically, a ground control survey is required that is limited in scope. The crew will need to identify National Geodetic Survey (NGS) points, benchmarks associated with the dam, and water surface elevations. It is recommended to locate and obtain known coordinates of established points (from NGS or local office) prior to mobilization.
   b. Will more ground survey be required than described above? If so, include time for this in the staff-day estimate.

c. How will access be granted to existing control points on the dam and proposed base-station control points? Include extra staff time as necessary for site access, including drive time and obtaining a key if necessary.

d. Prior knowledge of Reclamation Project Vertical Datum (RPVD) will be helpful, if known. If the project datum is not known, include extra staff time to make this determination.

Estimating Post Survey Office Work

1. **Bathymetric data processing**

   a. Consider multi-beam, ADCP, and single beam data processing.

      i. Conservative estimate is two days of processing for every one day of field data collection for multibeam data. More days may be required in certain cases of difficult bottom or water column conditions (e.g., vegetation, soft reservoir bottom creating multiple returns, high concentrations of suspended sediment).

      ii. Consider the number of days processing that might take place by a third person while in the field. This statement assumes two people on board the vessel and a third 'shore support' person that may spend time processing data.

   b. ADCP data typically takes less time to process than the multibeam data using the single beam editor in HYPACK; safe to estimate one day of processing for each day of field survey.

   c. Staff-day estimates for data processing normally assume familiarity with the processing software and data processing. Add time if personnel do not have processing experience and require mentoring.

2. **Ground survey processing** – include about one day of office processing per survey, unless there are unusual circumstances.

3. **Obtain above-water data**

   a. Availability of recent aerial data.

      i. Will it need to be re-projected to match survey projection and units?

      ii. What's the delivered format (DEM, points, LAS[1])?

   b. If the client is not providing above-water data, plan on some time for a Geographical Information System (GIS) group to research the availability of lidar/photogrammetry/DEM. There may be a cost to acquire these data.

[1] LAS is a standard file format for lidar data.

c. Is there a vertical gap between highest elevations of bathymetric data and lowest elevations of the lidar? This may complicate building the digital surface of the reservoir bottom, thus increasing time and cost to ensure appropriate interpolation methods.

d. Comparisons of ground and lidar data should be made to gain confidence that the surveys match. If lidar and sonar data overlap, compare bathymetry data to lidar data to be sure of a reasonable match. It is necessary to at least compare ground survey points to lidar/DEM data.

4. **Creating Digital Elevation Model**

   a. Cost is typically proportional to the difficulty in merging bathymetry data with above-water data. Lidar and multibeam bathymetric data may contain millions of data points and can take considerable time to work with in a GIS software.

   b. It is likely that elevations will need to be shifted to match RPVD.

   c. Produce a DEM (most often in TIFF format) for area-capacity analysis and main report.

   d. A reservoir map will need to be made for the report appendix. This is most often done with contours.

   e. Include additional staff time if a reservoir surface is available from a previous survey to create a map of sediment deposition thickness (isopach maps).

5. **Error analysis/uncertainty for quality check**

   a. Requires processing of two small rasters (approximately 0.3 to 0.5 acres) of overlapping data to obtain an elevation comparison to determine relative error. This can be accomplished with the performance test collected during the survey.

   b. Obtain mean error and standard deviation, compare to published U.S. Army Corps of Engineers (USACE) standards (USACE 1989, USACE 2013)

6. **Area-capacity data processing**

   a. This step is completed once the digital map has been generated

      i. Additional staff time may be needed if there are multiple previous ACAP tables that need to be incorporated into the plot and analyzed for trends (separate plot to show sedimentation rate)

      ii. If previous area and capacity tables exist, the capacity values can be recomputed using the latest version of the ACAP program (developed by SRH) for consistency in comparison.

7. **Reporting**
    a. This task is not normally less than 12 staff days for authors, including the ACAP report. When reporting involves multiple historical surveys or other analyses several staff days may need to be added.
    b. Consider the staff time required for the following:
        i. Do prior surveys exist? If so, extra time should be allotted to acquire previous reports, evaluate sedimentation trends, create plots, fill out Table ES-1, etc.
        ii. Technical checking
        iii. Peer review
        iv. Prepare transmittal memo
8. **Technical Report Writing**
    a. Obtain cost estimate from technical writer for formatting, finalization, and 508 compliance.
    b. Include ACAP results (including ACAP plot, ACAP coefficients, and write-up) in the final report appendix. Be sure the ACAP appendix includes a header stating the reservoir name, survey date, and computation date.
    c. Prepare and sign the transmittal memorandum.
9. **Project Management**
    a. Meetings with client.
    b. Meetings to plan survey (survey team).
    c. Time to plan survey (survey lead).
    d. Time to prepare boat(s) and equipment ahead of the trip.
    e. Time to unload boat(s) and equipment upon return.
    f. Project close-out meeting
10. **Archiving**
    a. Organize files on a Reclamation network drive (e.g., T-drive reservoir project folder for TSC) and remove unnecessary files that are no longer needed for archive (e.g., old versions of rasters, partial work files, duplicate files, etc.).
    b. Perform a project close-out meeting with client.

c. Post data and reports to the TSC reservoir surveys web page, RISE, RESDATA, and RSI[2] databases. This should be discussed in an internal close-out meeting.

11. **Contingencies** – There should be a field contingency and an office contingency.

   a. The field contingency is intended to absorb unexpected cost while conducting the survey. This can include, but is not limited to: boat problems, sonar/survey equipment problems, reservoir conditions (e.g., wind, lightning) preventing survey, truck/trailer repairs, additional cost due to inability to moor boat and/or obtain fuel on the reservoir, etc. Field contingency minimum is recommended as 1 - 2 days for each field person, depending on reservoir size.

   b. The office contingency is intended to include unforeseen cost associated with data processing, development of the digital surface, mismatch between current and past survey(s) that need to be investigated, etc. Office contingency is recommended as 2 days. These contingencies should be adjusted as appropriate for reservoir size.

[2] RISE = Reclamation Information Sharing Environment, a public facing website (data.usbr.gov); RESDATA = Reservoir Data, Reclamation's internal reservoir survey database; and RSI = reservoir survey information, a USACE reservoir survey database.

Rapid Cost Estimating Tool for Planning

To assist with long-term planning by Reclamation staff in facilitating implementation of FAC 02-01 reservoir survey monitoring plans, there is a need to obtain a preliminary cost estimate for one or more reservoir surveys to better understand budgeting needs. This section explains the methodology used in creating the reservoir survey cost estimating spreadsheet that accompanies this report (found here). This tool is intended to be a quick process, bypassing all the details included in the previous section. Because of this, the results of this tool are not as precise as using the primary cost estimating method intended for service agreements. This tool assumes that a reservoir will be surveyed to develop an updated area-capacity table. The rapid cost estimate tool also assumes that the entire wetted area of the reservoir will be surveyed with approximately 75% coverage, using interpolation between data swaths to create a surface map of the reservoir bottom, with the exception of the area near the dam where overlapping coverage is expected. The rapid estimating tool utilizes the on-water survey time estimator #2 (Appendix 2) for estimating the number of days spent on the water. Several factors are required to arrive at an estimate of on-water time, including reservoir area, reservoir capacity, shoreline length, boat survey speed, and sonar swath width.

A linear regression was developed using actual days on the water and actual cost for 13 reservoir surveys performed by the TSC (figure 2). The cost for Nambe Falls and Paonia Reservoirs, surveyed in 2013, were adjusted to 2022 dollars. All other surveys were performed between 2019 and 2022. The regression provides an approximate cost given an estimated number of days on the water, shortcutting the longer, more detailed primary cost estimating process to provide a more precise cost estimate. The reservoir shoreline length (perimeter) and reservoir surface area are obtained using the BORGIS on-line database. It is noted that the reservoir perimeter and surface area values in BORGIS are typically larger than those delineated using manual methods on a rectified aerial photograph. Nonetheless, these values provide a legitimate and consistent means for a rapid, preliminary cost estimation.

In equation 1, the number of on-water survey days is represented by T_{days} and the estimated reservoir survey cost is represented by C. The formula is taken from the best fit line, shown in figure 2. Costs estimated using Equation 1 may have to be adjusted in future years (cost indexing) to account for inflation and additional reservoir survey cost data. Reservoir surface area and perimeter values must come from BORGIS/TESSEL/RGIS[3] for this formula to work properly.

[3] BORGIS/TESSEL/RGIS = Bureau of Reclamation Geographical Information System, online database

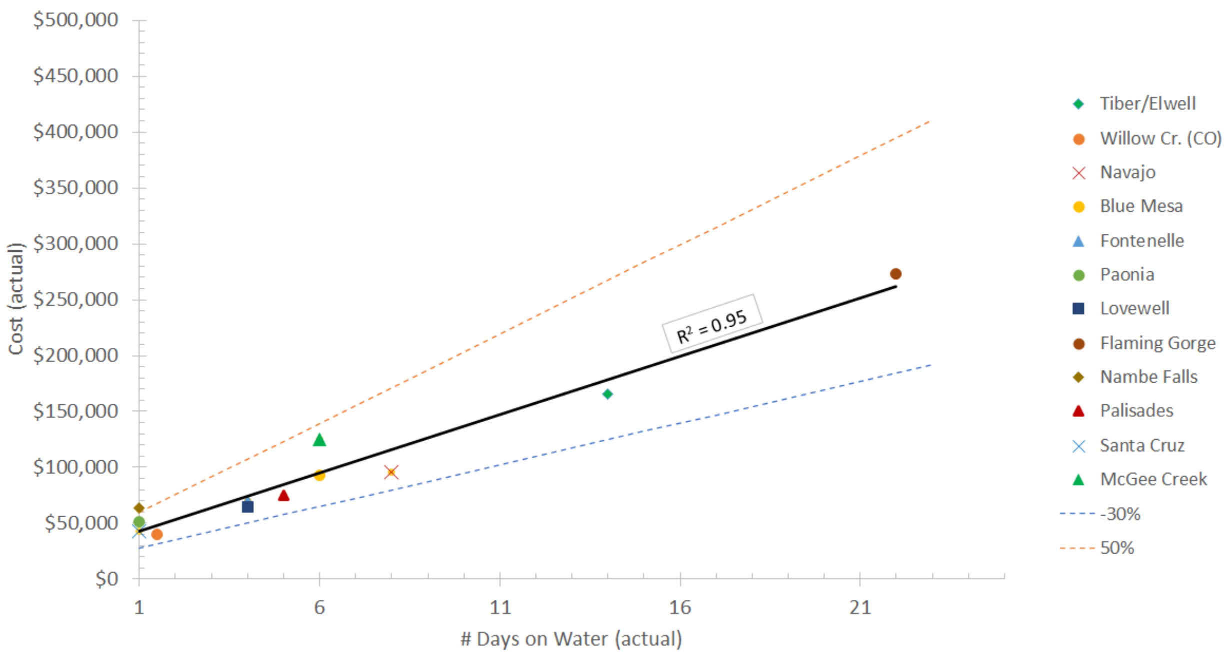

Figure 2. Plot of actual reservoir survey cost and actual number of days on the water. The black solid line represents a best fit of the data, resulting in the regression shown below in equation 1. The assumed error is shown with the orange dashed line (+50%) and the blue dashed line (-30%).

$$C(\$) = 10{,}425 * T_{Days} + 32{,}276 \; (-30\% \; to + 50\%) \qquad \text{Eq. 1}$$

The bathymetric survey costs used to create Figure 2 are in some cases inconsistent. All cost estimates using this method assume a reservoir shoreline survey; however, a shoreline survey was not performed on Navajo Reservoir (Varyu 2021) due to deep water near the reservoir margin and nearly vertical sides throughout most of the reservoir. Drive times were not differentiated in this analysis, nor was the number of boats and crews used during the survey. Flaming Gorge Reservoir and Lake Elwell surveys involved the use of two boats and two crews. The long duration of the Flaming Gorge survey included additional costs associated with swapping survey crew members halfway through the survey. Table 1 shows the data used to create the plot in Figure 2.

It is expected that a refined cost estimate for a service agreement will most often be within -30% and +50% of this preliminary estimate. The error stated here was taken from ASTM (2006), which provides a generic classification system for cost estimating. The error values are based on a cost estimate for scoping work that includes technical complexity and a low degree of project definition.

The percent coverage of the reservoir is an approximation, not an exact measure of what was actually surveyed. The theta value (on-water time estimator #2, Appendix 2) is determined by the coverage angle of a specific multibeam sonar. In this example, the angle was reduced by 10 degrees to account for removing the outer 5 degrees on each side of the multibeam swath during post processing to reduce the bottom measurement error. The Odom MB1 multibeam sonar has a swath width of 120 degrees, reduced to 110 degrees. The Norbit iWBMSh[4] multibeam sonar has a variable swath width and the most effective swath width is determined with a performance test. Future surveys by the Sedimentation and River Hydraulics Group will use the Norbit sonar. See Appendix 2 for more details about this on-water survey time estimator.

The reservoir survey cost estimating spreadsheet includes all the necessary data to approximate the cost for all Reclamation's high and significant hazard potential reservoirs. When using this spreadsheet for reference, it's important to remember that some anomalies have been noted in the reservoir area and perimeter values. Reservoir survey cost estimates resulting from this spreadsheet should be considered preliminary and updated with the implementation cost estimating method for final service agreement development. In the companion spreadsheet the estimated number of days on the water was rounded up to the next largest integer and the calculated cost was rounded up to the nearest $1,000.

[4] Wide Band Multibeam Sonar, manufactured by Norbit.

Table 1. Table of values used to create the data in Figure 1

Reservoir Name	Reservoir Perimeter (mi)	Reservoir Area (mi^2)	Capacity (ac-ft)	Approximated Percent Coverage	Odom MB1 theta (degrees)	Norbit iWBMSh theta (degrees)	Shoreline Boat Speed (mph)	Open Water Boat Speed (mph)	Survey Year (FY)	Actual Days on Water
Elwell (MT)	248	38.5	1,200,000	80.0	------	145	4	6.5	2021	22
Willow Creek (CO) 2021	7.4	0.42	10,600	90.0	------	150	5	6.5	2021	1.5
Willow Creek (CO) 2022	7.4	0.42	10,600	90.0	------	150	5	6.5	2021	1.5
Navajo (NM)	187	24.5	708,600	70.0	110	------	4	6.5	2019	8
Blue Mesa (CO)	95	14	940,800	70.0	110	------	4	6.5	2019	6
Fontenelle (WY)	47.4	12.4	345,400	70.0	110	------	4	6.5	2019	4
Paonia (CO)	8	0.5	20,950	75.0	110	------	4	6.5	2015	1
Flaming Gorge (WY & UT)	413.9	63.2	3,788,700	70.0	110	------	5	6.5	2019	22
Lovewell (KS)	28.6	7.9	92,150	50.0	110	------	5	6.5	2020	4
Nambe Falls (NM)	2.1	0.08	2,023	90.0	110	------	5	6.5	2013	1
Palisades (ID)	75.4	24.9	1,402,000	65		155	4.5	6.5	2022	5
McGee Cr. (OK)	88.7	5.9	113966	80.0	------	150	4.5	6.5	2022	7
Santa Cruz (NM)	2.8	0.15	3,534	90	------	150	4.5	6.5	2022	1

mi = miles, ac-ft = acre-feet, mph =miles per hour, FY = fiscal year

Above-Water Surveys

Reservoir sedimentation surveys require topographic or photogrammetric data above the reservoir pool at which the bathymetric survey was collected to create a continuous surface representing the full range of reservoir operations (typically up to the spillway crest but can be higher in some facilities). There are multiple means to accomplish the above-water survey, the most common of which is airborne lidar. Other online lidar data may be available and should be checked for applicability prior to contracting a new data collection effort. The closer in time the lidar data are collected to the bathymetric data, the more accurate the combined map will be. Additionally, a lidar survey performed at low water conditions allows for overlap by the bathymetric survey, preventing mapping artifacts due to interpolation across gaps in survey data coverage.

Smaller reservoirs with limited shoreline may be able to take advantage of unmanned aerial system (UAS) surveys using photogrammetry or lidar to obtain elevation data for the exposed portion of the reservoir. Another option is to attach a lidar system to the boat so that the shoreline topography can be scanned while conducting the bathymetric survey. In some cases, older surveys of the above-water portion can be used; however, the applicability depends on whether or not the reservoir shoreline or delta have significantly changed since the data were collected. If shoreline erosion or landslides are not a factor and the reservoir delta has not eroded or prograded since the last aerial survey, older surveys can likely be used.

The above-water survey needs to include all land elevations at and below the elevation of the dam crest, reservoir deltas, and tributaries influenced by the dam operations. Reservoir deltas can extend upstream from the full reservoir pool at higher elevations, sometimes for miles along mildly sloped rivers. Surveys of these deltas can have important implications for reservoir flood storage, increases in upstream flood stage, and fish passage (Randle et al. 2021). Tributaries entering the reservoir will also need to be included in the above-water data collection to represent elevations below the spillway crest and any sedimentation effects that may extend farther upstream.

When water is drawn down for any purpose (annual operations, drought, maintenance, etc.) aerial surveys can be performed with greater efficiency and possibly lower cost compared to bathymetric surveys (Baker et al. 2016). Low-water conditions during drought periods often affect multiple reservoirs in close proximity, and those reservoirs can be surveyed in a single effort, improving the economy of scale with lidar or UAS contracts (Baker et al. 2016). Aerial lidar or UAS surveys will provide high resolution data for 100 percent of the dry portion of a drawn-down reservoir. The reduced area of the reservoir that remains under water can be surveyed using bathymetry at a reduced effort and cost following the aerial data acquisition, if needed.

If above-water topographic data is unavailable from recent or planned aerial surveys, U.S. Geological Survey (USGS) Digital Elevation Models (DEM) can be used. However, these maps often have accuracy and resolution that is marginally acceptable for the determination of reservoir area and capacity. Additionally, the DEM surface may require special interpolation where it would interface with the bathymetric data to address inconsistencies that can be difficult to resolve.

Recent Cost Examples for Reservoir Surveys

This section reviews available information on cost data for reservoir aerial surveys. Examples from two separate data collection methods include UAS and airborne lidar. Baker et al. (2016) provides unit cost data for reservoir surveys using both bathymetry and lidar. However, using unit costs as a means for estimating the cost of a reservoir survey can lead to wild under or over estimations. The unit costs can vary more than an order of magnitude and provides a less accurate means to estimate the cost of a reservoir survey than has been covered in this report. However, the means for cost estimations provided in previous sections of this document do not include the cost for above water surveys. The section below will provide some examples of aerial surveys to either obtain just the above water topography or the entire reservoir when it is drawn down.

UAS

A recent example of an aerial survey performed during reservoir drawdown is Willow Creek Reservoir in Montana (Bradley and Collins 2021). This reservoir was drawn down for maintenance purposes, leaving more than 90 percent of the reservoir bed exposed. A UAS survey was performed by a private contractor at a cost of $45,733 over 1,499 acres. This contract value includes survey data processing and delivery. The TSC used the aerial data to create a digital map, calculate the updated reservoir area-capacity tables, and produce a report. It is worth noting that the cost of this aerial data collection and processing is similar to the cost of a bathymetry survey for this small reservoir, including area-capacity determination and reporting. However, it would likely have been necessary to obtain above-water elevations had this reservoir been surveyed using sonar, because bed elevations are needed up to the dam crest.

Another recent example of UAS data collection is on Willow Creek Reservoir (~300 acres) in Colorado (Hilldale 2022). To obtain above-water topography at Willow Creek Reservoir, River Science (Cañon City, Colorado) flew a camera-equipped drone to obtain photogrammetry using structure from motion at a 1-foot horizontal resolution. The photography did not include the wetted portion of the reservoir. These data were combined with bathymetric survey data collected one week prior to provide a complete reservoir map over the full range of reservoir elevations. The cost for the aerial drone survey was $20,954. This cost includes constructing the digital surface map by combining the above-water aerial and below water bathymetric data.

Avalon Reservoir (NM) was surveyed in spring 2023 using UAS photogrammetry during a full reservoir drawdown at an approximate cost of $95,130.

LIDAR

In 2022 Guernsey Reservoir (WY) was drawn down for maintenance. The reservoir covers 1,944 acres (~ 3 mi^2). During the drawdown aerial lidar was flown over the drained reservoir to obtain a survey of the reservoir bottom to update the area-capacity table for the reservoir. No bathymetric survey was performed. The lidar cost was $101,000, which provided aerial photography (RGB color) and airborne lidar with a planned average point density of 4.5 points/m^2. An additional $15,000 cost was incurred to pay for the contract acquisitions process and 5 staff days to develop contract documents (e.g., technical specifications, independent government cost estimate, market research), and manage the contract. The budget required to complete the area-capacity table and reporting was $33,600 (Hilldale et al. 2022). This cost includes a quality check of the lidar, construction of the digital surface, ground survey to determine the vertical shift from NAVD88 to RPVD, creation of the ACAP table, and reporting.

In October 2022 aerial photography and lidar was collected for Palisades Reservoir (ID) for the above water portion of the topographic surface generated for ACAP analysis. The total cost of the aerial survey was $83,000 which was contracted by the Columbia Pacific Northwest Regional Office of Reclamation (does not include regional staff time to implement contract). Palisades Reservoir is a somewhat narrow reservoir approximately 16.5 miles long. Under the same contract and budget, lidar was also collected along 13 miles of the Snake River downstream of the dam in anticipation of future studies. Bathymetry was also collected in June 2022 for the purpose of updating the area-capacity table. The budget required to complete the bathymetric survey, digital terrain model development, ACAP analysis, and reporting was $114,000.

Funding the Cost of a Reservoir Survey

The cost for the bathymetric survey portion of all 240 high and significant hazard potential reservoirs is approximately $22 million (-30 to +50% error) based on the rapid cost estimating tool. This cost could double if recent aerial surveys for above water portions are not readily available. The median bathymetric reservoir survey cost estimate is $54,000, and about 80% of the surveys are estimated to cost less than $100,000 (-30 to +50% error). About 20% of Reclamation's reservoirs are large enough that the estimated rapid cost is over $100,000 (-30 to +50% error). Reservoir sedimentation surveys should be completed on a routine basis, approximately every 5 to 10 years with some needing more frequent surveys and others less frequent, depending on sedimentation rates (USACE, 2013). Only 57% of Reclamation high and significant hazard potential reservoirs have been resurveyed at least once since original construction, indicating an urgent need to start planning for how to fund the cost to implement sedimentation surveys. Of the 57% of reservoirs that have been resurveyed, the average frequency is one survey every 61 years, far below the recommended 5 to 10-year interval. Examples of Reclamation facilities that have conducted more frequent sedimentation surveys include Brantley Reservoir and Elephant Butte in New Mexico at 11- and 13-year frequencies, respectively. A Reclamation Reservoir Survey Team Board has been created with representation from each region and the TSC to work on strategic planning in FY23 to FY25 for funding reservoir surveys to meet the requirements of FAC 02-01. The cost of surveying Reclamation reservoirs is usually borne by the associated regional or area office and in some cases water district partners operating the dam. However, there are occasionally other opportunities to obtain funding or matching funds for reservoir surveys. In situations where there is a research question associated with the reservoir, the Science and Technology (S&T) Office may contribute funds if successfully awarded through the annual competitive call for proposals. A recent example is Willow Creek Reservoir in Colorado, where the S&T Office is paying for bathymetric surveys in 2020 through 2024 because of the research interest in understanding the rate and magnitude of increased sedimentation impacts to storage capacity following a large wildfire in the watershed. In this specific case, the Northern Colorado Water Conservancy District partnered with Reclamation and is contributing in-kind funds for the surveys. In some instances, a partial reservoir bathymetric or aerial survey is needed for maintenance, inspection, or dam safety purposes. When this need arises, there may be an opportunity for matching funds to pay for a complete survey to acquire updated area-capacity values.

Conclusions

This document provides two methods for estimating the cost of a reservoir survey. The primary cost estimating method is intended for implementing a reservoir survey, complete with the associated cost estimate for a service agreement. On-water survey time for this method can be estimated using either Appendix #1 or #2. The rapid cost estimating tool, developed for building the reservoir survey cost estimating spreadsheet, is intended for planning purposes only. This method allows for quick reference to approximate costs for an individual or multiple reservoirs.

The actual cost information utilized to develop equation 1 is time sensitive and will need to be updated periodically. When considering aerial surveys, there is an economy of scale that can reduce survey costs compared to what they might otherwise be if a single reservoir was surveyed in an individual contract. Fixed costs can be shared across multiple reservoirs in a single contract.

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Appendix 1:
On-Water Survey Time Estimating Method #1

(Detailed on-water survey time estimate)

Method #1 On-Water Survey Time Estimator

The cost of bathymetric surveys depends primarily on the water surface area and perimeter of the reservoir, water depth, and type of depth sounder. The greater the surface area and perimeter, the longer the distance a survey boat will have to travel to complete the survey. A key factor in determining the field data collection cost is the amount of time needed by the survey crew to measure and collect the data. The number of on-water survey hours (T_S) can be estimated by dividing the total length of survey lines (L_S) by the average speed of the survey boat (V_B) and the number of survey hours per day (H_D). The number of on-water survey hours per day is typically 6 – 8 hours during a 10 – 12 hour work day.

$$T_s = \frac{L_w}{V_B} \qquad \text{Eq, 1-1}$$

The total length of survey lines (L_S) is estimated by breaking down the reservoir into reaches and estimating the length of all survey lines for each reach (Figure 1-1). Parallel survey lines should be laid out and lengths totaled for each of the survey lines in each reservoir reach. In addition, survey distance along the reservoir shoreline should be estimated. Figure 1-1 is an example of the map showing the layout of reservoir survey reaches and the corresponding table for computing number of survey lines, lengths, and boat time for Blue Mesa Reservoir near Gunnison, Colorado. A good approximation for survey speed is 5-6 mph.

When a single beam depth sounder is used, the parallel survey lines should be spaced close enough that linear interpolation of data between survey lines will be adequate. Consideration should be given to representing topographic breaks, particularly where there is a rapid change in surfaces (refer to original surface map if available) or slope (e.g., tributaries or upstream segments).

A multi-beam depth sounder provides far greater data coverage than a single beam depth sounder along a given survey line. The greater the water depth, the greater the width of data coverage. This method includes a fixed swath width for each reach, which is determined by the swath angle on the multibeam transducer. The swath width and the desired coverage will determine the line spacing. Parallel survey lines should be spaced close enough to provide overlapping coverage between survey lines in deep areas near the dam. In shallow and/or flat areas of the reservoir, such as deltas, it may not be practical to achieve full coverage. The reaches were created in areas with similar depth so that line spacing can be estimated in each reach. For example, reach 1 had an average depth of 300 feet, which required line spacing approximately 900 feet apart. In contrast, reach 6 had an average depth of 250 feet, which required a different line spacing of 750 feet.

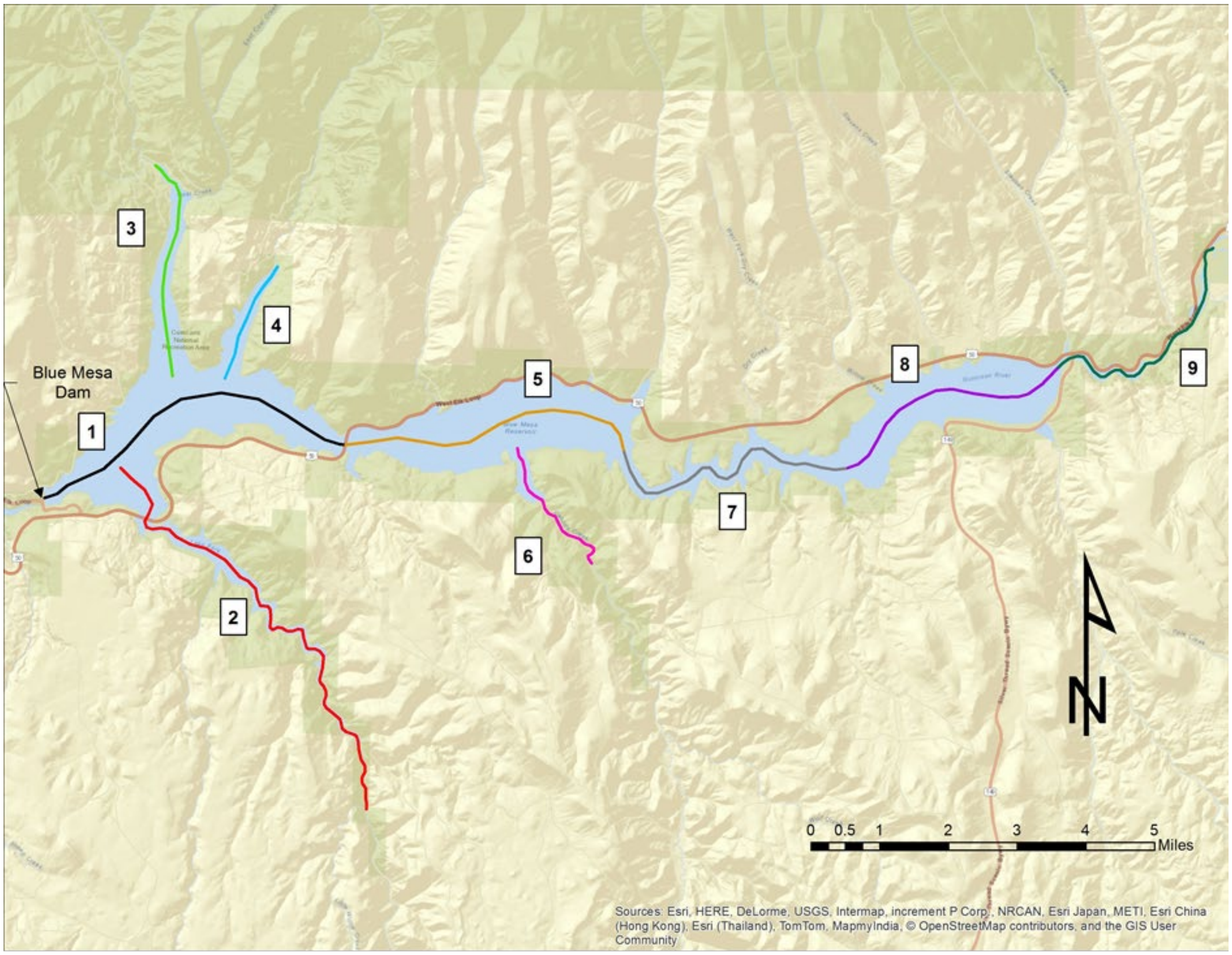
This requires some knowledge of approximate reservoir bed elevations, which can be obtained from prior surveys. Another source of approximate reservoir depth is available at the website *i-Boating*. The depth values shown are gathered with personal fish finders and then uploaded to create a map of the reservoir bottom. In the case of a reservoir, water elevation is not used when these data are collected, and depth will be relative to an unknown water level. These maps are accurate enough for estimating survey time covered in this appendix, but not for quality digital maps and area-capacity analyses.

A survey crew of three people may be ideal:

1. boat pilot;
2. operator, managing the computer, depth sounder, GPS instruments, and data collection software; and
3. data processor and shore support.

With this three-person crew, data processing may occur while the survey data are being collected. Data processing in the field will ensure adequate data coverage and good data quality before leaving the reservoir. Additional staff days in the office will be required for final data processing, development of the digital terrain surface and maps, computation of the storage capacity tables, and writing of the sedimentation survey report. A three-person crew may not be beneficial for small reservoir surveys.

For large reservoirs, it is sometimes beneficial or necessary to move from one marina or boat launch to another to access the areas to be surveyed more efficiently. This method can help identify the timing of such a move and help guide the logistics of marina and lodging reservations (if the team switched lodging). In this example (Figure 1-1) it was determined that after 4 survey days it would be beneficial to move from a marina in reach 1 to a marina in reach 7.



Reach No.	Reach Name	Length (miles)	Top Width (feet)	Avg. Depth (feet)	Swath Width (feet)	No. Survey Lines	Survey Length (miles)	Survey Time (hours)
1	Gunnison River 1	5.0	4224	300	900	9	45	6.4
2	Lake Fork Gunnison River	6.8	845	275	825	2	13.6	1.9
3	Soap Creek	3.4	1320	275	825	3	10.2	1.5
4	West Elk Creek	1.8	1320	275	825	3	5.4	0.8
5	Gunnison River 2	4.4	5280	225	675	15	66	9.4
6	Cebolla Creek	3.5	845	250	750	3	10.5	1.5
7	Gunnison River 3	4.1	1320	150	450	6	24.6	3.5
8	Gunnison River 4	3.8	4050	75	225	34	129.2	18.5
9	Gunnison River 5	2.3	634	50	150	8	18.4	2.6
						Totals	**323**	**46**

Figure 1-1. Example of survey reach layout map and corresponding table for the computation of on-the-water time necessary to complete the bathymetric survey (Blue Mesa near Gunnison, Colorado).

Appendix 2: On-Water Survey Time Estimating Method #2

(Simple on-water survey time estimate)

Method #2 On-Water Survey Time Estimator

This document provides a description of how to estimate the amount of time it will take to survey a given body of water. This in turn can be used to estimate the number of days on the water. The time on the water is made up from two distinct parts: the shoreline survey and the coverage survey.

The time it takes to complete a shoreline survey is estimated as the length of the shoreline (the perimeter of the reservoir) divided by the (depth averaged) boat speed during collection. The boat speed during a shoreline run is typically lower than that during a coverage survey.

The coverage survey can be estimated using the following parameters:

- Storage capacity (volume) of the water body
- Surface area of the water body
- Swath angle of the MBES
- Survey speed of vessel
- Percent coverage that is desired or specified.

The storage capacity and the surface area of a water body are available from a range of potential sources, including BORGIS, USBR website, Wikipedia, recreation websites, or Reclamation (regional, area, field) offices.

Equation 2-1 demonstrates the calculation for the shoreline survey, and equation 2-2 demonstrates the calculation for the coverage survey.

$$T_{shoreline} = \frac{L_{shoreline}}{v_{shoreline}} \qquad \text{Eq. 2-1}$$

Where $T_{shoreline}$ = time to conduct shoreline survey (hours)

$L_{shoreline}$ = length of shoreline (miles)

$V_{shoreline}$ = boat speed during a shoreline run (miles per hour)

$$T_{coverage} = \frac{\left(A_{surface}\right)^2 \cdot \%_{cover} \cdot k}{Cap \cdot v_{coverage} \cdot 2\tan\frac{\theta}{2}} \qquad \text{Eq.2-2}$$

Where $T_{coverage}$ = time to conduct coverage survey (hours)

$A_{surface}$ = surface area of the water body (square miles)

$\%_{cover}$ = desired/required coverage of the reservoir (-)

k = conversion factor = $(640\ ac/mi^2)\cdot(5280\ feet/mi)$

Cap = capacity of the reservoir (acre-feet)

$V_{coverage}$ = boat speed during coverage surveying (miles per hour)

θ = swath angle of the MBES (degrees)

Adding together $T_{shoreline}$ and $T_{coverage}$ will provide an estimate for the hours of data collection needed to obtain the desired coverage. It is worth considering additional time for things such as patch tests, performance tests, obtaining velocity profiles, areas of higher coverage (dam face, water intakes, etc.). Once this has been determined, the number of days on the water needs to be estimated, which will be based on the hours per day that actual data collection can occur. The hours per day estimate need to consider the following at a minimum:

- Travel time between lodging and boat access (marinas, ramps)
- Whether boats are moored at a marina or need to be launched and retrieved each day
- Whether fuel is available on the water or if gas cans need to be filled each day

$T_{coverage}$ calculation, explored

The **coverage area** of the survey is unlikely to be the surface area of the reservoir. In some cases, the need for highly accurate data would require collecting overlapping swaths of data (greater than 100% coverage). In other cases, complete coverage of larger reservoirs may become cost-prohibitive (less than 100% coverage). The swath width largely dictates how efficient a reservoir survey can be and is a function of the swath angle and the depth of the water column below the boat. This can be determined with a performance test. Figure 2-1 provides the ratio of swath width to depth as a function of swath angle. Different MBES units have different capabilities when it comes to the usable swath angle.

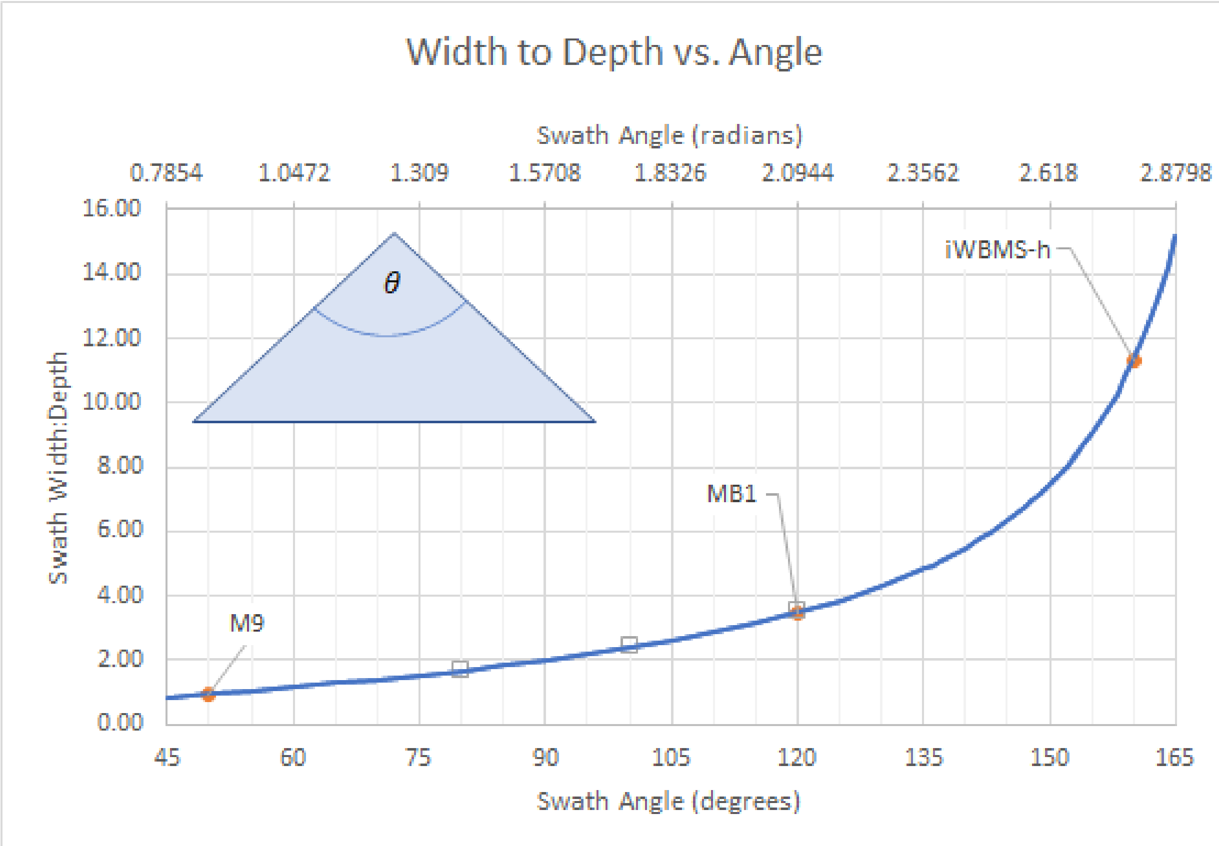


Figure 2-1. Swath width to depth ratio for a range of swath angles.

The swath width is calculated as

$$W_{swath} = 2\tan\left(\frac{\theta}{2}\right) \cdot d \qquad \text{Eq. 3}$$

Where W_{swath} = width of the bathymetric swath (ft)

θ = swath angle (radians)

d = depth of the water column under the MBES (ft)

The water depth varies across the reservoir domain and is an unknown. Therefore, an average depth can be estimated from the reservoir volume and surface area.

$$d_{ave} = \frac{Cap}{A_{surface}} \qquad \text{Eq. 4}$$

Where d_{ave} = average reservoir depth (ft)

Cap = reservoir capacity (acre-ft)

$A_{surface}$ = surface area of the reservoir (acres)

Substituting equation 4 into equation 3 yields equation 5

$$W_{swath} = 2\tan\left(\frac{\theta}{2}\right) \cdot \frac{Cap}{A_{surface}} \qquad \text{Eq. 5}$$

The product of boat speed and swath width provides an area per unit time, which can be combined with the desired coverage area to get a time on the water

$$T_{coverage} = \frac{\%_{cover} \cdot A_{surface}}{v_{coverage} \cdot W_{swath}} \qquad \text{Eq. 6}$$

Combining equations 5 and 6 yield equation 2.

Appendix 3: Client Questionnaire

Reservoir Survey Client Questionnaire

1. What is the purpose of the survey and spatial extent needed? This will help determine cost and methodology. Purposes include:
    a. Sedimentation survey of entire reservoir up to dam crest for updated surface area and storage capacity tables. For area-capacity table updates, what is the maximum elevation needed? Are there any critical elevation ranges that are high priority?
    b. Rough estimate of the sedimentation volume and longitudinal distribution using a reconnaissance survey
    c. Assistance with construction or maintenance activity
    d. Numerical modeling specific to temperature, flood routing, sediment routing during operations
    e. Other. Please explain
2. Does a contour map of the original, pre-dam reservoir surface exist? If so, is it available in digital form and has it been rectified to a known projection?
3. Has the reservoir been surveyed since dam construction? If so, for what years and are the survey data and reports available? Were new area-capacity tables generated from the survey(s)?
4. Is the relationship between the Reclamation project vertical datum and a modern datum (NAVD88)[5] known?
    a. Are there known control points on the dam or along the reservoir shoreline?
    b. Are the coordinates and datums of these points known and available?
    c. Is a regional licensed surveyor available to assist with survey control?
5. Who will provide local access to the dam, any known control points, and inside the reservoir boom during the survey? Other local support may be needed.
6. Is recent above-water survey data available (lidar, photogrammetry)? What elevation range does it cover (compare dates of above water collection with reservoir stage data)? Is it representative of current topography?

[5] NAVD88 = North American Vertical Datum of 1988

7. Are there any recent aerial photographs of the reservoir area?

8. Are there any specific areas of interest where higher detail is needed (e.g., dam outlet works, reservoir water intakes, recreation areas, levees/dikes/berms)? The area at and near the dam is normally surveyed in high detail.

9. What is the time frame for the survey?
    a. When is the reservoir typically full? When is the projected highest elevation in the year to be surveyed?
    b. Are there any planned drawdowns of reservoir during which time lidar or photogrammetry could be collected?
    c. Are there any near-future plans to change regular reservoir operations (e.g., maintenance, downstream needs etc.)?

10. What are the expected bottom conditions for the survey? Are there any known conditions that would prevent our sonar from measuring the true reservoir bottom?
    a. Suspended sediment (fluff) layer above the true bottom?
    b. Dense vegetation or trees (typically in shallower areas)?
    c. Areas of aeration in the water column or near the bottom?

11. Are there any special considerations for the survey? For example, potential construction conflicts, excessive vegetation growth, boat ramp access, unique hazards, recreation use (fishing derby, water skiing competition), weather constraints, etc.

12. Is there any instrumentation on the reservoir that may interfere with our sonar signal (e.g., depth sounders, pressure transducers, etc.)?

13. Can the boat be stored safely on the reservoir overnight? This could be a marina or secure shoreline.

14. Is gas available on the reservoir (e.g., marina)?

15. What are the current reservoir sediment management concerns (storage reduction, burial of intake, burial of marinas, delta fish passage barriers, impacts to fisheries in downstream river, other)?

16. Is sediment currently released through the dam (density current, pressure flushing through gates, drawdown through gates) and if so, what time of year and through what outlet?

17. Has reservoir sediment been dredged or is there a plan or expectation that dredging will be required? If so when and in what general area of reservoir (delta, near dam, at intake, near facilities)?

18. Have there been any extreme events since last survey that may have changed sedimentation loading to reservoir (wildfire, tributary event, upstream dam removal, etc.)?

19. Is there a need for sediment coring? If so, what is the purpose (particle size and/or chemical analysis)?

20. Is there a need for sediment load measurements into reservoir or downstream of dam?