Chapter 9

Reservoir Survey and Data Analysis

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by

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9.1 Introduction

This chapter provides guidelines, techniques, and information that can be used by Reclamation and others for planning, collecting, analyzing, and reporting of reservoir and river survey studies; the ultimate goals are preservation of the information and uniformity of collection and analysis. This chapter mainly refers to the reservoir survey applications, but much of the equipment, techniques, and technology can be adapted for river and above water data collection.

This chapter mainly addresses the bathymetric or underwater field survey process, but the overall sedimentation analysis usually consists of data for the entire study area. In this guide, the term "bathymetric survey" specifically refers to the collection of water depths, while the term "hydrographic survey" refers to the entire survey, including the above and below water portions of the study area. The term "reservoir survey" implies a variety of field observations and measurements, data processing, analyses, and report preparation that can also be applied to river surveys.

The above water portion of the reservoir can be measured by several means. Conventional surveying techniques using stadia rods, transits, and total stations, and global positioning systems (GPS) can be used, along with photogrammetric mapping or aerial surveying, which provides a more automated means for above water collection. The Sedimentation Group usually coordinates with the Reclamation regional offices or other groups within the TSC to obtain the necessary above water data for an ongoing study. Some Reclamation offices have the capability of setting the necessary ground control and conducting the photo interpretation, some offices use a contracted professional surveying service for only the aerial flight or aerial field collection, and some offices contract the complete above water surveying services.

The survey technology has changed significantly over recent decades with the dramatic increase in the speed of data acquisition and computer system processing. GPS has significantly reduced the time and cost for data collection by changing the techniques of collection. Analysis procedures have also improved with the continued development of computers and data collection software. These trends of rapid technological advancements will likely continue well into the future. Many of the presently used collection and analysis techniques are addressed in this chapter, but it is the responsibility of the study manager to keep up with the latest technology and choose the proper methods for their study needs. This can be accomplished through publications, Internet Web sites, and attendance at conferences.

9.2 Purpose of a Reservoir Survey

Reservoirs come in all shapes and sizes and are designed for purposes such as retention for flood control, debris/sediment storage, irrigation, municipal water supply, power production, recreation, navigation, conservation, and water quality control. The reservoir size, shape, and operation affect the location and nature of the sediment depositions (figure 9.1). Reservoir sedimentation is an ongoing natural depositional process that can remain invisible for a significant portion of the life of a reservoir. However, lack of visual evidence does not reduce the potential impacts of reservoir sedimentation on functional operations of a reservoir (Lin, 1997). As sediment deposition depletes reservoir storage volume, periodic reallocation of available storage at various pool levels may be necessary to satisfy operational requirements of water users.

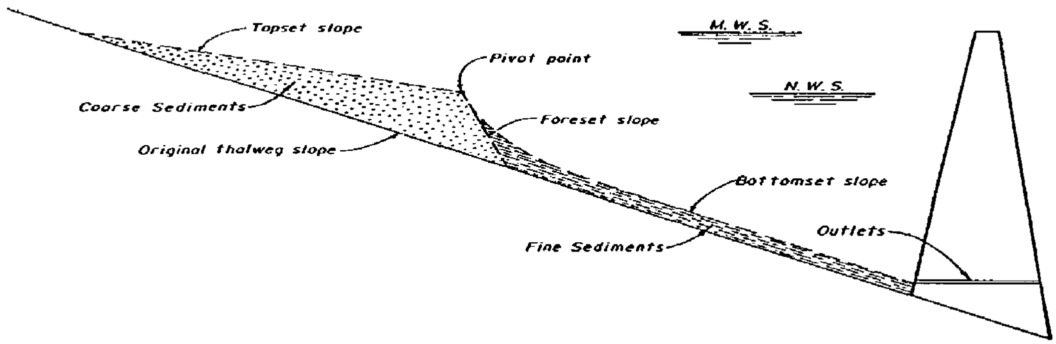


Figure 9.1. Profile of reservoir delta formation (Strand and Pemberton, 1982).

As rivers and streams enter a reservoir, the flow depth increases and the velocity decreases, causing a loss in the sediment transport capacity of the inflow. The loss of sediment transport capacity and the damming effect of the reservoir may cause deposition of sediment in the stream channels above the reservoir water surface and in the upper reservoir area. The sediment deposition process in reservoirs generally follows the same basic pattern, with coarser sediments settling first in the upper reservoir area as the river inflow velocities decrease, forming a delta. Deposition continues from upstream to downstream, with the sediment gradation becoming finer as the deposition progresses towards the dam until the inflowing sediment is deposited throughout the length of the reservoir. Some of the inflowing fine sediments (silts and clays) typically stay in suspension and may discharge through the dam outlets or spillways. As sediments deposit near the dam outlets, they eventually will be discharged downstream as releases are made from the dam.

In the United States, reservoir sedimentation seldom receives attention until the reservoir storage capacity has been significantly reduced or the reservoir operation or surrounding area is affected. The delta formation can cause local problems before sediment deposition significantly reduces reservoir capacity or causes operational problems at the dam. Some local problems that have been attributed to sediment deltas are increased elevation of the flood stage and ground water table, silting of pumping and intake structures, and blockage of navigation passages. Once at the dam, the released sediments have downstream impacts on river fisheries and municipal water systems.

The primary objective of a reservoir survey is to measure the current reservoir area and capacity. The main cause of storage capacity change is sediment deposition or erosion. Typical results from reservoir survey data collection and analysis include measured sediment deposition since dam closure and previous surveys, sediment yield from the contributing drainage, and future storage-depletion trends. Survey results can also include location of deposited sediment (lateral and longitudinal distribution), sediment density, reservoir trap efficiency, and evaluation of project operation.

The Sedimentation Group typically computes reservoir sediment accumulation by comparing the measured original capacity, prior to inundation, to the updated measured capacity. This method calculates a long-term sediment deposition value used for future sediment projections. Making comparisons to the original survey, rather than previous surveys, prevents errors that might exist in previous resurvey results from being included in the analysis. The calculations typically rely on accurate original reservoir topography available for many of Reclamation's reservoirs, but this must be evaluated on a case-by-case basis. Modifications to the analysis and study objectives must be made for cases where accurate original reservoir topography is not available. This was the case for the 1995 Theodore Roosevelt (Roosevelt) Reservoir survey (Lyons-Lest, 1996) and the 2002 Deadwood Reservoir survey (Ferrari, 2003).

The Roosevelt and Deadwood Reservoir resurveys measured finer detail than the original survey data. The 1995 Roosevelt survey was the eighth since dam closure in 1909, but the first to use aerial photography that provided more detail of the upper reservoir elevations than the original 1909 survey and the resurveys. Comparing the detailed 1995 survey with previous mapping information was not a means for computing sediment accumulation due to the precision differences between the surveys. The previous resurveys of Roosevelt Reservoir were valid for computing sediment inflow since they utilized a range line collection method that monitored the same range lines over the years. The changes at these locations were compared to the original topography for estimating the sediment deposition. The detailed 1995 Roosevelt Reservoir survey will be used as the basis for future comparisons. The same was true of the 2002 Deadwood Reservoir resurvey. The detailed aerial and multibeam data from the 2002 survey could not be compared to the less detailed original data for computing sediment accumulation.

Additional objectives of Reclamation's reservoir survey studies are to determine current reservoir topography, estimate the reservoir's economic life, and resolve storage capacity conflicts. The resulting study information is beneficial for describing existing conditions for a specific reservoir, monitoring upstream land management practices, evaluating current operation of a reservoir, and planning future reservoirs. The results from the study can provide insight for such operational objectives as sluicing sediment deposits to increase reservoir volume and possibly enhancing the downstream river environment, establishing bench marks for forecasting future reservoir depletion rates, revising intake or outlet design, assessing water quality control methods, and designing recreation facilities, structures, and operational schedules.

Reservoir sediment accumulation and distribution can be approximated theoretically. However, an accurate reservoir sedimentation survey is the best means for monitoring current reservoir sedimentation and for projecting future sediment inflow and deposition. Obtaining an accurate value requires measuring the complete reservoir area, or as much of the sediment delta as possible. As seen on figure 9.1, the majority of the delta may form in the very upper reaches of the reservoir but, eventually, the inflowing sediments can deposit throughout the reservoir. Full coverage requires both above and below water measurements that significantly increase the field collection time and cost. If the measurements are only under water, the survey should be scheduled when the reservoir is as full as possible. Although other types of factors must be considered, cost usually is the deciding factor in the data collection plan.

9.3 Sediment Hazards

As better understanding and management of sediments are achieved, a major issue will become how to deal with the associated hazards while maintaining the goal of preserving existing water resources. To sustain healthy management of the watershed, knowledge of sediment movement under different flow conditions is needed. This knowledge can assist in the evaluation of different sediment management options: ignoring, storing in place, or flushing downstream are a few examples. Regardless of options, the hazards must be addressed (Wohl, 1998). These hazards may only be local, or they may affect a large portion of the basin upstream and downstream of dams, resulting in excessive sediment deposits, contaminated sediments, or even decreased sediment concentrations. Excess sediment can fill a reservoir and change river channel patterns and features such as fish spawning sites. Contaminated sediments may include heavy metals from mine runoff or excessive levels of nutrients from urban and agricultural phosphorus. The excess phosphorus can create algal blooms that reduce dissolved oxygen and harm fish populations.

Sediment hazards have been indirectly created due to human activities such as timber harvest, crop cultivation, grazing, road construction, and urban development. They have also been directly created by dams and reservoirs, river channel altering from dam and dike diversions, channelization, and mining. A decrease of natural sediment supply downstream of a dam means the river is capable of transporting more sediment than the supply, resulting in channel erosion, riverbank collapse, bridge-pier scour, and channel downcutting.

There are many examples of problems associated with excess sediments. In some cases, excess sediments bypassed to maintain dam and reservoir functions resulted in immediate large fishkills, long-term effects on fish reproduction, and instantaneous and long-term effects on water quality. Possible contaminants attached to the sediments must be addressed if alternatives such as flushing and/or dredging disturb the sediments. There have been studies that measure the magnitude and duration of the effects these contaminants have on the surrounding environment for options such as leaving sediments in place or bypassing downstream. Past studies have collected reservoir sediment and determined the age of the material based on the amounts of DDT and lead measured and knowledge of when these contaminants were discontinued. The decrease of downstream sediment below dams has caused excessive erosion of the river channel and banks affecting the management of rivers. Loss of very fine sediment has affected the infiltration rate of downstream diversion ditches and the reproduction of fish that used this material to guard against predators.

9.4 Sediment Management

Reclamation's ability to manage current and future sediment hazards will be determined by knowledge of the problem and available options. A sediment management plan must address the social, environmental, and technical options with a goal of avoiding legal and political pressures in making important decisions. The sediment management plan must consider different alternatives such as ignoring sediment, allowing it to accumulate onsite for future generations to deal with, keeping it out of the reservoir with better upstream management practices, removing it from the reservoir, and flushing it downstream (beneficial in some cases). These management plans are difficult to develop with our present limited knowledge of the problems and hazards associated with the reservoir sediments. Aside from gaining a better understanding of the loss of reservoir capacity due to sediment accumulation, an understanding of possible contaminants within the sediment deposits is also needed. The knowledge of possible contaminants in both the deposits and within the mobilized sediments due to dredging, erosion, and flushing is needed. Increased knowledge of sediment transport in river channels and reservoirs is also needed, requiring the development of models that can describe how the sediments are transported in the different river channels and reservoirs. Along with other applications, these models could be used to determine the minimum flushing flows necessary to minimize reservoir sedimentation and downstream effects. Calibration and confirmation of these models can be obtained with accurate field data.

9.5 Frequency and Schedule of Surveys

The schedule and frequency of conducting reservoir surveys should depend on the estimated rate of reservoir sediment accumulation, along with the current operation and maintenance plan. However, the current need to address site-specific problems, along with available funding, usually determines if and when a survey is conducted. The frequency of resurveys may depend on the estimated rate of sediment accumulation in the reservoir. For example, some have used a 7.5-percent storage reduction between surveys or a 5- to 10-year interval. For Reclamation reservoir surveys, the decision on if and when a survey will be conducted is usually made by the responsible operations office. Influential factors in the decision include occurrence of a large flood, severe drawdown of the reservoir, planned construction of an upstream dam, loss of recreational area due to sediment encroachment, change in erosional characteristics of a basin due to land use or forest fires, raising of the dam, or changes to the reservoir operations. For Elephant Butte Reservoir in New Mexico, the frequency of surveys is set by a compact agreement between the states and Federal Government, using a projected 5-percent loss of capacity (Collins-Ferrari, 1999). The responsible office and available funding determine the method of collection. For example, the decision on whether or not an aerial survey for the above water portion of the data collection is conducted is usually based on cost and the amount of shoreline erosion. The Sedimentation Group works with the responsible field office to obtain the best study results within the allowable budget.

Reclamation has over 400 storage facilities, but only about 30 percent of these have had a resurvey conducted since initial filling. Of these resurveys, about 30 percent have had multiple surveys, with some reservoirs requiring 5 or more resurveys for monitoring high sediment inflow and for developing present area and capacity tables. The majority of these high sediment inflow sites are located in the southwestern United States and include Theodore Roosevelt in Arizona with 8 resurveys, Elephant Butte Reservoir in New Mexico with 11 resurveys, and Lake Mead in Arizona with 3 resurveys. There are Reclamation reservoirs in the state of Wyoming with high sediment yields that have had several resurveys, such as Buffalo Bill Reservoir with 3 resurveys and Guernsey Reservoir with 11 resurveys. All of these reservoirs are located in drainage basins with high sediment yields requiring multiple resurveys for effectively monitoring reservoir sedimentation rates and future impacts.

The schedule of the survey may be determined by methods of collection, weather, and reservoir operations. If aerial data are collected, it is recommended that collection take place when the reservoir is as low as possible and prior to the bathymetric survey. In most cases, this is in the fall, winter, or early spring and allows better coverage due to less vegetation. The bathymetric survey should be scheduled when the reservoir is as full as possible or with as much aerial coverage overlap as possible. This allows complete mapping of the reservoir and speeds up the underwater collection if the aerial collection covered the shallow water and underwater hazard areas. Due to cost, some Reclamation surveys are restricted to underwater collection and use existing above water maps to complete the analysis. For these types of surveys, all attempts are made to schedule the survey when the reservoir is as full as possible, requiring some survey delays during low runoff years. For some surveys, limited amounts of above water data are collected to complete the analyses. Usually, the data are collected in the upper tributaries where exposed sediment deltas had formed (Ferrari, 1996 and 2005).

The decision on when to schedule and at what frequency to conduct a reservoir survey must be made on a case-by-case basis. Current available equipment (i.e., GPS, digital depth sounders, and heave compensators) allows for year-round data collection and has significantly reduced actual field collection time. Advances in equipment technology and data collection techniques have also reduced the staff size and the amount of preliminary field work required by previous survey methods. Presently, collection systems are more compact and require less field staff for setup and operation, reducing the cost of downtime due to extreme weather conditions. However, each project contains unique conditions that must be considered when determining the timing, survey equipment, and frequency of the reservoir resurveys.

Many reservoirs are relatively small in size, requiring smaller survey vessels. Modern survey equipment can be more easily adapted for the smaller vessels. When available, an enclosed cabin on the survey vessel is a desirable option that protects the crew and equipment, and it allows surveys to be conducted safely throughout the year. Equipment can also be purchased that is weather proof, allowing open boat data collection in most weather conditions. Today's equipment has minimized the effect of rough water on data accuracy, but its effect on the collection crew must be considered. Although a nearly full reservoir during a nonrainy season is the best condition for conducting a reservoir survey, the equipment and survey vessel should be set up to cope with all conditions, since they can change at any time. The Sedimentation Group has collected data in all weather conditions (including snow and heavy rain) because the equipment and crew are usually housed in an enclosed cabin on a large, stable vessel.

Other means of determining frequency of reservoir sediment surveys include measured sediment rates from previous surveys and sediment records from inflow streams. In the United States, high operating costs have reduced the number of gauging stations that measure sediment inflow, requiring records from similar reservoirs, gauges, and drainages to be used. Observations of sediment deposition during a reservoir drawdown may also be used; however, as illustrated in figure 9.1, these observations may give a false impression of the severity of the problem if the exposed sediment delta is the majority of the deposition. A reconnaissance type survey can be conducted to periodically measure changes at a few previously established reservoir sediment range lines, but cost must be considered if the collection crew must travel an extended distance to the study site.

In general, larger reservoirs require less frequent resurveys. More frequent surveys are usually required if reservoirs are operating under conditions of greater risk, such as flood control or water supply storage, or if located in metropolitan areas. Small flood control reservoirs on the South Platte River in the metropolitan area of Denver, Colorado, have been resurveyed at about 5-year intervals. For similar type reservoirs, it is recommended that this short interval remain until enough years of data have been collected to determine if long-term sediment deposition trends exceed the original design projections. Fort Peck Lake on the Missouri River in Montana is situated in an isolated area, has a storage volume nearly 600 times larger than these Denver reservoirs, and has half the projected storage depletion rate. Initially, Fort Peck Lake was resurveyed at 5- and 10-year intervals until it became evident that the long-term depletion rate was substantially slower than originally expected. The resurveys are currently scheduled on 20-year intervals.

In Taiwan, capacity lost due to sedimentation is much more critical because of the limited capacity available within the total reservoir network and the relatively high percent of annual loss of capacity due to higher average sediment yields compared to the United States. For these types of situations, the reservoir resurvey interval should still be based on the individual reservoir, drainage basin characteristics, and need. In some cases, the interval may need to be as short as 1 year or following each major storm event that might generate a high sediment inflow and have a dramatic impact on a small capacity reservoir. In general, smaller reservoirs in Taiwan with higher sediment inflow would require shorter collection intervals than for reservoirs in the United States that are generally larger and have lower rates of sediment inflow (Yen, Pei-Hwa, 1999). Present collection systems and analysis software have made it possible to measure impacts from individual storms, but the need for and benefit of such information must be determined.

An additional factor in the survey schedule is the inflow of unconsolidated material that may create a soft reservoir bottom and erroneous echo sounder depths. The use of low frequency sounders, along with depth verification may provide quality assurance (QA) of the depth measurements. However, these additional verifications, add time to the collection and concerns about the accuracy. The lower frequency echo sounders can penetrate the soft layer and provide depths of the harder bottom, but these depths could be somewhat subjective to what the true bottom is. It would be best to avoid such conditions, but for some reservoirs, these soft bottom reservoir conditions always exist. For soft bottom reservoir surveys, echo sounder depths should be confirmed by manual measurement, despite the extra cost. However, manual measurements are somewhat subjective to individual judgment and are difficult in deeper reservoirs. The soft bottom fluff conditions appeared to be a factor during the December 2004 and May 2005 Lake Powell surveys (Clarke, 2005). In 2005, a multibeam survey was conducted from May 12-21, 2005, on the entire length of Lake Powell. During low and high frequency depth collection on the upper San Juan reach, the high frequency readings were, at times, several meters shallower then the low frequency readings, indicating the soft fluff bottom of the reservoir's inflowing sediments.

9.6 Reservoir Survey Techniques

Survey techniques have evolved around the development of equipment and analysis systems. Prior to computerized data collection and analysis systems, the **range line method** was commonly viewed as the only practical method for collection due to its relatively low field and analysis costs (Blanton, 1982). The range line method was used most often on medium to large reservoirs and on river modeling studies requiring underwater data collection for monitoring changes.

For reservoirs, the collection and analysis consists of determining sediment depths along predetermined range lines (usually established prior to inundation). Analysis requires detailed and accurate original reservoir topography. Various mathematical procedures have been developed to produce the revised reservoir contour areas at incremental elevations for the surveyed range lines. The range line method is still a valid means of conducting survey studies for certain reservoir conditions or if more modern collection and analysis systems are not available. For the 1986 Lake Powell survey (Ferrari, 1988), the range line collection and analysis method was used due to very deep (greater than 500 feet at the dam) vertical wall conditions and good original topographic maps. It now is possible to completely map Lake Powell in detail using a GPS, multibeam system, and aerial collection, but the range line method should still be considered, since it would be less costly for collection and analysis. Multibeam surveys on a large portion of Lake Powell in 2004 and 2005 covered many of the range lines surveyed in 1986. The multibeam surveys covered in days what took weeks to cover during the 1986 survey. A report, *Reconnaissance Technique for Reservoir Surveys*, presents the results from these surveys and a modified range line method to generate updated area–capacity tables (Ferrari, 2006).

For river collection, the field procedure is similar to reservoir collection where predetermined range lines are selected prior to the underwater collection. The range lines are usually established perpendicular to the riverflow and are used for monitoring and numerical modeling of the changes in the river over time. This method requires the survey vessel to run the underwater portion along the alignment of the selected range lines in a predetermined direction, but river conditions such as flow velocity and location of shallow water areas usually dictate the actual alignment. Advances in equipment and computer analysis systems now allow much more variance in river collection techniques, resulting in the collection of much more data in a safer manner. Many USACE river surveys are conducted in rivers utilized for navigation by large transport vessels. This large boat traffic hinders data collection by conventional range line method where the survey vessel must run from bank to bank perpendicular to the river alignment. Current collection systems allow data to be collected continuously in a diagonal direction or along the alignment of the river in a safer fashion and with enough density to generate detailed contours of the river channel. If needed for study purposes, there are computerized routines that can interpolate cross sections or range lines from these developed contours.

The **contour method** has become the preferred method for data collection and analysis with the development of electronic collection and analysis systems. It requires large amounts of data to be collected and stored, something that present systems can easily handle. The contour method results in more accurate reservoir topography and computed volumes than the range line method, but it usually takes more time for field data collection. This method revolves around computer and software packages that provide a means of organizing and interpreting large data sets. Contour development and analysis may be quicker than the range line method. The hydrographic survey data is usually collected in an x, y, z coordinate format conforming to a recognized coordinate system such as Universal Transverse Mercator (UTM), latitude/longitude, state plane, or other systems that represent the Earth's 3-dimensional features on a flat surface.

The most accurate contour map product is obtained when both the above and below water portions of the reservoir area are surveyed. The ideal contour map is developed by photogrammetry (aerial) when the reservoir is empty, exposing all areas to be measured, but this condition seldom occurs, making a combination of aerial and bathymetric survey necessary. To reduce the time and cost associated with underwater data collection, aerial data should be collected when the reservoir is as empty as possible, and the bathymetric survey should be conducted when the reservoir is as full as possible, providing maximum overlap of the two data sets. Surveying the underwater portion after the aerial survey with a large overlap reduces the time and cost, since the survey boat does not have to maneuver in shallow water portions already mapped by the aerial survey.

Due to cost of aerial data collection, some contour reservoir resurveys do not include an updated survey of the area above the existing reservoir water surface. For these surveys, the bathymetric survey should be scheduled when the reservoir is as full as possible. The above water area may be measured using the original or most recent contour map of the reservoir area. In this case, it is assumed that no change has occurred since the above water area was last mapped. Some Reclamation resurveys have used U.S. Geological Survey (USGS) quadrangle maps for the above water areas, since it was the best data available. It must be noted that an assumption of no change can cause computation errors for reservoirs with significant shoreline erosion or where the majority of the sediment settles in the shallow upper end not mapped by the bathymetric survey.

Recent improvements in conventional survey equipment (GPS) allow accurate measurement of point data and provide a cost-effective method for smaller reservoirs. A combination contour and range line method may be used where the range line method is used to measure the areas of exposed sediment deposition, as was done for the 1994 Boysen Reservoir Sedimentation Survey (Ferrari, 1996). This method does not accurately measure the surface area of the above water areas where significant reservoir changes have occurred due to bank erosion, but it is a viable alternative for measuring exposed sediment deltas in the upper reaches of the reservoir.

There are many contour development software packages on the market. The Sedimentation Group develops contours for the reservoir area from the compiled data using various methods; the most common is the triangular irregular network (TIN) package (Environmental Systems Research Institute, 2005 and HYPACK, 2005). A TIN is a set of adjacent, nonoverlapping triangles computed from irregularly spaced points with x, y, z values and was designed to deal with continuous data such as elevations. Triangles are formed among all collected data points, including boundary points, preserving each collected survey point. A digitized polygon enclosing the collected data can be developed such that interpolation is not allowed to occur outside the boundary. A linear interpolation option is then used to interpolate contours from the developed TIN.

9.6.1 Shoreline Erosion

The 2002 Tiber Reservoir underwater survey showed extensive shoreline erosion throughout the reservoir area. During collection, the GPS positions were found, at times, to be outside the digitized USGS quadrangle contour location, indicating that the boat was on dry ground. These USGS quadrangle contours were developed from aerial photography taken in the 1960s. At times, the position of the boat was found tens of feet outside their boundary. In addition, a major windstorm occurred during the 2002 survey, and the crew witnessed vertical sections of the shoreline collapsing into the reservoir area for days afterwards. Even with the shore erosion, the survey vessel was, at times, able to hug the vertical banks in deep water where previous collapses into the reservoir had occurred. It appears that, over time, the collapsed material washed further into the reservoir by wave action similar to shore ocean waves. This is possible because the shoreline material dissipated in the water and consisted of little to no rock or large cobble material. Figures 9.2 through 9.5 document these shoreline conditions at Tiber Reservoir (Ferrari and Nuanes, 2005).

The photographs show different stages of the shoreline erosion, along with the extent of occurrence. If the erosion were just below the reservoir high water mark, the total volume of the reservoir would not be greatly affected. What occurred in the upper reservoir elevations resulted in a gain in surface area and volume. This volume gain at the higher reservoir elevations offsets the loss of surface area and volume in the lower elevations of the reservoir due to the eroded shore material depositing at the lower elevations. The photographs show the large amount of the eroded material above the reservoir area, meaning that a portion of the loss of the original total reservoir volume is due to the shoreline erosion, along with the incoming river sediments. The only means to accurately measure the extent of the shoreline erosion would be an aerial and full bathymetric survey. Reconnaissance surveying techniques cannot be used in reservoirs with these types of conditions (Ferrari, 2006).

Figure 9.2. Eroded material depositing forming a shelf (photo by S. Nuanes).

Figure 9.3. Large areas of erosion above the reservoir maximum water surface (photo by S. Nuanes).

Figure 9.4. Recent eroded material that has not moved further into the reservoir (photo by S. Nuanes).

Figure 9.5. Eroded bank material depositing below the water line (photo by S. Nuanes).

9.6.2 Data Density and Line Spacing

The extent of data collection is determined by the project needs, reservoir conditions, cost of collection and analysis, and capability and limitations of the collection system. Typically, the GPS horizontal positions can be updated once per second, a single beam electronic depth sounder can provide continuous output of 20 or more depths per second, and a multibeam underwater collection system has the capability of several hundreds of thousands of points per minute. The advancement in the computer collection systems allows all of these data to be stored, but it is up to the study manager to determine what system and collection interval is necessary and practical. During collection, the most advanced available system should be used and the maximum amount of data should be stored. Filtering of the data that may be necessary for final computations should be conducted during data postprocessing.

For single beam collection systems, survey line spacing must be selected to provide the needed density for the study results. The study manager must understand the goals of the study and must determine the data density to meet the goals while staying within budget. The range line method assumes uniformity of the terrain between the survey lines, which is a valid assumption unless an abrupt change occurs. The challenge is knowing if and where abrupt changes occur and spacing the lines to best represent the bottom conditions. The survey crew needs to monitor the survey line during collection for possible changes and examine existing topographic maps that may warrant a modification of the line spacing during field collection. Typically, about 5 percent of the project study area is covered by the single beam collection method, which means care must be taken to collect adequate data to ensure accurate topography development.

The Sedimentation Group's single beam collection method typically begins with a 300-foot spacing and adjusts in the field to meet the study objectives. For smaller reservoirs and to show more bottom details, the data collections may be adjusted to 100- to 200-foot spacing. For some of the larger reservoirs, with flat bottom conditions with little or no detail, and when collection time and budget is limited, the spacing has been adjusted to 500, 600, and at times 2,000 feet. The upper delta of Canyon Ferry Reservoir in Montana was fairly flat with little to no channel detail in the deposited sediment. Those conditions permitted the collection crew to increase the profile spacing, allowing data collection during favorable weather conditions and reducing field collection time while maintaining the quality of the product (Ferrari, 1998). For the Salton Sea survey in California, the range line spacing was adjusted to 2,000 feet due to the limited budget for data collection and the relatively flat unchanging bottom conditions (Ferrari, 1997). The Canyon Ferry and Salton Sea surveys were conducted on large water masses with assumed uniformity of terrain between surveyed range lines justifying such large spacing. Parallel surveyed range lines and perpendicular survey lines confirmed the uniform bottom assumption for these large water surveys.

The use of a multibeam collection system provides the capability of full bottom coverage of the underwater reservoir areas, but it requires more time for collection and analysis than many budgets will allow. The multiple-transducer and multibeam collection systems can provide 100-percent coverage that removes the unknowns between the survey line spaces, but the costs and operation of such systems are more difficult to justify. It is up to the study leaders to determine the extent of collection to meet the study goals within the budget. For the 2001 Lake Mead study, the collection was limited to the original river channel areas where the majority of the sediment deposition was projected to occur. Only about 30 percent of Lake Mead was covered by the multibeam survey, but the 20 million data points mapped the majority of the submerged, deposited sediment elevations that could be collected by the survey vessel. This allowed the field collection to be accomplished in 3 weeks and within budget, while obtaining the needed detail to meet the study needs (Ferrari, 2006) (Twichell, Cross, and Belew, 2003).

9.6.3 Cost of Conducting a Reservoir Survey

Survey productivity has increased by a factor of 75 since the 1960s and a factor of 10 since the 1990s (USACE, 2004). The productivity increases are mainly related to electronics and computer development. Planning a survey is usually controlled by a budget that determines detail and method of collection, analyses methods, and who will be conducting the study. Before the use of electronic positioning systems, the collections were conducted using visual or manual distance tag lines. The manual method required significant setup time to establish range line locations and utilized large survey crews, often requiring two to three vessels and crews of five to eight people to conduct the survey. Depending on conditions, the crews were able to collect data from one to five range lines per day. Computer microwave system development reduced the crew size during collection, but it still required significant amount of time prior to the underwater collection to locate and establish control around the reservoir and river study areas. The field crew size during the underwater collection was usually around five, but as few as three could complete smaller jobs. Collection of sediment range line data increased from 5 to 10 range lines a day, but the major benefit was the possibility of detailed mapping of the reservoir bottom. The development of GPS hydrographic collection systems significantly reduced the time and cost of a survey by increasing field collection productivity and decreasing the number of staff days required to conduct the overalls study. The greatest cost savings occurred because the detailed control network required prior to the underwater survey was significantly reduced.

The Sedimentation Group conducts the majority of their surveys using sonic depth recording equipment interfaced with a real-time kinematic (RTK) GPS that gives continuous sounding positions throughout the underwater portion of the reservoir covered by the survey vessel. The RTK GPS system allows control to be established in hours, rather than days or weeks with conventional land surveys. The hydrographic crew size is usually two, compared to the previous three to five crew members. One result of using GPS and field computers is the automated collection and storage of massive amounts of data. For multibeam systems, the initial cost is significant, meaning workload and budgets should be sufficient to support the cost and necessary personnel for operation. The major benefit of this system is full bottom coverage with greater detail and less uncertainty in the results. For many studies, the mobilization and demobilization costs can exceed the actual survey cost. For small survey jobs, the Sedimentation Group attempts to schedule more than one survey per trip to reduce this cost. An experienced collection crew can significantly reduce the cost, since less time is needed for planning, preparation, and training, which allows the work to be conducted more efficiently and safely.

9.6.4 Selecting Appropriate Hydrographic Data Collection System and Software

The goal of any collection program is to obtain the highest quality data possible with the equipment available to the survey crew. Currently available hydrographic surveying equipment has the capability and flexibility to be used for bathymetric surveys in small and large reservoirs, and rivers, and for above water surveys. The equipment can be utilized for many different collection techniques, such as range line and contouring. The demand for data collection and required accuracy, along with the training and experience of the users, should dictate the type and quality of the equipment. Continual upgrades in location and sonic sounding instrumentation, along with computer collection system electronics, have greatly improved accuracy and speed of collection. These improvements have been so dramatic that resurvey data now has the potential of being more accurate than any of the previously collected data, even data collected prior to inundation, when most of the reservoir area was exposed. Technology has reduced the overall time and cost of data collection and analysis for hydrographic surveying projects and provided larger quantities of higher quality of data. Previous systems required more planning, extensive surveys to establish ground control, and larger field crews to complete the job.

When determining reservoir resurvey needs, selecting a reservoir survey data collection system, or establishing a reservoir survey program, several basic questions should be asked:

- What is the primary goal of the study?
- What are the needs or requirements of the final product?
- What is the desired or necessary level of detail?
- How often will the system be used?
- What experience, interests, and longevity do the operational personnel possess?

Other factors to consider are the cost of purchasing the system, the operational cost, and possible lease of the collection system, or components that would provide the latest technology. One potential problem with leasing may be the amount of time necessary to gain the expertise to use the system properly. Many of the commercially available software packages accept instrumentation from several manufacturers, so that after the user becomes proficient operating the software, adding and removing instrumentation becomes less of a concern. After addressing these issues and estimating associated expenses, it may be concluded that the more cost-effective solution is to contract out the study or studies.

The continual development of computer and electronic instrumentation has greatly changed the data collection and analysis methods for reservoir sedimentation surveys and is expected to bring additional changes in the future. This change requires collection programs to be flexible. There are no generic packages that meet all survey requirements. It is recommended that the system be built around the software that will be used for field data collection and analysis, requiring the equipment that is purchased to be adaptable to various software packages. There are some users that collect small amounts of data for one small project without hydrographic or survey software. Conducting the study without some form of software is very labor intensive during field collection and analysis and also increases the potential for collection and analysis errors.

Writing customized software for the system needs is a possibility since purchasing hydrographic software can be costly, ranging from $5,000 to $20,000. However, compared to the total cost of the hydrographic survey system and the time required to develop and maintain such programs, the cost of software procurement is less prohibitive. An additional concern with writing customized software is the availability and longevity of the programmer for making modifications to the software. While existing commercial software may not meet all of the needs initially, several software vendors provide customization of their software to meet the customer's needs.

Commercial software is often upgraded to incorporate the latest technology and upgrades are usually available to the users for an annual maintenance fee. Some hydrographic crews use the hydrographic software for the field collection and initial processing only, and then develop the final product using different software. Reclamation's Sedimentation Group collects and processes field data into x, y, z data sets with a portable computer and hydrographic software, then completes the contour mapping and final calculations with a desktop computer and commercial contouring software.

There are several versatile software packages capable of simultaneously receiving data from multiple devices during collection and processing the collected data for complete analyses. Some options include collection, postprocessing, and editing of single and multibeam data, geodesy transformations, tide corrections, TIN modeling, and volume computations. The packages vary but usually contain internal drivers that support equipment from numerous manufacturers for range-azimuth, range-range, mapping and survey grade GPS, and single and multibeam depth sounder instrumentation. In addition to collecting data from numerous instruments simultaneously, the computer and software can be set up to integrate data from various sensors such as gyros, acoustic systems, heave-pitch-roll indicators, magnetometers, and seabed identifiers. These computer programs are for the frequent user, due to the considerable time required to become proficient in the use of the software and survey instrumentation. These programs are very powerful, have a worldwide customer base, provide technical support by the phone and internet, and are usually adapted to the latest technology. Recent and continuous improvements of portable computers are making it easier to install and utilize software and numerous instruments on smaller survey vessels. The computer purchased that is purchased should be as advanced as possible with enough hard drive space for 5 to 50 megabytes (MB) of software and 1 to 2 MB of data storage per day for single beam data or as much as 10 MB per hour for multibeam data. Since computers may only have one serial port, additional hardware containing multiple ports will be needed to accommodate the number of measuring instruments in the system.

9.7 Hydrographic Collection Equipment and Techniques

Hydrographic survey equipment has transformed dramatically throughout its history, with the greatest changes occurring over the last decade. The latest major change in horizontal positioning is the GPS, which is more accurate and less costly to operate than past survey methods. No former positioning system has been so rapidly adapted to hydrographic collection systems. The most recent significant development in depth sounders is the multibeam system that allows massive amounts of data to be collected. The multibeam system provides the option of complete coverage of the underwater areas, thus removing the unknowns of previously unmapped underwater areas.

Equipment for hydrographic surveying varies, depending on reservoir size, field conditions, availability, familiarity to the collection crew, and cost. The positioning equipment for hydrographic surveys has varied over time, with the latest major change for measuring horizontal positioning being GPS. Although relatively new and still undergoing technological advancements, GPS is more accurate and less costly to operate than previously used conventional survey methods and has been rapidly integrated into hydrographic collection systems. GPS is a very versatile instrument for measuring horizontal positions, but it is not ideal for all reservoir and river situations. Past horizontal positioning equipment and techniques are still viable where site conditions may prohibit the use of GPS. Such systems include marked tag lines stretched along the range line, electronic distance meters that measure distances from a known point to the survey boat as it proceeds along the range line, range-azimuth positioning that involves the intersection of an angular and distance observation, and range-range positioning where survey vessel distances are measured from two or more shore stations. These previously used techniques and equipment are still viable positioning methods as described in more detail in other available publications (Blanton, 1982 and USACE, 2004):

- Constant boat speed, usually for reconnaissance type surveys
- Cutting in, or triangulation-intersection that uses two transits or theodolites
- Stadia rod and common transit for reconnaissance type surveys
- Tag line or calibrated cable for measuring range lines
- Electronic distance meter (EDM) for measuring distance from shore to boat on range lines
- Range-azimuth measuring of angular and distance observations from a reference station.
- Microwave range-range was the preferred method prior to GPS

9.8 Global Positioning System

The GPS has rapidly become the preferred positioning system for hydrographic surveying and does not require the time-consuming calibrations necessary for previously used systems. Although relatively new and continuously undergoing technological advancements and operational policy changes, GPS-based systems are the most accurate, least expensive to operate, and versatile positioning systems for obtaining positions of static monuments or moving platforms. Previous systems, such as range-range and range-azimuth, are limited to line-of-sight coverage from the shore-based earth stations, while GPS does not have that limitation. GPS can operate in all weather conditions requiring only a clear view of the sky.

Navigation Satellite Timing and Ranging (NAVSTAR) GPS is an all-weather, radio-based, satellite navigation system that enables users to accurately determine three-dimensional positions (x, y, z) worldwide. The NAVSTAR system's primary mission is to provide passive global positioning and navigation for land, air, and sea based strategic and tactical forces and is operated and maintained by the United States Department of Defense (DOD). The GPS receiver measures the distances from the satellites and determines the receiver's position from the intersections of the multiple range vectors. Distances are determined by accurately measuring the time a signal pulse takes to travel from the satellite to the receiver.

The NAVSTAR system consists of three segments:

1. The space segment is a network of 24 satellites maintained in precise orbits about 10,900 nautical miles above the earth, each completing an orbit every 12 hours. Satellites are spaced in orbit so that a minimum of 6 satellites is always in view anywhere in the world 24 hours a day. The satellites continuously broadcast the position and time data used by the receivers.

2. The ground control segment tracks the satellites and determines their precise orbits. The main control station is in the United States, in Colorado Springs, Colorado, with additional monitoring stations located throughout the world. The control stations determine and

periodically transmit ephemeris parameters (such as the satellite's position, correction, health status, and other system data) to each satellite, whereupon the data are retransmitted to the user segment receivers.

3. The user segment consists of the GPS receivers located worldwide for both military and civil activities for many different applications in many different conditions at air, sea, or land-based locations. The individual receivers process the NAVSTAR satellite broadcast signals and calculate their position.

The GPS receivers use the satellites as reference points for triangulating their position on earth from distance measurements to the satellites. To calculate the receiver's position on earth, satellite distance and position in space are needed (determined by ground control). The satellites transmit signals to the GPS receivers for distance measurements, along with data messages about their exact orbital location and operational status. The satellites transmit two "L" band frequencies for the distance measurement signals, called L1 and L2. Modulated on these frequencies are the coarse acquisition (C/A) and precise (P) codes. An additional message contains the satellite ephemeris and health status.

A minimum of four satellite observations is required to mathematically solve for the four unknown receiver parameters (latitude, longitude, altitude, and time). The time unknown is caused by the clock error between the expensive satellite atomic clocks and the imperfect clocks in the GPS receivers. For hydrographic surveying, the water surface elevation parameter may be measured by means other than GPS. This means that only three satellite observations are theoretically needed to track the survey vessel. However, to obtain the most highly accurate position, the survey vessel GPS receiver tracks all available satellites.

There are high-grade GPS collection systems with RTK surveying capability that accurately measure the position and altitude of the moving survey platform with obtainable centimeter accuracies for both horizontal and vertical measurements. RTK needs a minimum of five satellites for initialization, but after initializing, it can collect high precision data with a minimum of four satellites (Chisholm, 1998).

All GPS solutions depend on the accuracy of the known coordinate position of each observed satellite and the relative geometry of the satellites. The accuracy of a GPS-measured position can be characterized by its geometric dilution of precision (GDOP). GDOP describes the geometrical uncertainty and is a function of the relative geometry of the satellites and the user. Generally, the smaller the angle between the satellites and receiver, the greater the GDOP value, and the lower the measured precision. GDOP is broken into several components, such as position dilution of precision - x, y, z (PDOP) and horizontal dilution of precision - x, y (HDOP), where the components are based on the geometry of the satellites and should be monitored and recorded during the survey.

There are two basic operation methods to obtain GPS positions: absolute and differential.

9.8.1 Absolute Positioning

Absolute positioning normally involves only a single GPS receiver and is not accurate enough for use in most hydrographic positioning. A single GPS receiver's absolute position is not as accurate as it appears in theory because of range measurement precision and the geometric position of the satellites. Precision is affected by several inherent factors that cannot be eliminated but can be minimized. These factors are time (because of the clock differences), atmospheric delays (caused by the effect of the ionosphere on the radio signal), receiver noise (due to quality of GPS receivers), and multipath (errors caused by signal arrival by different paths, usually due to signal reflecting from obstacles). Due to these factors, estimated absolute real-time position accuracies of only ±10 to 16 meters are common. The absolute mode for positioning does not provide sufficient positional accuracy or precision for the majority of hydrographic survey studies.

Previously, the largest error source in GPS collection was caused by false signal projection, called selective availability (S/A). The DOD implemented S/A to discourage the use of the satellites as a guidance tool by hostile forces. Positions determined by a single receiver when S/A was active had errors of up to 100 meters 95 percent of the time horizontally and up to 180 meters 95 percent of the time vertically. S/A was eliminated in May 2000, but the absolute positioning of a single receiver caused by other error sources is still only around ±10 meters and usually will not satisfy the majority of hydrographic surveying requirements. The error sources can be eliminated or minimized by using Precision Positioning Units or differential GPS techniques.

The GPS satellites provide two levels of navigation services: Standard Positioning Service (SPS) and Precise Positioning Service (PPS). SPS receivers use available GPS information broadcast to anyone in the world, but security devices such as the anti-spoofing (A/S) factor guard against fake transmission data by encrypting the P code with a classified Y code denying the SPS user the higher P code accuracy. The position accuracies for SPS receivers are only around ±10 meters. None of these factors significantly affect the GPS users operating with differential positioning techniques.

Precise Positioning Service is an accurate worldwide positioning technique available to the military. With DOD authorization, nonmilitary government agencies can utilize PPS, which has the capability of deciphering the encrypted GPS signals. The encrypted or anti-spoofing P and Y codes guard against fake transmissions of satellite data and are available only to DOD authorized users. These PPS receivers can use the Y code and provide predictable autonomous horizontal positioning accuracies of ±4 meters. These positions are possible in real time, since they are not subjected to S/A. This is an absolute positioning mode with obtainable ±4 meters accuracy that, in some cases, meets the standards and requests of the current hydrographic survey systems. Prior to GPS, most hydrographic surveying systems operated with an accuracy of ±2 to 5 meters. Most studies now are calling for much greater accuracies and require the use of systems such as differential GPS (DGPS).

9.8.2 Differential Positioning

Differential positioning requires at least two receivers and can provide precisions necessary for real time hydrographic surveying. One method of collection to resolve or cancel the inherent errors of GPS (satellite position or S/A, clock differences, atmospheric delay, etc.) is called differential GPS. Differential surveying is the positioning of one point in reference to another. The basic principle is that errors calculated by multiple GPS receivers in a local area would all have common vectors. DGPS determines the position of one receiver in reference to another and is a method of increasing position accuracies by eliminating or minimizing the uncertainties. Differential positioning is not concerned with the absolute position of each unit, but with the relative difference between the positions of two units simultaneously observing the same satellites. The inherent errors in satellite positions and atmospheric delays are mostly canceled because the satellite transmission is essentially the same at both receivers.

The method includes setting one receiver over a known geographical benchmark programmed with known coordinates. This receiver, known as the master, base, or reference unit, remains over the known benchmark, monitors the movement of the satellites, and calculates its apparent geographical position by direct reception from the satellites. The inherent errors in the satellite position are determined relative to the master receiver's programmed position, and the error corrections or differences are applied to the mobile GPS receiver on the survey vessel.

The attainable accuracies using differential survey techniques usually depend on the grade or cost of the GPS receivers. The average grade-mapping receivers that determine differential positions from the L1 frequencies can obtain accuracies of ± 2 to 5 meters. The better grade-mapping receivers or low-end, survey grade receivers that determine differential positions from both the L1 and L2 satellite frequencies can obtain submeter accuracies. The high-end survey grade receivers can obtain subcentimeter accuracies. Hydrographic survey system needs to collect the most accurate survey information possible, but cost and need must be considered when assembling a system. For reservoir mapping, water capacity, and sediment volume situations, 1- to 2-meter position accuracy is generally considered an acceptable system at this time, but consideration must be given to collecting the most accurate data possible with the latest available technology.

There are different ways to apply DGPS collection methods to hydrographic surveying, including postprocessing and real-time DGPS. During postprocessing DGPS, the master and mobile GPS receivers record satellite tracking observations simultaneously as standalone units with no active data links between them. The master station is located at a known datum in the study area, or a community GPS base station is used. Differential correction software is used at a later time to combine and process the collected data. With this method, the mobile GPS receiver will be in the absolute mode and provide erratic positioning and tracking information during the time of collection. This method is not recommended if a precise range line survey method is used, but it is a valid means for collecting contour data if care is taken to ensure complete coverage.

To be valid for the study area, the master or reference station must be placed on a known survey monument located in an area having an unobstructed view of the sky. The GPS antenna should not be located near objects that would cause multipath or interference. Areas to avoid would be near other antennas, microwave towers, power lines, reflective surfaces, and other obstructions such as vertical walls, dams, and vegetation. In the United States, GPS community base station information is available from several sources including Federal, state, and county agencies along with local universities. There are also commercial services available for real-time differential data that may also provide data for postprocessing. For community GPS base stations, there are some limitations that need to be addressed using the provider's specifications.

Real-time DGPS is the current standard for hydrographic positioning. To collect data using real-time DGPS, a master receiver is stationed over a known datum where it computes, formats, and transmits correction information through a data link to the mobile GPS receiver on the survey vessel. The mobile GPS receiver requires the data link to receive the transmitted GPS corrections from the master receiver. Collecting in real time allows highly accurate positioning data to be merged with other collected data, such as depths, into a single file that significantly reduces the postprocessing.

In an attempt to standardize differential correction transmissions, the Radio Technical Commission for Maritime Services developed the RTCM-104 format for GPS that allows transmitted master station information from several sources. There are some community base stations maintained by United States Federal, state, and local government offices that transmit correction information that can be utilized by any manufacturer's mobile receiver. The U.S. Coast Guard operates high-frequency DGPS radio beacons positioned along coasts and major waterways, such as the Mississippi River and the east and west coasts. There are also commercial services that offer real-time correction information that is transmitted in RTCM-104 format from such devices as geostationary satellites and local radio station towers. One problem with these services is signal destruction when surveying in areas with canyon walls and vegetation, but radio repeaters can be used to resolve this issue. Currently, these sites may not provide the centimeter accuracy corrections needed for some studies. The Sedimentation Group uses DGPS with a master receiver set over a known geographical benchmark in the study area. It must be noted again that obtaining centimeter accuracies requires a real-time survey grade GPS with the master receiver located over a known datum near the survey vessel. The master GPS receiver transmits the calculated difference correction information through available communication data links such as high frequency (HF), very high frequency (VHF), and ultra-high frequency (UHF) radios. HF radios transmit over long distances but require a relatively large antenna. VHF and UHF radios are small, lightweight, and require smaller antennas, but the radio signals are somewhat limited to line-of-sight.

UHF and VHF systems are commercially available at a lower cost than other systems and are the recommended communication systems for DGPS. The disadvantages are the limited range due to the line-of-sight, licensing issues, and the effects of signal shadowing and multipath. All frequencies must be authorized for operation to avoid interference with other activities in the area. Allocations of the frequencies are handled through the National Telecommunications and Information Administration of the U.S. Department of Commerce, and it is the responsibility of the purchaser, user, and vendor to gain approval before any transmission occurs. Other possible means for transmitting the correction signal are microwave radios and cellular telephones.

The biggest weakness in all real-time collection systems is the communication link between the master and mobile GPS receivers. Surveying on open water removes many of the obstacles, but communication problems can occur with all systems when surveying in areas with obstructions such as mountains, cliffs, vegetation, and structures along the shoreline. When these situations occur, the flexibility of the hydrographic survey crew in being able to move the master receiver to new locations makes surveying more viable but, at times, more costly.

Plotting of position data during and after collection may indicate any problems with the GPS signals. Some collection software programs monitor parameters such as the differential correction signal and HDOP values where loss of correction signal or high HDOP values cause an error signal to be broadcast to the collection crew, indicating low-quality data is being measured. When these conditions occur, the collection can be delayed until the condition improves.

In theory, the master and mobile GPS receivers are simultaneously observing the same satellites, but, in practice, this is not always the case. The survey crew must be aware of this situation and take all practical measures to obtain simultaneous satellite observations. The best way to accomplish this is to place the master unit near the area to be surveyed. In the northern hemisphere, the satellite observations are obtained in the southern skies. For reservoirs with high bank and vegetation conditions, it may be best to place the master unit on the north bank of the reservoir, where the southern hemisphere is visible, allowing the master unit to obtain the majority of the satellite signals. The mobile GPS receiver on the boat should always be monitored, especially when surveying near obstructions that could affect the satellite and radio signals. Monitoring the mobile receiver includes checking PDOP or HDOP readings and tracking the survey vessel path on a helmsman display where a large jump in correction information may mean a loss of the differential signal, bad satellite geometry, or multipath.

9.8.3 Real-Time Kinematic GPS

RTK GPS in hydrographic surveying provides the highest precision of positioning. The major benefit of RTK versus DGPS is that precise heights can also be measured in real time. This is a major benefit for surveys in tidal and river conditions. The basic outputs from an RTK receiver are precise three-dimensional coordinates such as latitude/longitude/height with accuracies on the order of 2 centimeters horizontally and 3 centimeters vertically. Kinematic GPS employs at least two receivers that track the same satellites simultaneously, just like DGPS. The receivers track the L1 C/A code and full cycle L1 and L2 carrier phases observable even during periods of P-code encryption. The additional data logged from the second frequency facilitates faster resolution of the ambiguities that allow on-the-fly centimeter level measurements.

RTK GPS uses the carrier phase, rather than a code phase used by DGPS. Initializations of the RTK receivers are required at the start of survey and after continuous tracking of all available satellites signals are hindered. The hindrance or loss of a satellite signal in hydrographic surveying can occur while surveying under a bridge or near blockage by trees, dams, and surrounding topography such as vertical walls. RTK GPS receivers may take about 1 minute for initialization while satellite information is acquired for accurate positioning. Once initialization has been gained, the hydrographic survey can begin. With DGPS, the accuracy computations are instantaneous after acquiring the satellite signals and require a minimum of three satellites (if only horizontal positioning is measured). RTK needs a minimum of five satellites to start initialization, but only four satellites are needed when surveying. RTK may require 1 minute or more to reinitialize after reacquiring the satellite signal, but it can provide 2- to 3-centimeter accuracy if the base station is located close to the survey site. These real-time measurements allow accurate monitoring of the elevation changes of river, tide, and reservoir water surfaces, along with survey vessel elevation changes due to squat, weight changes, and water surface swells. The real-time centimeter accuracy also allows the survey crew to establish any necessary control around the study area, further reducing the field time for conducting the survey. By default, the RTK receives output precise 3-dimensional coordinates in latitude, longitude, and height in the GPS datum (WGS84), but there are options to output the coordinates and height for a selected local datum.

9.8.4 GPS Errors

GPS measurements are affected by similar sources of errors as previous collection systems (humidity and multipath, for example). GPS also must contend with the ionosphere and troposphere layers of the earth that delay the satellite signals that travel from 20,000 kilometers out in space. The tropospheric error, up to 3 meters, includes humidity that can delay the signal. Satellites low on the horizon send signals across the face of the earth through the troposphere, while satellites directly overhead have less troposphere to deal with. Masking the horizontal angle of the mobile receiver from 10 to 15 degrees above the horizon minimizes the tropospheric error. The ionospheric error includes sunspots and other electromagnetic phenomena that can cause GPS errors up to 30 meters during the day and 6 meters at night. The errors can be estimated, but the assumption that the error is the same at both the reference and mobile receivers eliminates it when using DGPS techniques.

Multipath occurs when the signal to the GPS receiver is reflected and is not a direct signal from the satellite. This reflection can occur below and above the GPS antenna and can be difficult to identify. The occurrence of multipath is less over water, but it is still present and can be constantly changing. Careful placement of the GPS receiver antenna can avoid areas of multipath such as rock outcrops, metal roofs, buildings, cars, ships, dams, and chain link fences. It is best to set the reference station away from these conditions, but another solution may be to increase the height of the GPS antenna to reduce the possibility of multipath. Masking out the satellite signals below 10 to 15 degrees above the horizon can also reduce multipath. Antenna ground planes are designed to reduce the effects of multipath and should be used for both the master and mobile GPS locations when practical. It must be noted that multipath occurrence from the satellites to a receiver, at a static location, can change over time, since the satellite location is constantly changing.

There are no prescribed calibration requirements for GPS as there were with previously used positioning systems, but there are items that can be monitored to check for operator errors. One item is an incorrect project or geodetic reference datum. Most GPS units output coordinates in latitude/longitude/height on the WGS84 ellipsoid, and the collection software converts the collected information into the project's coordinate system, such as state plane or UTM. The operator must confirm these conversion calculations prior to starting the data collection. It is recommended that, after programming, the GPS rover receiver be set over a known datum point to confirm the output coordinates, but, for many study locations, these known points are not easily available. It is also recommended that a map of the study area be available during collection to confirm locations during the survey by plotting the survey vessel at known locations on the map. Common errors that should be doubled checked are incorrect master station coordinate values, incorrect GPS antenna heights at either the master or rover receiver, or DGPS mode not operational due to a lost correction signal or radio not turned on at the base location. It must be noted that multipath effects are not eliminated by calibration, since they are dependent on the GPS antenna location for both the master and rover units.

9.9 Horizontal and Vertical Control

The basic horizontal control for many Reclamation projects varies from region to region and from project to project (Bureau of Reclamation, 1981). There were many project datums located and developed with conventional survey equipment on local horizontal and vertical coordinate systems. There are some projects that were tied to National Geodetic System (NGS) or USGS monuments but have not been referenced or adjusted with the current national network. Many of the Reclamation projects are tied to the national state plane coordinate system in NAD27 (North American Datum of 1927), and some projects cover several zones of the state plane coordinate system. Care must be taken to ensure the collected data and final results conform to the requested datum for the study.

It is recommended that all new surveys conform to the national network and that all study results clearly state on all maps and reports the horizontal and vertical datums used, along with the year the datum was established. For positions reported in state plane coordinates, the units of feet or meters should be stated with the state plane zone and year, such as NAD27 or NAD83. The UTM coordinate system is also an acceptable measuring projection that should be clearly labeled with proper zones and years.

Differential GPS collection systems are used for horizontal control for the majority of the hydrographic collection. The horizontal datum used for GPS is WGS84 that is essentially equivalent to NAD83. It is suggested that all new surveys be conducted and reported in NAD83 or WGS84, but NAD27 is also an acceptable horizontal datum for a project study. Even if the final results are to be reported in NAD27 or a local datum, it is recommended that all GPS data be collected in WGS84 or NAD83, then converted to NAD 27 during postprocessing. Collecting the data in WGS84 or NAD83 preserves the data in a raw format that can easily be used and imported into Geographic Information Systems (GIS) without worrying about datum conversion errors generated by the field crew and collection software.

The vertical controls for Reclamation projects cause more problems and confusion than the horizontal controls. This is mainly because most Reclamation projects have a vertical datum that was established during project design and construction and has been used since initial operation. There are some projects where Reclamation, USGS, Bureau of Land Management, state, water district, project, and NGS datums were all established over time, resulting in several different vertical elevations for the same point. The final results from the reservoir survey should clearly state the datum used and, if possible, reference it to permanent project features, such as top of dam, spillway crest, and outlet elevations, as a means of clarifying datum differences. Many recent studies have established new survey control with the hope of clarifying multiple vertical datums. However, some surveys failed because previous resurveys were not tied to any permanent reference object. Survey grade GPS, when used properly, will bring in the most accurate horizontal and vertical positions, but care must be taken to tie new control to previously established control, such as brass caps, sediment range line monuments, water surface gauge monuments, or top of the dam, spillway, and outlet works.

Ideally, the horizontal and vertical datum adjustments should be made on all projects in local datums in a uniform, orderly, and timely manner, but, realistically, they will only be performed on certain projects. In some cases, datums will not be adjusted at all because the time and expense would be far greater than the benefit of doing such adjustment. There are some Reclamation projects that have operated for nearly 100 years with a local datum, and all drawings and records for these projects were developed with these datums. Making any adjustments would be a great expense if it results in all past records having to be adjusted. At Elephant Butte Reservoir, which started initial operation in 1915, the project vertical elevations are 43.3 feet less than the National Geodetic Vertical Datum of 1929 (NGVD29).

9.9.1 Datums

Many Reclamation projects were established with horizontal and vertical control in a local project datum or referenced to the North American Datum of 1927, which was converted to the local state plane coordinate system. Since the majority of the hydrographic surveys are established and surveyed using DGPS in the control of the nationwide network, there is little need to adjust or establish supplemental horizontal control for the study. It is highly recommended that all GPS coordinates be collected in the WGS84 system and all conversions are to NAD83. There is a small difference between WGS84 and NAD83, but it is not significant for hydrographic applications. The WGS84 system can be converted on the fly to state plane or UTM with most hydrographic software. If the final product needs to be in NAD27, it is recommended that these conversions be conducted in the office environment during final processing. One reason for this is that the collected data should be in the cleanest format before conversion so it can be made available for other studies.

GPS satellite positions are based on the three-dimensional earth-centered WGS 84 ellipsoid. For study purposes, the WGS 84 ellipsoid information is usually converted to a user-defined ellipsoid/datum such as NAD27 or NAD83. The North American Datum of 1927 (NAD27) is a horizontal datum based on a comprehensive adjustment of a national network of traverse and triangulation stations. NAD27 was developed and best fitted for the continental United States with the fixed datum reference point located at Meades Ranch, Kansas. The original network adjustment used 25,000 stations referenced to U.S. survey feet. The North American Datum of 1983 (NAD83) used about 250,000 stations to readjust the national network. For practical purposes, NAD83 is equivalent to WGS84 and is currently the best available geodetic model of the worldwide shape of the earth's surface. The reference units are in meters.

9.10 Depth Measurements

9.10.1 Single Beam

Over the last 50 years, the majority of all hydrographic surveys have been conducted using some form of acoustic depth sounder. Manually operated sounding lines and poles may be considered outdated, but they are still viable means of depth measurement in reservoirs with thick vegetation and shallow depths. These manual measurements can also be used as confirmation of electronic depth soundings. Faulty or questionable readings from depth sounders may be caused by noise from vertical walls and structures or from silty bottoms containing "fluff" or light suspended material. Manual collection methods can be used to confirm "fluff" type conditions and possibly determine the type of material on reservoir and river bottoms. Brief summaries of manual collection techniques may be obtained from other publications (USACE, 2004 and ASTM, 2005).

The electronic method using **sonic (echo) soundings** has been the norm in hydrographic collection systems for measuring the bottoms of small and large reservoirs for several decades. The echo sounders have the capability of recording continuous profiles of the reservoir bottom, providing an analog bottom profile chart and digital records stored on the computer system. The computer system software matches these depths with other digital information such as horizontal positioning and heave components. Acoustic depth sounding equipment is preferred because it provides a continuous record and chart of the bottom profile. The basic components are the recorder, transmitting and receiving transducer, and power supply. With careful calibration and correct collection techniques, a high degree of bottom profile accuracy can be obtained and recorded.

The echo sounders are usually portable recorders that measure the time required for a sound wave to travel from its point of origin to the bottom and back to the origin. The time interval is converted to distance (depth) below the face of the sending plate or transducer. The transmission of sound is dependent on the properties of the water and reflecting surface and assumes a constant velocity throughout the depth measured. Since constant velocity is not the case, hydrographic system sounders usually are designed to permit adjustments (calibration) for the variations in the sound velocity in the water. Calibrations of the echo sounder are critical in assuring high-quality depth measurements by the hydrographic survey system. The largest and most critical correction results from the variability of the sound velocity in water due to temperature changes, but other factors such as water density, salinity, turbidity, and depth also affect sound velocity. In fresh water at 60 °F, echo sounders are generally calibrated for a sound velocity of 4,800 feet per second (1,463 meters per second), but water property variability can make it range from 4,600 to 5,000 feet per second. Most reservoirs and rivers exhibit large variations in temperature and water chemistry with depth, which means that the velocity of the sound wave will not be constant for the distance from the sounder's transducer to the bottom and back. The effect of the variation can be significant with a temperature change of 10 °F changing the velocity by about 70 feet per second or changing the depth measurement 0.8 feet per 50 feet of depth. For reservoirs such as Lake Mead and Lake Powell, the summer surface temperatures can be in the high 70s, while the bottom depths are still in the 40-degree range, causing a significant change in the sound velocity through the vertical temperature zones. A 10 parts per thousand salinity change can vary the velocity by around 40 feet per second or 0.4 feet in 50 feet.

For most single beam, shallow water, echo sounding work, an average velocity of sound is usually assumed. A bar check calibration determines the actual depth at the study area, and the sounder is adjusted to measure the correct depth. If the study is conducted in areas with known large variations in velocity by depth or location, the sounder should be set to measure the average or deeper depths that will be encountered during that time over the area being surveyed. For these types of conditions, more frequent calibrations are needed. The sound velocity can be determined by a bar check calibration or measured directly using a velocity probe. The velocity probe can measure the sound velocity at every foot of depth, and an average value can be computed from these measurements. Current hydrographic software allows the depth incremented velocity measurements to be recorded, stored, and used during postprocessing to adjust the sounder measurements to actual depths. The method of using a velocity probe for measuring depth-related sound velocities is more critical for the outer beam depth adjustments of multibeam systems when correcting raw field readings.

The velocity probe calibration method is being used more extensively with hydrographic systems, but depths/velocities should also be periodically checked using a bar check type system. A bar check consists of lowering an acoustic reflector, such as a flat metal plate or I-beam, to a known depth (below the transducer) and manually adjusting the sound velocity to produce an equivalent depth reading. Bar checks can be conducted in 1-foot and greater depths. For shallow conditions, a survey rod can be used in place of the reflector bar. The lines used to lower the bar should be of marked flexible steel wire or chain that does not stretch. The bar check suspension lines must be periodically checked to ensure accuracy of the line markings. The bar check should be conducted in relatively calm water with minimum wind conditions. Mild to strong wind will shift the sounding vessel so that the calibrating bar will be suspended at an angle from vertical, causing the narrow beam signal from the transducer to miss the bar or give false depth readings. In water deep enough for calibration, the survey vessel can be tied to an available buoy, pier, or other object during the calibration to stabilize the boat in windy conditions. The survey crew should conduct a bar check and record results on a depth chart or logsheet. Comparisons at predetermined intervals throughout the depth range of the survey should be recorded during both descent and ascent of the bar. Any adjustments to the speed of sound of the echo sounder should be noted. Figure 9.6 shows a typical chart produced during a bar check.

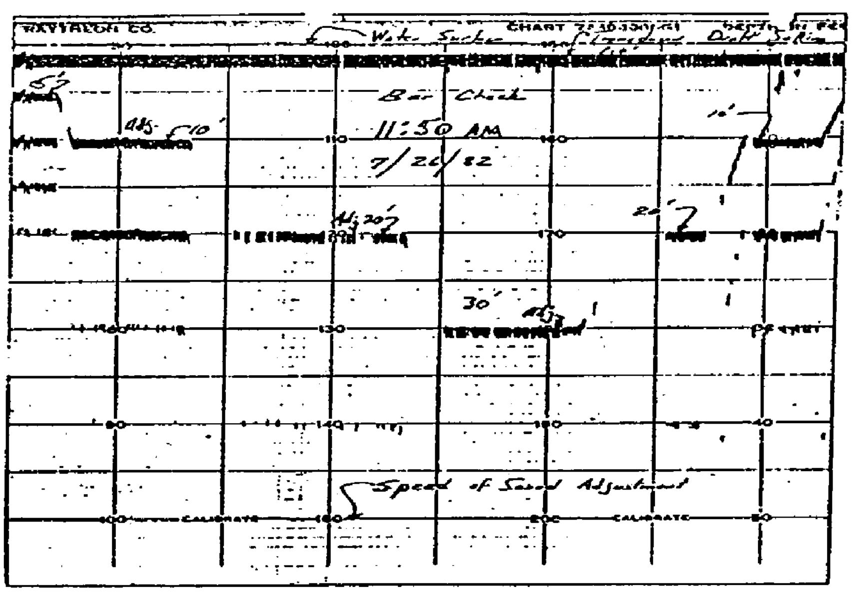


Figure 9.6. Bar check calibration sounding chart (Blanton, 1982).

The weight and structural design of the bar are dependent on the underwater currents and depths to be surveyed. The typical bar may weigh from 20 pounds to more than 100 pounds and can be designed to allow additional weight to be added. Some boats are designed with a center-mounted, spherical calibration ball where the ball is suspended by a single line, providing the advantage of less drift due to current. For small boat setups, a small plate suspended over the side by a single marked cable can be used.

The calmest water conditions for conducting bar checks usually occurs in the early morning or late evening. For areas where salinity and temperature of the water are unknown or are not well mixed, the echo sounder should, at a minimum, be calibrated before the start and end of each day's work. Additional calibrations should be conducted if the survey vessel is moved to a different location of the study area, such as from the main body to a significant tributary of the reservoir. For larger jobs, where stable water velocity conditions are known to exist, the number of bar checks can be reduced to one per day if previous calibrations confirm stable conditions. If previous calibrations indicate unstable conditions, more calibrations become necessary. Calibration of electronic echo sounding instruments is inherently an imprecise process. Bar check and velocity meter calibrations are performed while the vessel is stationary, so actual dynamic survey conditions and different study zones are not truly simulated.

There are different procedural methods of conducting a bar check calibration, but the goal is always to obtain the actual depths of the study area. All procedures require the lowering of a plate a fixed distance below the depth sounder transducer and adjusting the draft and sound velocity settings to match echo sounder depth measurements to know bar depths. A common bar check process is as follows:

- Turn echo sounder on 10 minutes prior to the calibration process to warm the machine up.
- Set initial settings (tide, draft, speed of sound) according to manufacturer's specifications.
- Lower the bar into the water to the 10-foot mark, ensuring the bar is directly underneath the transducer (may want to use a 5-foot mark if conducting shallow water work).
- Adjust the sounder's settings (draft) so that the depth tracing or digital reading matches the 10-foot depth reading on the sounder.
- Lower the bar to the cable increment mark closest to the greatest anticipated sounding depth.
- Adjust the speed of sound control setting so that the sounder's depth matches the bar's depth.
- Raise the bar to the 10-foot position and readjust the sounder's draft if necessary. If no adjustment is needed, then the echo sounder is calibrated.
- Repeat the above steps, starting with lowering the bar to 10 feet, as necessary, until the correct sounder's settings ($\pm$0.1 foot) are obtained for both deep and shallow water.
- Upon completion, intermediate readings between the maximum and minimum depth should be checked to compare the displayed value with the known bar depths.

When complete, the echo sounder should be calibrated at the shallow water (10-foot) and deep water depths. If the sound velocity is constant, the sounder should also be calibrated for the depths between the minimum and maximum depths. If the velocity of sound is not relatively constant throughout the working depth range, it will not be possible to adjust the instrument so that it reads equal to the bar check at each depth increment. One method of accounting for sound velocity variability is to not adjust the echo sounder, but to record the error at each depth and apply corrections during postprocessing. An alternative approach is to place the bar at the maximum study depth and set the depth sounder speed of sound for this observed bar reading. The bar is then raised at set increments as it is retrieved from the water, while sounder readings versus bar readings are recorded. The depth readings can be corrected during postprocessing.

The development of portable velocity meters has provided an additional acceptable means for calibration where the sound velocity in the water column is directly measured for different depth increments. This method provides a fast, reliable means for calibration of the depth sounders with speed of sound, but periodic verification of sounder readings using a standard bar check is still necessary. If repeated comparisons between the bar check and velocity probe provide consistent depth measurements, less checks are necessary. Major advantages of the velocity probe versus the bar check include its ability to perform rapid calibrations, calibrate in rough sea conditions, and perform more frequent calibrations. To ensure quality performance of the probe, it should be tested daily, simply by obtaining sound velocity readings in fresh water in a bucket. There are several companies that manufacture profilers consisting of a probe attached by a waterproof, depth-marked cable to a hand-held control unit. Some models use a pressure sensor for depth determination, which is necessary in deeper reservoirs to minimize the cable slant error. The velocity meter records the speed of sound at water depth increments (set at 1 foot or 1 meter) as it is lowered in the reservoir. These readings may be recorded and used by the hydrographic software for processing the actual depths, or the probe measurements can be used to provide an average sound velocity over the entire water depth that is then entered into the depth sounder.

The echo-sounding instrument consists of the recorder, the transmitting-receiving transducers mounted in the hull or side of the survey boat, and a power source from either a battery or generator. The depth of water is measured continuously at hundreds of soundings a minute and may be recorded on chart paper and/or computer at a prescribed interval. The chart becomes the official record of the depth measurements and should contain the file name, line identification, date, time of day, changes in chart speed, changes in vertical scale, water surface elevation, and any other information needed to interpret the charts. A typical range sounding chart is shown in figure 9.7. During data analysis, the charts are used to verify digitally recorded depths before final contour development. The trend now is for the hydrographic system to include paperless depth sounders. The key advantages of the paperless charts are their smaller size and fewer moving parts. There are several manufacturers of paperless sounders that provide a color sonogram display that looks similar to paper charts of the measured bottom. Some offer the option of storing the entire sonogram for future playback and printing if it becomes necessary during the analysis.

An echo sounder's transducer has many frequency options and should be selected to meet the majority of the study needs. The Sedimentation Group surveys are conducted using a 200-kilohertz, high-frequency echo sounder that also has a low-frequency, 24-kilohertz option. In general, the higher frequency transducers of 100 kilohertz and greater provide more precise and detailed bottom depth measurements due to the frequency characteristics and narrow beam width. The major disadvantage of higher frequency transducers is that they tend to reflect off of first signal change, which may provide false readings of the actual depth for such conditions as suspended sediment (fluff) and bottom vegetation. The lower frequency transducers of less than 40 kilohertz are less subject to attenuation and are capable of greater depth measurements since they can penetrate the suspended sediment or fluff type conditions. However, the lower-frequency transducers have a larger beam width, which may provide readings that are distorted due to smoothing of irregular bottom features and the side slopes. An experienced operator, along with some manual depth readings, is needed to assist in making a distinction between the fluff and actual bottom readings. For several years, the vendors have offered dual-frequency sounders that allow the operator to measure separate, simultaneous, high- and low-frequency depths. During the last few years, portable sounders offering variable and multiple frequency settings have been developed.

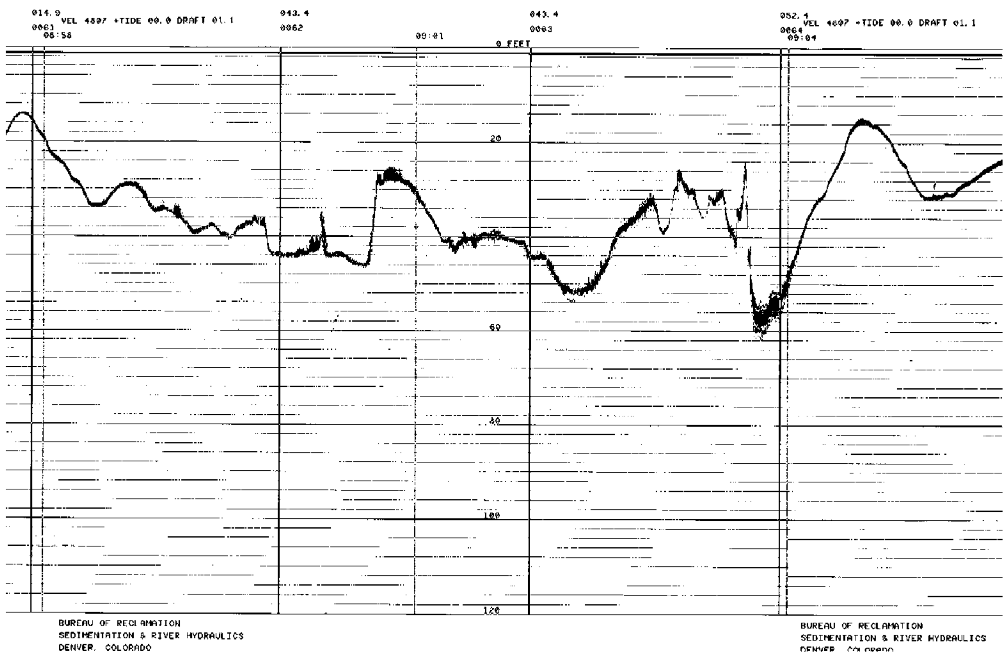


Figure 9.7. Range sounding chart produced from an Innerspace 448.

9.10.2 Multibeam

Multiple beam echo sounders have become more popular over the last few years. The multiple transducer method was mainly developed for situations where detection of navigational obstacles was the primary concern. Initial multiple transducer systems consisted of individual transducers mounted in the boat hull and along booms extending from each side of the boat (figure 9.8). Maneuvering the survey vessel was difficult with this system, and it was not suitable for rough water. The booms came in varying lengths, with some having a hydraulic design that could be automatically extended or withdrawn. The system used a vertical sounding beams system, just like the single beam system except there were multiple units. In theory, the system was simple to operate and the separation of the transducers and their width of coverage provided sweep coverage for full bottom mapping. The coverage depended on the beam length and number of transducers, and it is still used by the USACE for performing dredge measurement and payment surveys.

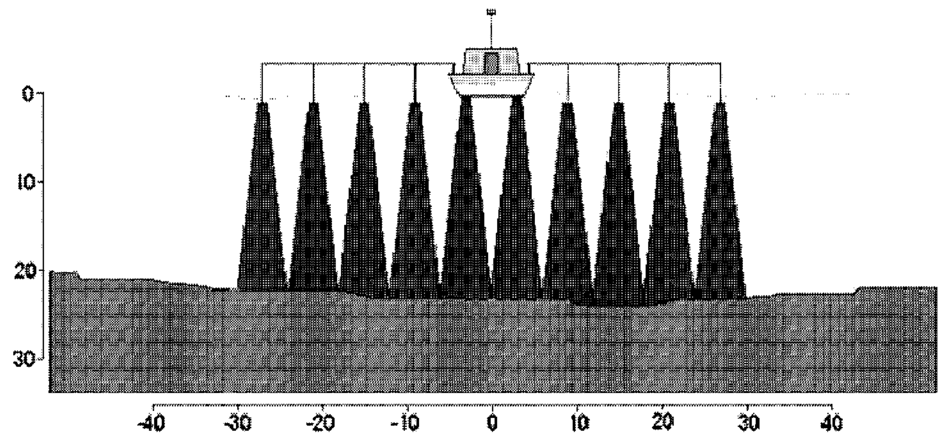


Figure 9.8. View of a multitransducer survey vessel (HYPACK, Inc.).

Recent improvements in collection and analysis techniques through multibeam survey technology have made it a standard for many survey groups, replacing several of the multiple beam systems that were in operation by the USACE. In 2001, the Sedimentation Group acquired a multibeam system, enhancing the capability their existing hydrographic collection system. The system was first used to survey the sediment deposition in Lake Mead from the dam to the upper shallow water areas of the reservoir. The end products of the Lake Mead survey were cross sections every 5 meters for the surveyed area, allowing detailed mapping of the sediment deposition. The detailed collection of the underwater portion of the Lake Mead sediment deposition was completed in less then 1 month with a two-person crew. Compared to the 6 months and 6-person crew required to collect 407 cross sections for the 1986 Lake Powell sedimentation survey using a single beam collection system, the potential time saved using a multibeam system becomes clear.

Multibeam technology was originally developed in the 1960s for deep water ocean mapping. In the 1990s, the technology was further developed and extended to shallow water applications. There are several vendors that manufacture these systems with the software needed for collection and processing of the data. The manufacturer's manuals need to be used for instructions on system operation and collection and processing of the acquired data. Multibeam systems are fan-beam acoustic sounding systems comprised of a number of narrow beam transducers mounted in close proximity and focused at equally spaced angles from one location under the survey boat (figure 9.9).

Each transducer acts as a separate acoustic-distance measuring unit, like a single beam, vertical mount system, except the multiple transducer beams are at a given angle with respect to the mounted single vertical transducer. Computations determine the depth of each beam from the slant-distance signal adjusted to incorporate the velocity profile data. Multibeam vessels can survey in rougher water and offer greater coverage. The coverage area is dependent on the water depths. For a fan of 120 degrees, the bottom sweep width is around 100 feet in 30 feet of water and around 350 feet in 100 feet of water. It must be noted that, for navigation type surveys, it is recommended that a 50-percent overlap of the survey sweeps is maintained for quality control

(QC). Most Reclamation surveys are not performed for navigation purposes, so the fan overlap can be reduced. The overlap should be enough to assure the outer beams of the two sweeps are collecting high-quality data. The fan angles for multibeam systems typically vary between 90 and 220 degrees. The primary justification for purchasing and using a multibeam system is that the majority of the water depths of the study area are greater then 30 feet. Some multibeam sonars can be tilted for mapping reservoir banks and features such as dam faces and outlet works; however, accuracy may be sacrificed, since the larger errors with a multibeam system occur in the outer beams (figure 9.10). Some multibeam systems and software provide the option of multibeam sidescan imagery that, in general, is not as good as the images from towed sidescans, but is a byproduct of the system that should be considered.

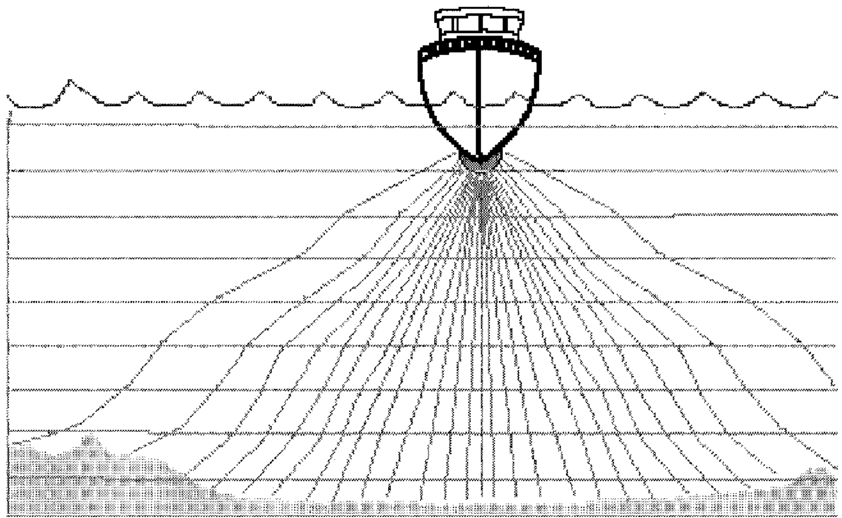


Figure 9.9. Multibeam collection system.

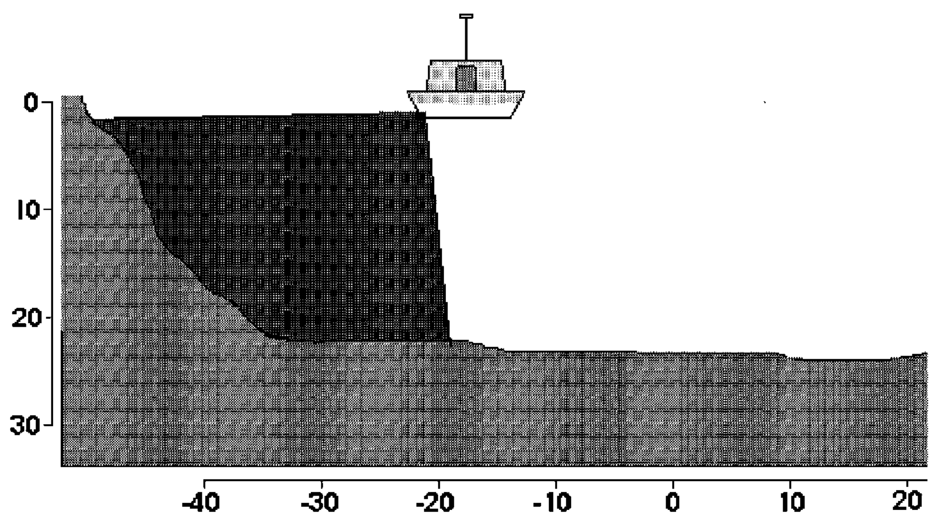


Figure 9.10. View of mounting options with multibeam survey boat (HYPACK, Inc.).

The horizontal and vertical accuracy of the collected data relies on many components necessary to complete a multibeam survey system. These components include the computer system with software, sensors for heave/pitch/roll and heading, positioning system, and velocity profiler for calibration. Multibeam systems have a very high data acquisition rate. With data collection rates in the thousands of depth points per second, manual editing in no longer feasible. With this in mind, an extensive calibration is necessary prior to starting the data collection. The calibration is necessary to determine the magnitude of such error sources as the vessel roll, pitch and yaw, mounting angles of the sonar, and incorrect x, y, z offset errors between positioning antenna and sonar.

In single beam soundings, the sounding or ping travels downward and upward along a vertical path with virtually no change in direction. The majority of the multibeam sonar beams are not vertical and encounter changes in sound velocity resulting in ping speed changes, along with slight changes in direction. When the sound velocity increases, the ray is bent upward; when the velocity decreases, the ray is bent downward (figure 9.11). Correction for these sounding refractions requires an actual velocity variation with depth table of values that are used in postprocessing of the depth data. This information does not come from the bar check procedure, but from a sound velocity probe that measures actual velocity variations with water depth. For the Lake Mead survey, a velocity probe was used that had a 100-meter cable length and readings were taken every meter of the depth zone. Other components of the system include a heave compensator for measuring the up and down motion of the boat, gyro for vessel heading, and motion reference unit (MRU) for measuring the pitch and roll data. All of these measurements are needed to correct the multibeam data and are monitored by the hydrographic collection software, and all data are stored and processed on the field collection computer. Proper system operation requires an experienced crew and good calibration practice. The cost of these systems is considerably more than for a single beam system, but, since it collects much more data, the final results may justify the greater expense.

Field calibration of multibeam systems is more critical and complicated than what is required for single beam systems. Periodic precise calibration is absolutely essential to ensure that the multibeam positions and elevations are accurate. The horizontal positioning accuracy is dependent upon the ability of the system to compensate for pointing errors caused by vessel roll, pitch, and yaw, where a small degree of roll can cause large errors in the outer beams. For high-accuracy surveys, restrictions are typically placed on the use of the outer beam data. Manufacturer suggestions and experience should be used to determine the use of these outer beams. It is very critical to collect velocity profile data for all beam measurements, but mainly for correction of the outer beams. Velocity profile readings should be taken a minimum of once per day, but it is recommended that a reading be collected several times per day and when the survey vessel relocates to a different portion of the study area. There are set QC calibrations and QA test procedures for multibeam systems to assure highly accurate data collection. These tests and procedures are generally available in the hydrographic software. The calibration of the system determines time latency, along with roll, pitch, and heading bias. Some calibrations are performed just once after the system is installed to measure sensor alignment and offsets, while other calibrations are performed on a more frequent basis, as recommended by the manufacturer, and are needed to ensure the validity of survey results.

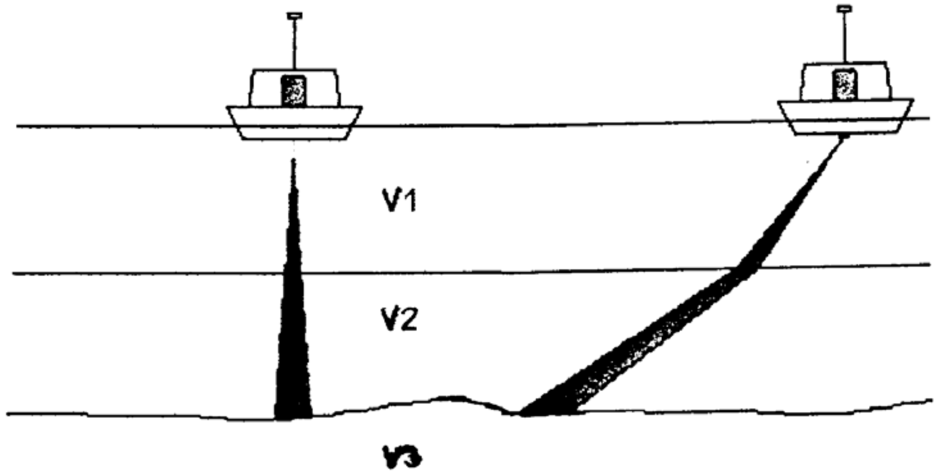


Figure 9.11. Sound beam bending due to change in sound velocity (sound velocity increase in zone V2) (HYPACK, Inc.).

One calibration method, called a "patch test," is performed after initial installation, after any sensor modification, and periodically to confirm previous system alignment. This comprehensive patch test includes a latency test for measuring position time delay and tests to determine the pitch, roll, and yaw or azimuth offsets. Velocity profile corrections are a must for a hydrographic survey using a multibeam system and need to be performed periodically during the day. It is recommended that the velocity profile correction be completed at least twice per day and more frequent in locations where physical changes in the water column are suspected or measured from observing previous collections. A traditional bar check can be used to verify the settings and corrections of the measured multibeam depths. The bar test can also be set up to check some of the outer beam depths, and it is an excellent method to confirm the draft settings of the system. The manufacturers and software vendors have manuals with detailed descriptions on performing the patch and performance tests necessary to ensure the quality of the survey data set. The performance test may compare overlapping survey data sets such as multibeam data overlapping a single beam data set in the same area.

Following is a brief description of a patch test that can be completed (including data collection and processing) in a few hours. The patch test should be conducted in calm conditions in a typical project area. The roll test is run in a flat bottom topography area where one line is run twice in opposite directions at typical survey speed. The latency test consists of running one line on a steep sloping bottom or well-defined feature twice in the same direction at two different speeds. The higher speed should be about double the slower speed. The pitch test consists of running one line on a steep sloping bottom or well-defined object twice in opposite directions at survey speed. The yaw test consists of running two adjacent parallel lines with a well-defined target or slope between them. The line spacing should be about two times the water depth where the swath overlap is between 30 and 70 percent. Each line is run once with reciprocal headings at survey speed.

Raw multibeam data sets are very large, usually with many data spikes, requiring a great deal of filtering and editing before they can be used for final map development. The hydrographic survey software packages contain many routines for manipulating and editing these large, raw data sets. Filtering and editing can be conducted automatically in the software editing processes but must be conducted with much caution to avoid accidental elimination of useful data. In the automated editing process, there are manual editing procedures where it is possible to view each cross section. This procedure can be very time consuming, but it should be performed on most of the data set as a means of conducting QC of the automated filtering process.

Even after the raw data sets are edited and filtered, additional depth data reduction may be necessary for the final data sets. The data sets can be so massive that generating the final map product may be impossible, or at least very time consuming. There have been filtering processes developed, tested, and incorporated into the software routines that allow final data filtering without sacrificing the quality of the study. These filtering routines must be used with caution, but the software saves the previous data set so the user can try different options before settling on a procedure for the filtering. The filtering can also be adjusted to identify important details for such areas as dam faces, possible sinkholes, and trashracks. One of the filtering methods is called gridding and has the option of saving one depth per set cell. The grid size depends on the study needs. It is common for the grid size to be set from 1 to 5 meters. There have been studies with irregular topography and underwater structures that were mapped with data from a grid size of 20 centimeters to obtain the necessary detail.

There are several other viable methods of mapping reservoir and river bottoms that will be mentioned, but manufacturer references and manuals by the USACE and others should be consulted for more detail (USACE, 2004). The Sedimentation Group acquired a multibeam depth sounder and incorporated it into their hydrographic survey system, mainly because it measures x, y, z data in real time, compared to the side scan option that produces only an image without the associated coordinates. The side scan image can be obtained from the multibeam system, but the quality is not as good as data collected with a side scan sonar system designed specifically to collect side scan data. The Sedimentation Group has leased equipment for site-specific studies such as low-frequency (24-kilohertz) transducers and a side scan sonar system with operator. The low frequency system was used in an attempt to locate soft bottom conditions on the Salton Sea. In an attempt to locate sinkholes at Horsetooth Dam in Colorado, an analog side scan sonar system was leased in 1998 and 1999. The collected images appeared to indicate a sinkhole in the left abutment area, which was confirmed once the reservoir level was dropped to expose it. It is the general conclusion that the combination multibeam and side scan system could have located and confirmed these conditions more easily.

9.10.3 Additional Sonar Methods

Side scan sonar is a high-resolution tool that provides a map on both sides of a survey vessel's path. The system does not provide absolute elevations of objects; however, it will provide relative elevations of the surrounding topography. The map images can be recorded as an analog image paper chart or a digital data image that allows mosaics to be produced and merged with other data sets such as multibeam data (Twichell, Cross, and Belew, 2004). The quality of sonar data is often a function of the height of the towfish above the bottom. Multibeam systems have the capability of providing a side scan image, but the quality is not as good as the towed side scan systems.

Airborne Light Detection and Ranging (LIDAR) hydrographic surveying method is a means of collecting above and below water data. The Sedimentation Group and other agencies have successfully used airborne LIDAR to conduct shallow water river surveys (Hilldale, 2005). The primary constraint of LIDAR is water clarity. LIDAR has been successful at collecting bottom data through as much as 40-meter depths of clear water. In less clear waters, LIDAR data collection has been successful at depths of two to three times the visible depth.

There are other systems and methods under development that should be monitored as they become more viable for survey applications. Hydrographic systems development can be monitored by attendance at conferences, through Internet research, and by belonging to technical groups associated with hydrographic and general surveying that provide periodic magazines and newsletters.

9.10.4 Single Beam Depth Records

The following information will deal with single beam systems. Knowledge and understanding of the single beam systems can be applied when working with the more advanced multibeam systems. When setting up and using any system, the manufacturer specifications and manuals should be consulted.

Interpreting depth records takes experience. The most reliable interpretation usually comes from the survey collection crew or someone who has survey collection experience. During interpretation, a plot of the digital record and bottom charts should be studied. In general, if any recorded traces on the graphic or digital record cannot be attributed with reasonable certainty to reflections from the reservoir bottom, the traces should not be part of the final recorded files. The echo sounder's trace on hard bottoms will reflect more strongly than on soft bottoms and will appear as a thin, dark trace on analog charts. In shallow conditions, multiple echoes may appear with the actual depth being the shallowest reading of the trace. Soft bottoms of unconsolidated materials may produce a broad trace, and sometimes the thickness of the fluff or soft layer can be determined by a split in the echo trace on the analog chart. These types of conditions usually need to be resolved in the field to confirm the true bottom versus the digital reading. This may be done by using the lead-line or sounding-cable method. Interpretations of the analog and digital depth data are sometimes made very difficult by the presence of heavy vegetation, floating objects, bottom projections and depressions representing sudden bottom changes, and steep bottom slopes (figure 9.12). Figures 9.13 through 9.15 are analog chart samples.

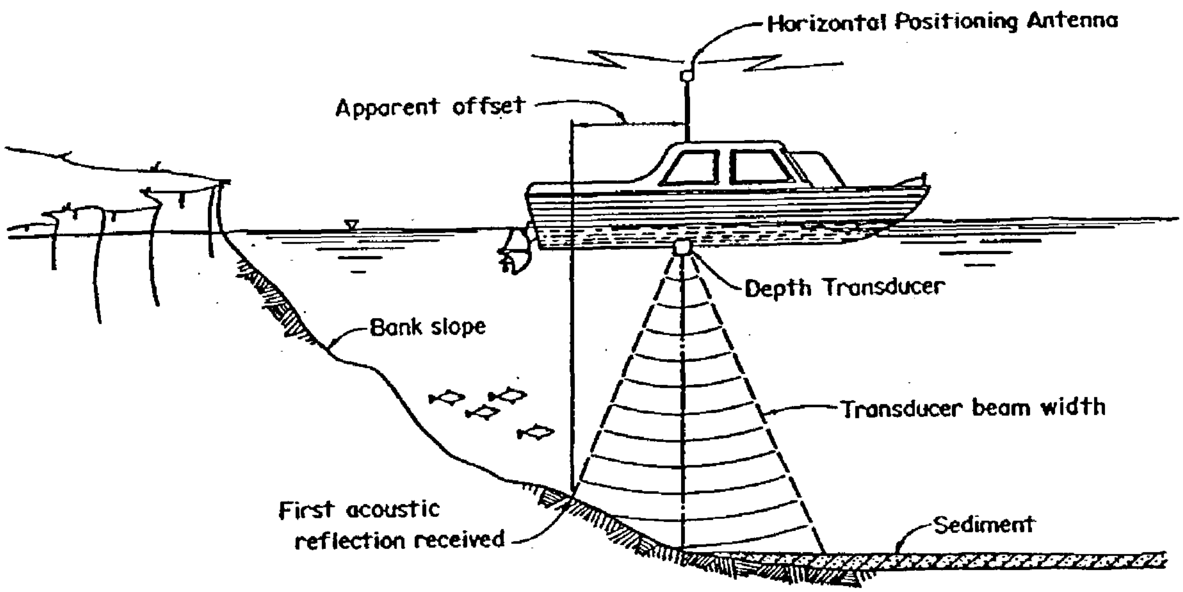


Figure 9.12. Position error due to side slope effect and sediment (Blanton, 1982).

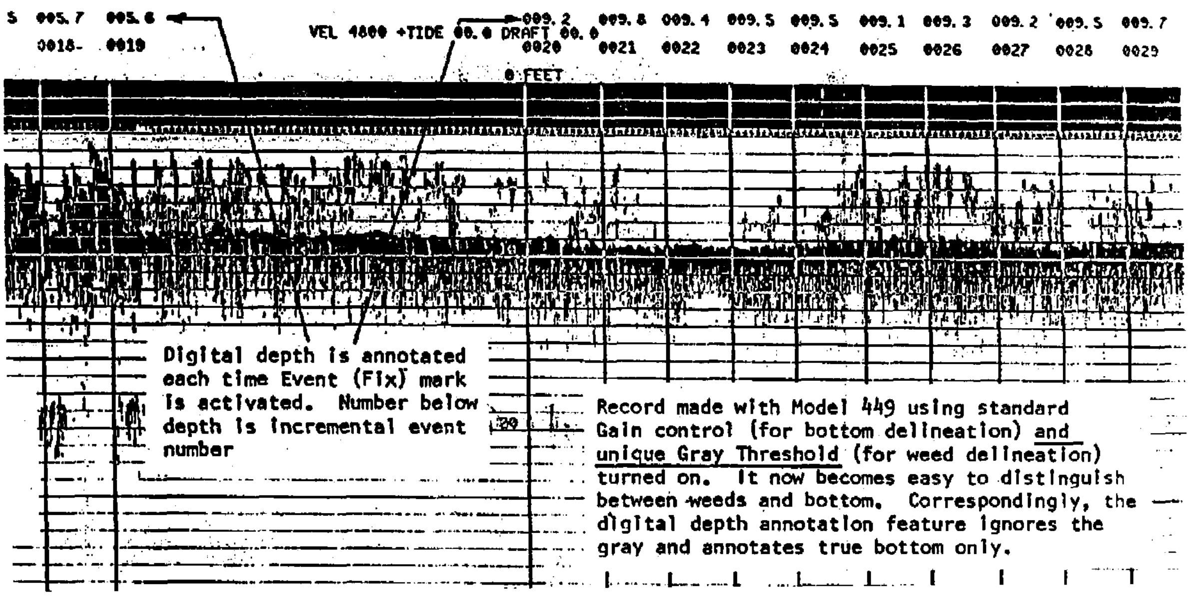


Figure 9.13. Chart from 27-kilohertz sounder, showing weeds and bottom (Innerspace, Inc.).

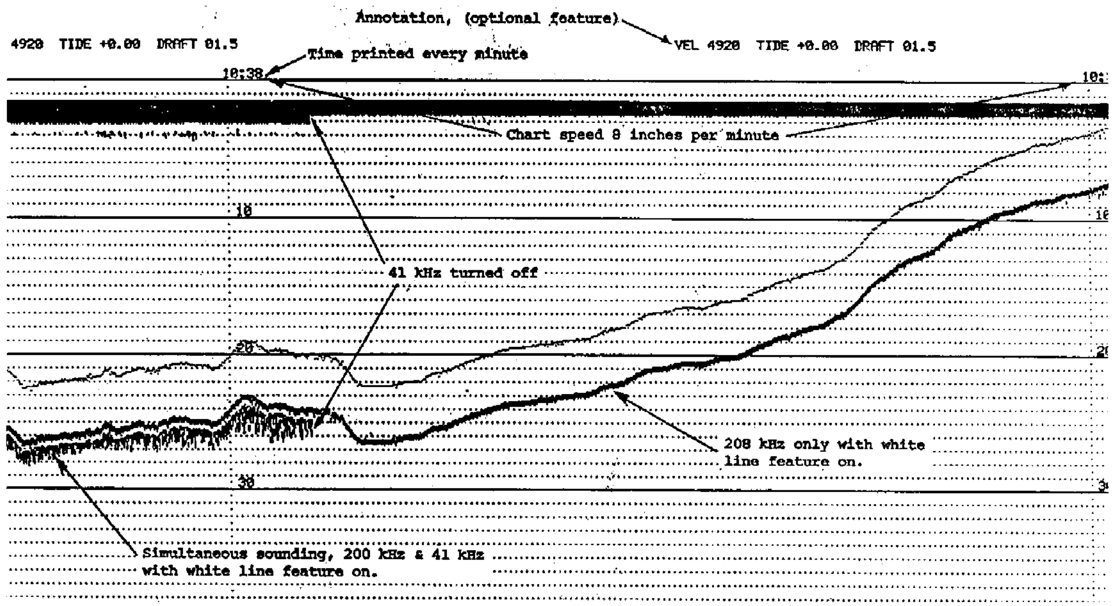


Figure 9.14 Simultaneous sounding chart, 41 kilohertz and 208 kilohertz (Innerspace, Inc.).

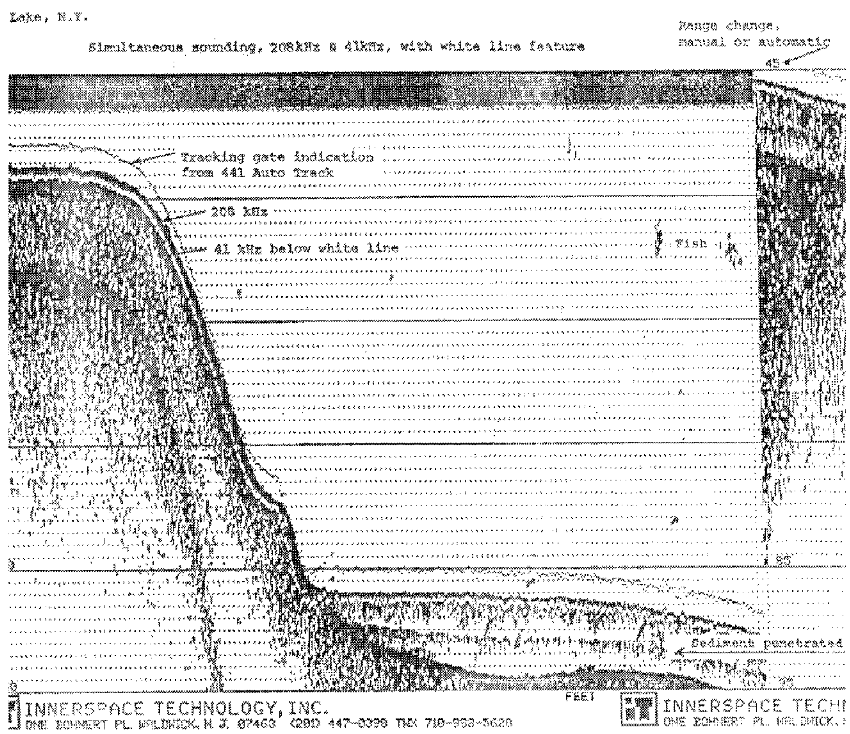


Figure 9.15. Chart from 41-kilohertz and 208-kilohertz sounder, showing fluff (Innerspace, Inc.).

Factors leading to possible errors in depth measurement need to be considered when conducting a reservoir survey and during the analysis of the survey depth data. Detailed descriptions of these factors are summarized by Hart and Downing (1977). Some of the most significant factors are as follows:

Acoustic velocity propagation. The velocity of sound through water varies with temperature and salinity. For many storage reservoirs, the most significant factor is reservoir water temperatures that can vary, in the summer season, by as much as 45 ^{o}F between the surface and deep water. Bar and velocity probe checks are designed to correct the measurement variation and provide necessary correction information that can be applied during field collection and data analysis. Multiple bar and velocity probe checks are essential where any significant variation exists.

Transducer location. The draft or vertical location of the transducer's bottom face with respect to the water surface can be set within the more advanced sounding instruments or within the hydrographic collection software. As shown on figure 9.16, the location of the transducer face with respect to a static water surface is different when the sounding boat is in motion. The effect of the boat motion on draft may be corrected in the calibration of the instrument. The effects of the boat speed on the transducer location can be measured by a squat calibration test and corrected during data processing (USCOE, 2004).

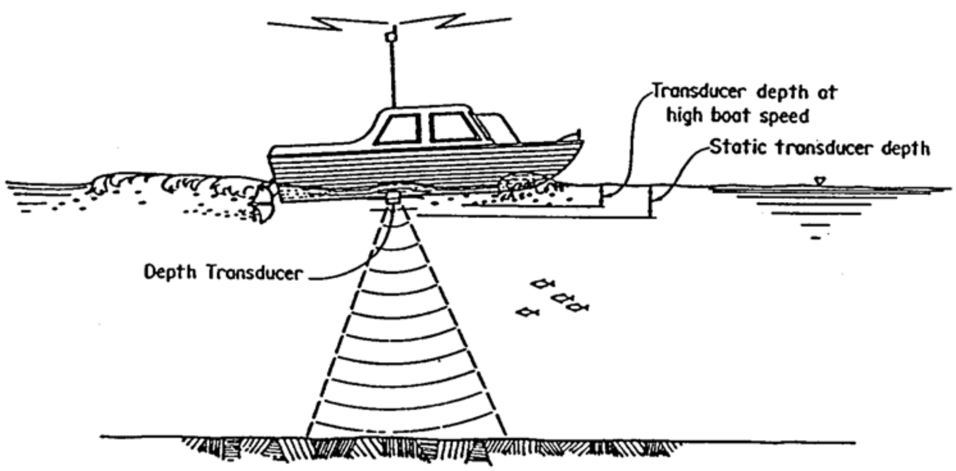


Figure 9.16. Motion effect on depth measurement (Blanton, 1982).

Wave action. The vertical and rotational motion of the boat due to wave action, as shown on figure 9.17, can result in severe fluctuations in the bottom trace. To ensure the safety of personnel and equipment when working in relatively small boats, the underwater collection should be temporarily halted when wind-generated waves affect the safety of the collection crew and compromise the data being collected. All wave-produced fluctuations in the bottom trace should be smoothed during data processing to produce acceptable data. However, more accurate data can be obtained if the survey is delayed in such conditions. Many errors due to wave action that causes survey vessel heave, roll, pitch, and yaw can be significantly reduced using accurate motion sensing instruments as part of the hydrographic collection system.

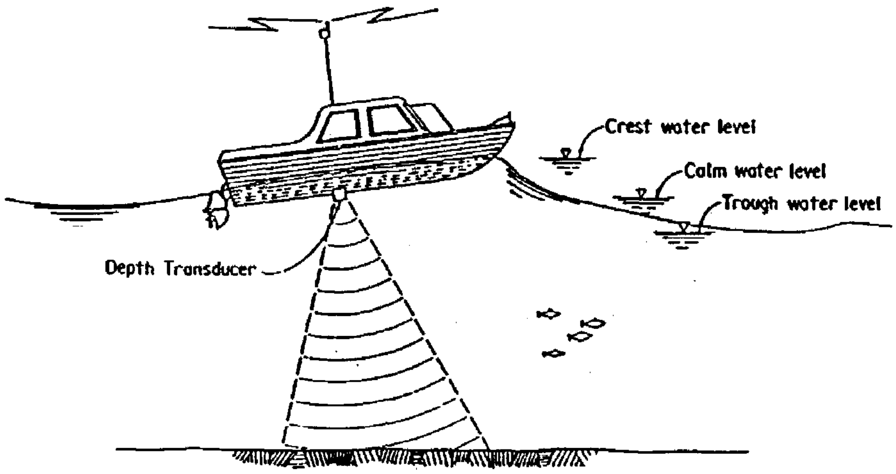


Figure 9.17. Wave effect on depth measurement (Blanton, 1982).

Bottom conditions. The reflective surface on the reservoir bottom may vary widely, as illustrated on figure 9.18. Vegetation attached to or suspended above the bottom and isolated boulders or manmade objects produce false bottom depth measurements that should be eliminated from the data. Very low-density sediment, suspended as a fluff above more compacted sediments, can result in dual depth readings (figure 9.15) unless the condition is anticipated and the sensitivity of the sound instrument is adjusted.

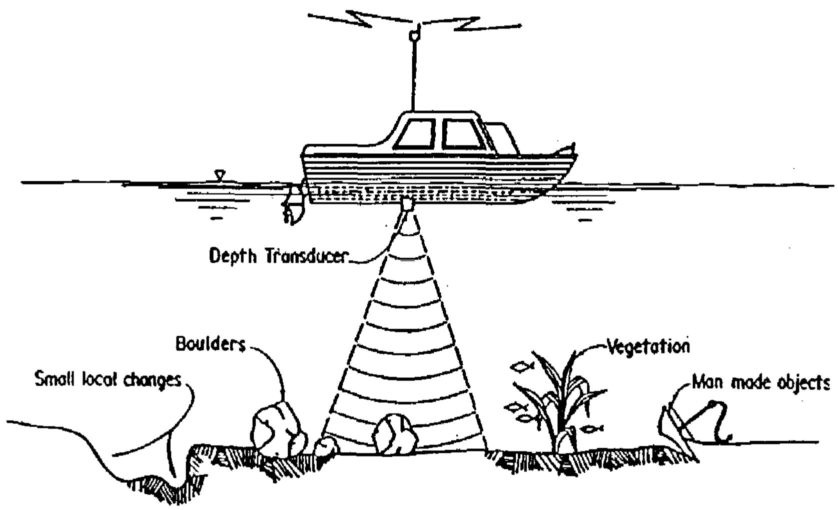


Figure 9.18. Bottom condition effect on depth measurement (Blanton, 1982).

Other errors in depth measurement may occur due to special circumstances not always encountered in all reservoir surveys:

- Reservoir level fluctuations due to inflow and outflow may change the vertical control during the survey period and introduce depth errors unless considered.

- Backwater effects in narrow canyon areas or in river portions above the main body of the reservoir may produce a water surface slope or change in the stage, which negates use of reservoir water surface for vertical control.

- Constant wind blowing from one side of a reservoir to another may cause reservoir level changes on each side of the reservoir and should be considered when operating in high wind conditions.

The use of a RTK GPS with centimeter vertical accuracies can be used to monitor and measure changes of the water surface during reservoir and river surveys, minimizing these errors. For a single beam survey in choppy water, mounting the positioning antenna above the transducer, along with using a heave compensator, reduces many of these errors, resulting in the collection of more reliable data.

9.11 Survey Accuracy and Quality

The objective of the hydrographic survey program is to measure the highest quality data possible. The degree of accuracy is determined by the need of the study: reconnaissance, partial, or complete survey. The partial and complete surveys require a higher degree of accuracy than a reconnaissance survey, since they usually are performed for construction or volume computation purposes. The Sedimentation Group typically uses their most accurate positioning and depth measuring equipment for surveys, so the accuracy difference between surveys is not a function of the equipment accuracy and limitations but, rather, a function of the difference in the field collection procedures. There are several publications that are good references when addressing the accuracy and quality of a hydrographic survey program. Good references include chapters 3 and 4 of USACE's "Hydrographic Surveying" manual (USACE, 2004) and the International Hydrographic Organization "Standards for Hydrographic Surveys" (IHO, 2005). Throughout this manual, procedures and cautions are listed to assist with the goal of obtaining the highest possible accuracy of the collected data, while achieving and maintaining QC and QA of the hydrographic program.

The QC process is where the quality of work and survey equipment are measured and controlled in order to minimize errors in the individual data points. There are a variety of QC procedures that are recommended for the survey system instrumentation and data collection techniques to minimize systematic and random errors in individual data points. Examples of QC procedures include bar checks, velocity casts, patch tests, instrument alignment tests, vessel velocity limitations, multibeam beam-width restrictions, and overlapping coverage. Some of the QC procedures are contained in this manual, but the equipment manufacturer's operating manuals should also be consulted. It must be noted that even performing all recommended QC procedures does not necessarily guarantee highly accurate collected data.

QA procedures are tests used to verify the accuracy of the collected hydrographic depth data. QA tests would typically compare two nearly independent sets of elevation data collected over the same area, but for many hydrographic surveys, QA tests are not practical and may even be impossible. QA tests are essential for multibeam surveys and typically compare single beam data with multibeam measurements, generally using the same positioning system. Since the data sets are obtained from the same instrument platform, the same position inaccuracies could be encountered.

The accuracy of a hydrographic survey is difficult to monitor relative to conventional land-base surveys, due to the lack of available control checks. Care must be taken in instrument calibration and collection procedures to ensure quality data collection, since adjusting the data during postprocessing is very difficult. Calibrations and verifications of the collection systems are time consuming but are necessary procedures to ensure the quality of the data. The accuracy of the measured bottom is dependent on the many inherent errors in the measuring process, and it is up to the collection crew to minimize these errors. Using experienced collection crews that utilize good collection techniques is one of the best means of ensuring proper survey methods, usually resulting in accurate survey data. The horizontal position of a hydrographic survey is usually established by an open-end survey method with no independent check, so the accuracy is totally dependent on the measuring process. The vertical measurement reference is usually the variable water surface and is independent of the horizontal measurement, except for the time of collection relationship, which allows the hydrographic survey software to merge each depth measurement (elevation) with its corresponding position (horizontal coordinates). The accuracy of the hydrographic survey is dependent on the accuracy of each instrument, calibration, correlation of all system components, collection method and techniques, corrections to the collected data, equipment selection and maintenance, and analysis techniques.

An important distinction exists between the accuracy and precision of the hydrographic survey measurements. The estimated accuracy of a hydrographic survey is usually based on results from the equipment calibration. Other techniques to determine the accuracy of the hydrographic survey include cross-checking lines and repeat surveys. The depth sounder may give repeated depth precisions of $\pm$0.1 feet in a stationary position, but the accuracy of the depth during the survey may be only $\pm$0.5 feet when all error components are included (i.e., multipath, water temperature and salinity changes, and one of the biggest factors, boat movement). Computer software packages have routines to compute position accuracy for the automated hydrographic survey instruments that give the survey crew the option of making adjustments to minimize collection errors. One such statistical software package allows the collection crew to compute and display differences between intersecting survey lines (HYPACK, 2005). The program provides a statistical report that shows the standard deviation distribution and average error. The output report contains detailed information for every intersecting point along with a three-dimensional view of the intersecting survey lines displaying the depth differences (figure 9.19).

An additional error with the automated hydrographic survey systems is the synchronization of the recorded data by the collection software (latency time). Latency is the time delay from the instant a measurement is taken by a survey instrument to the instant the instrument outputs the measurement data to the survey computer software. This time delay is usually measured in milliseconds (where 1 millisecond equals 1/1000 seconds). The position error will usually increase with increased velocity of the survey boat, and some systems have a time delay as long as 2 seconds. Current software has several methods of determining the time lag and correcting for it. Cross section plots illustrate the shift in the horizontal positions if a time lag exists. The adjustments can be made during the analysis process, but it is best to determine the lag time prior to data collection.

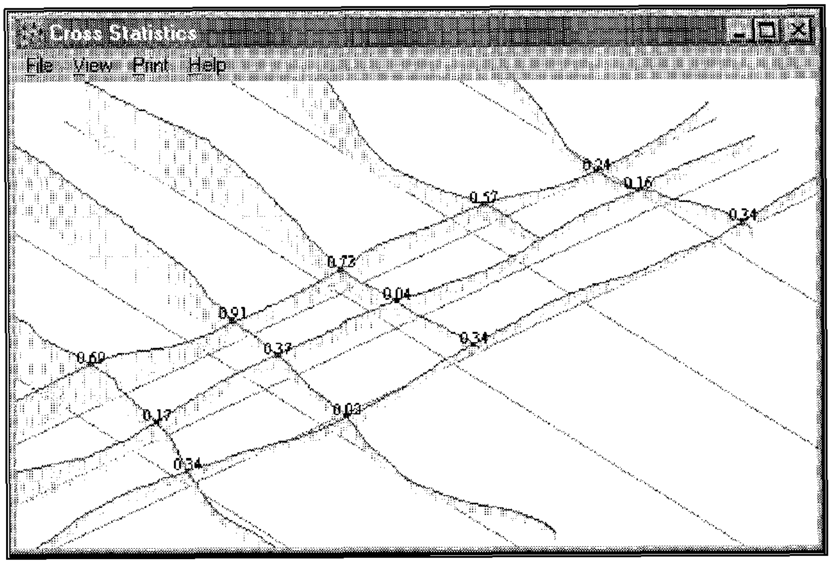


Figure 9.19. Cross-line check method (HYPACK, Inc.).

9.12 Survey Vessels

The type of survey boat is determined by the size of the reservoir and the equipment used. On small, shallow reservoirs, lightweight measuring equipment should be used on small, shallow-draft boats or rafts. Recent development of compact collection systems allows mounting on much smaller boats and easy transfer of equipment to different survey vessels. Reclamation has used vessels ranging from single-person, flat-bottom boats to large, multiperson, enclosed cabin vessels. For the survey of the sediment range lines in Lake Livingston in Texas, an airboat was used due to shallow lake conditions and many downed trees that made navigation impossible with conventional watercraft (Ferrari, 1993). For large reservoirs the travel time, safety, and housing for the equipment are important and require larger, faster, and more seaworthy survey vessels. The Sedimentation Group conducts many of its surveys in the 17 Western United States with their hydrographic survey equipment mounted in the cabin of a 24-foot, trihull aluminum vessel equipped with twin inboard motors. The hydrographic system contained on the survey vessel consists of the following equipment:

- RTK GPS receiver with an omnidirectional antenna
- Depth sounders (single and multibeam)
- Helmsman display for navigation
- Computers
- Monitors
- Gyro and motion reference sensors
- Hydrographic system software for collecting the underwater data
- An onboard generator (equipment can be powered by 12-volt batteries)

The cabin extends the life of the equipment and allows the collection of data in weather and reservoir conditions that are more difficult, or maybe even impossible, in smaller boats. The negative aspects of a larger boat are transporting the vessel to and from study sites and maneuvering in tight areas and shallow water reservoir conditions. Saltwater conditions warrant more care to protect the instruments and crew, further justifying an enclosed cabin. In the past, large survey vessels were required to house larger survey systems and reduce the effect of heave, pitch, and roll created by heavy seas, but state-of-the-art motion reference units have eliminated most of these effects, permitting the use of smaller survey vessels with more compact instrumentation.

9.13 Survey Crew

Personnel requirements vary by the size of the job, type of equipment, and method of collection. Qualified and experienced personnel are essential for an efficient and productive field operation, with a key being a hydrographic crew chief experienced in all phases of the field operations and knowledgeable about the computation and report needs of the study. The crewmembers must be capable of assisting in the operation and maintenance of the field instruments. Current systems allow data collection by as few as one person but, for safety purposes and assistance, a minimum of two field personnel is recommended for hydrographic survey vessel operations. For larger reservoirs, one or two additional crewmembers may be necessary for support of the survey, safety of the operation, operation of an auxiliary boat, transporting fuel and supplies to the survey boat, and setting up and maintaining any necessary shore-based equipment. Personnel should be trained in first-aid, cardiopulmonary resuscitation (CPR), and survey vessel operation.

There has been a push for a certification program for hydrographers. The American Congress on Surveying and Mapping (ACSM) offers a hydrographer certification program that is open to all persons to become certified. The applicant must demonstrate, to a certification board, the necessary knowledge to perform hydrographic surveys. The applicant must meet experience requirements by providing documentation of the understanding of hydrographic surveying and by passing an examination. To qualify for the examination the applicant must have 5 years of hydrographic surveying experience, with a minimum of 2 years being technically in charge and 2 years in the field. The applicants must submit an essay on the fundamentals of hydrography and their qualifications to perform hydrographic surveys.

9.14 Determination of Volume Deposits

Upon completion of the field surveys, the accumulated data must be assembled and analyzed for the purpose of calculating an updated elevation versus storage volume relationship for the reservoir. Comparing the new storage volume results with the original or previous baseline survey results can determine the volume of the accumulated sediment. It is recommended that all resulting long-term total sediment computations be compared to the original capacity.

For Reclamation reservoirs, the total volume of sediment deposited is generally determined as the difference between the original and updated reservoir capacity. This makes the sediment rate computation sensitive to the methods of measuring and calculating the reservoir volume. Ideally, identical computational methods should be used for each survey. For some reservoirs, advances in technology have made this difficult or impossible because the accuracy of the resurveys is better than the original collected data. In some cases, the accuracy difference is very pronounced, such as the Theodore Roosevelt Reservoir 1995 Sedimentation Survey (Lyons and Lest, 1996). The 1995 survey of Roosevelt Reservoir used GPS and aerial data collection to develop 5-foot contours. The original contour map was completed in the early 1900s using plane table techniques at 10-foot increments. Due to the method differences of the two surveys, comparing the results from the two contour surveys did not provide an accurate value of the total sediment deposition. For that study, the range line method would have provided a more accurate estimate of the sediment deposition since dam closure. The decision was made to use the 1995 contour map and resulting capacities as a baseline reference for computing future sediment deposition.

Many of Reclamation's reservoirs were originally measured by the contour method at 5-foot contour intervals prior to inundation, using aerial and plane table survey techniques. With this type of accuracy, the error differences due to the present collection methods used by Reclamation are somewhat minimized. With the development of RTK GPS and multibeam depth sounders, the resurveys could become more accurate than the original aerial developed reservoir contour maps. Due to complete bottom coverage, these new maps will give a better value of the actual capacity of the reservoir. However, when the sedimentation values are computed, it must be noted that a portion of the difference is due to the difference in collection methods.

As indicated before, in determining the *long-term* sedimentation rate, Reclamation figures the difference between the original recalculated capacity and the newly measured capacity of the reservoir. The original capacity is recalculated from the original surface areas using the same mathematical program used to calculate the present updated capacity tables. Reclamation computes the reservoir area-capacity using the computer program Area-Capacity Computation Program (ACAP) (Bureau of Reclamation, 1985). With all the improvements in collection and analysis methods and the accuracy of the survey instrumentation, it is possible to accurately measure even small sediment volume changes due to sediment inflow.

The range line survey and analysis methods are still used and are considered valid means for conducting reservoir survey studies. For some reservoirs, a combination of the contour and range line methods may be used. One example might be a large reservoir where the contour survey does not use photogrammetric collection to map the above water areas containing known sediment deposition. Range line surveys and analysis methods involve determining cross-sectional changes along range lines and applying the changes to the reservoir surface areas enclosed by the range lines. Water volumes or deposition volumes can be computed using the cross-sectional areas and the distance between the range lines, but these methods do not account for all volume changes occurring over irregularly shaped surface areas unless the range lines are closely spaced.

The range line method consists of laying out a system of representative ranges and determining the present sediment depths along those lines. The number and location of ranges depend on the shape and size of the reservoir being surveyed. Ranges subdivide the main body of the reservoir and its principal tributary arms so that sediment deposits in each subdivision or segment are represented by the average of conditions measured at the ranges. For the purpose of locating the sediment range lines during the resurveys, the end of each range may need to be marked above the normal shoreline with a permanent marker. With GPS survey capability, the range line end locations can be preserved by determining the range ends by digital geodetic locations and recording the information in a final report. The following methods have been used to compute the reservoir capacities when the cross-sectional areas of the ranges have been determined.

9.14.1 Average-End-Area Method

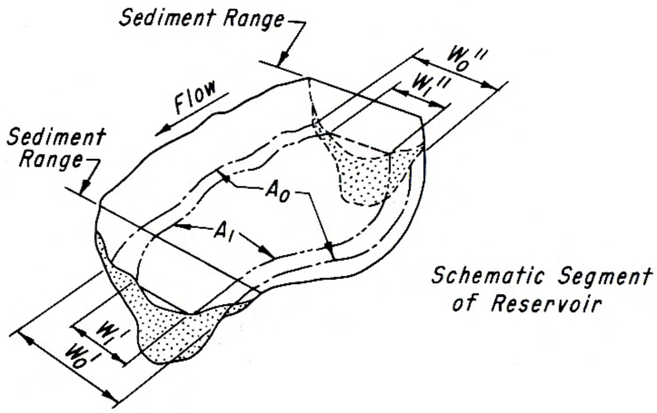
The average-end-area method for computing the capacity of a reservoir is an adaptation of the method commonly used in computing earthwork quantities. With contour maps, the average surface area enclosed by the contours is multiplied by the contour interval to compute the intermediate volume. With reservoir range line data, the cross-sectional areas of adjacent ranges are averaged and multiplied by the distance between ranges to compute the intermediate volume. This method does not account for the banks of the reservoirs that are indented with embayments and inlets, making it difficult to establish a range that is representative of any given reach. One solution is to increase the number of range lines surveyed, which increases the collection cost but may not proportionally increase the accuracy. The alignments of reservoirs are seldom straight, which makes it difficult to determine the distance to use between the range lines. Also, as the end area approaches zero (upper end of reservoir), the trapezoidal computation becomes a pyramid (or a triangle), and the error in using the average end area formula approaches 50 percent for this segment of the reservoir computation. Various methods have been developed to compensate for these problems, such as the width adjustment method.

9.14.2 Width Adjustment Method

In some earlier resurveys, new contour maps were drawn from range line survey data where all the contours between the resurveyed range lines for the new map were estimated by using the original contour map as a guide or control. The new contour locations were estimated based on changes that occurred at each range line. This method was abandoned for the constant factor method, which was further modified to the width adjustment method, as described by Pemberton and Blanton (1980).

In the width adjustment method, illustrated on figure 9.20, the new contour area, A_1, between any two ranges is computed by applying an adjustment factor to the original contour area, A_0, between the same two ranges. This adjustment factor is defined as the ratio of the new average width to the original average width for both upstream and downstream ranges at the specified contour. The revised segmented surface areas for each contour are then summed for the whole reservoir. The summarized segmented surface area versus elevation becomes the basic input for volume computations. The computation can be accomplished by hand or with commonly used electronic spreadsheet programs.

A simultaneous comparison of the plots of the original range profiles against the resurveyed range profiles displays the lateral distribution of the sediment at the measured points. Where these plots indicate that changes have occurred on the side slopes of the reservoir, engineering judgment is required to determine whether the change is due to survey inaccuracies or actual deposition or erosion.



Initial Survey	*New Survey*
A_o = *Contour Area*	A_1 = *Contour Area (Computed)*
W_o' = *Downstream Width*	W_1' = *Downstream Width*
W_o'' = *Upstream Width*	W_1'' = *Upstream Width*

$$A_1 = \left[\frac{\left(W_1^{'} + W_1^{''}\right)}{\left(W_0^{'} + W_0^{''}\right)} \right]$$

Figure 9.20. Width adjustment method for revising contour areas (Blanton, 1982).

9.14.3 Contour Method – Topographic Mapping

The contour method, which creates a new reservoir topographic map, has become the preferred method for collecting and analyzing survey data. The development of electronic measuring and computerized collection and analysis systems has made it possible for collection and analysis of massive amounts of digital data (x, y, z coordinates), and the final product yields an accurate detailed contour map of the present reservoir conditions.

The contour method involves determining current water volumes and sediment deposition from newly developed reservoir topographic contours, allowing a three-dimensional view on a two-dimensional medium. The final results from the reservoir contour maps are generated surface contours at selected elevation intervals that are used to compute updated volumes. There are multiple computer contour packages and routines for personal or work station computer systems that can be used for this purpose.

9.15 Final Results

There are several computer programs that can generate elevation versus surface area and capacity for a reservoir. The computer program generally used by Reclamation for this purpose is ACAP, where basic elevation versus surface area data developed from the survey becomes the input for the computation of the revised area and capacity tables (Bureau of Reclamation, 1985). A procedure called segmented least squares-fit is used most often. In this procedure, surface areas at specified elevation increments between the basic data contours are derived by linear interpolation, creating a basic area curve/equation over that interval between the contours. The respective capacities and capacity equations are obtained by integration of these area equations. The resulting capacity curve is a series of equations applicable over the full range of the data set.

Table 9.1 contains an example set of these equations. The final result of the computer program is a set of area and capacity tables for use in allocating storage and for operation of the reservoir (see Tables 9.2 and 9.3). The tables can be produced at 0.01-, 0.1-, and 1.0-foot increments.

Table 9.1. ACAP Area and Capacity Equations

WILLOW CREEK RESERVOIR - SUN RIVER PROJECT, MONTANA
2002 AREA-CAPACITY TABLES

EQUATION NUMBER	ELEVATION BASE	CAPACITY BASE	COEFFICIENT A1(INTERCEPT)	COEFFICIENT A2(1ST TERM)	COEFFICIENT A3(2ND TERM)
1	4084.00	0	.0000	.0000	.4500
2	4086.00	1	1.8000	1.8000	.4500
3	4088.00	7	7.2000	3.6000	.7500
4	4090.00	17	17.4000	6.6000	5.0750
5	4092.00	50	50.9000	26.9000	5.8250
6	4094.00	128	128.0000	50.2000	4.9750
7	4096.00	248	248.3000	70.1000	6.3500
8	4098.00	413	413.9000	95.5000	7.7000
9	4100.00	635	635.7000	126.3000	6.7250
10	4102.00	915	915.2000	153.2001	8.1500
11	4104.00	1254	1254.1999	185.8000	11.4800
12	4106.00	1671	1671.7200	231.7200	10.2200
13	4108.00	2176	2176.0401	272.6000	11.0000
14	4110.00	2765	2765.2400	316.6001	14.3999
15	4112.00	3456	3456.0400	374.2001	16.1499
16	4114.00	4269	4269.0399	438.8002	19.2499
17	4116.00	5223	5223.6402	515.7999	20.8001
18	4118.00	6338	6338.4403	599.0003	20.2248
19	4120.00	7617	7617.3404	679.8999	18.4750
20	4122.00	9051	9051.0400	753.8003	18.1998
21	4124.00	10631	10631.4405	826.5999	19.6500
22	4126.00	12363	12363.2404	905.2000	18.4000
23	4128.00	14247	14247.2405	978.7995	18.0252
24	4130.00	16276	16276.9402	1050.9002	25.4100
25	4135.00	22166	22166.6912	1305.0001	11.1000
26	4140.00	28969	28969.1915	1416.0002	11.6000
27	4145.00	36339	36339.1913	1531.9999	14.0000
28	4150.00	44349	44349.1917	1672.0000	13.8000
29	4155.00	53054	53054.1914	1810.0000	17.5000
30	4160.00	62541	62541.6921	1984.9993	15.0000

Area and capacity data are usually plotted as illustrated on figure 9.21 to compare the revised data with the original data. These plot comparisons are valuable during analysis, since they can illustrate possible problems with the data set. Problems identified on an area and capacity plot can include, but are not limited to, datum or elevation shifts if the original versus new surface area curves do not match where little or no change is expected.

Table 9.2. ACAP Surface Area Computations

WILLOW CREEK RESERVOIR - SUN RIVER PROJECT, MONTANA

2002 AREA-CAPACITY TABLES

ACAP92) COMPUTED
7/30/2005
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THE AREA TABLE IS IN ACRES

THE ELEVATION INCREMENT IS IN ONE FOOT

ELEV. FEET	0	1	2	3	4	5	6	7	8	9
4080					0.	1.	2.	3.	4.	5.
4090	7.	17.	27.	39.	50.	60.	70.	83.	96.	111.
4100	126.	140.	153.	170.	186.	209.	232.	252.	273.	295.
4110	317.	345.	374.	406.	439.	477.	516.	557.	599.	639.
4120	680.	717.	754.	790.	827.	866.	905.	942.	979.	1015.
4130	1051.	1102.	1153.	1203.	1254.	1305.	1327.	1349.	1372.	1394.
4140	1416.	1439.	1462.	1486.	1509.	1532.	1560.	1588.	1616.	1644.
4150	1672.	1700.	1727.	1755.	1782.	1810.	1845.	1880.	1915.	1950.
4160	1985.	2015.	2045.	2075.	2105.	2135.	2165.	2195.	2225.	2255.
4170	2285.									

Table 9.3. ACAP Capacity Computations

WILLOW CREEK RESERVOIR - SUN RIVER PROJECT, MONTANA

(ACAP92) COMPUTED
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2002 AREA-CAPACITY TABLES

THE CAPACITY TABLE IS IN ACRE FEET

THE ELEVATION INCREMENT IS ONE FOOT

ELEV. FEET	0	1	2	3	4	5	6	7	8	9
4080					0.	0.	2.	4.	7.	12.
4090	17.	29.	51.	84.	128.	183.	248.	325.	414.	517.
4100	636.	769.	915.	1077.	1254.	1451.	1672.	1914.	2176.	2460.
4110	2765.	3096.	3456.	3846.	4269.	4727.	5224.	5760.	6338.	6958.
4120	7617.	8316.	9051.	9823.	10631.	11478.	12363.	13287.	14247.	15244.
4130	16277.	17353.	18480.	19658.	20887.	22167.	23483.	24821.	26182.	27564.
4140	28969.	30397.	31848.	33322.	34819.	36339.	37885.	39459.	41061.	42691.
4150	44349.	46035.	47748.	49489.	51258.	53054.	54882.	56744.	58642.	60574.
4160	62542.	4542.	66572.	68632.	70722.	72842.	74992.	77172.	79382.	81622.
4170	83892.									

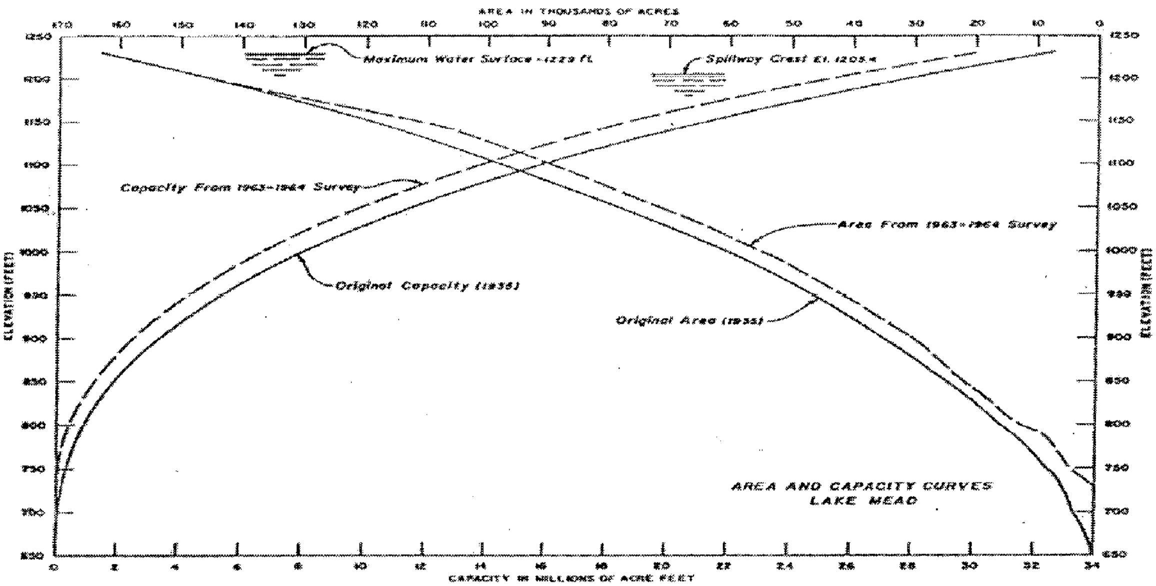

Figure 9.21 Area and capacity curves.

The tables for Willow Creek Reservoir were generated by means of the area-capacity program ACAP, using the least squares method of curve fitting developed by the Bureau of Reclamation's Technical Service Center. This program computes area at 1.0-, 0.1-, and 0.01-foot increments by linear interpolation between basic data contours. The respective capacities and capacity equations are then obtained by integration of the area equations. The initial capacity equation is tested over successive intervals to check whether it fits within an allowable error term. At the next interval beyond, a new capacity equation (integrated from the basic area equation over that interval) begins testing the fit until it too exceeds the error term. The capacity curve thus becomes a series of curves, each fitting a certain region of data. The final area equations are obtained by differentiation of the capacity equations. Capacity equations are of the form $y = a_1 + a_2x + a_3x^2$ where y is capacity and x is the elevation above an elevation base. The capacity equation coefficients for the Willow Creek Reservoir are shown below ($\varepsilon = 0.000001$).

Total volume of sediment deposited in the reservoir generally may be determined as the difference between the original reservoir capacity and the updated capacity computed from the resurvey. Both capacity computations should be made by the same method; that is, if the ACAP program is used to generate the updated capacity from the updated surface areas, it should also be used to regenerate the original capacity using the original measured areas. Even though all volume computation methods are basically similar, this eliminates any variation in calculations resulting from implicit differences between computational procedures. In reservoirs where significant compaction of sediment occurs between subsequent surveys, the difference in reservoir storage would not be truly representative of sediment deposition in the intervening time periods. For those reservoirs, the rate of sediment accumulation should be computed for the total storage period, based on the difference in capacity between the original and present capacity. The results should note the compaction. Ideally, bottom sampling should be part of these studies to provide density measurements for each survey.

Extreme caution must be taken in comparing survey results when it comes to vertical datums. With the use of GPS, which allows accurate horizontal and vertical control to be established, there are many new surveys conducted using the present vertical datum NAVD88 (North American Vertical Datum of 1988). Ideally, this procedure would always be followed. However, in doing so, all information such as survey control and sediment computations must take into account that original project or construction datums will more than likely require a shift to bring all values to a consistent reference datum. It must be noted that many of the Reclamation resurveys have updated the horizontal positions to presently used datums (such as state plane NAD83), but many of the vertical datums are tied to the original project datum. The main reason for retaining the original vertical datum is the cost required to inform all agencies of the elevation differences and the time and cost required to change all previous documentation to reflect the vertical datum shift. All new drawings and reports should state what vertical datum is being used and state the vertical shift needed to match the project datum to the present national vertical datum NAVD88.

Some reservoirs will be subject to significant bank erosion or bank collapsing caused by wave action or severe reservoir drawdown. In analyzing the survey data, the increase in contour surface areas at the higher reservoir elevations in areas where the bank line changes have taken place will offset some of the loss of surface area in the delta areas. In cases where the range line method is used for monitoring sediment, the increases in surface area of higher elevations will usually not be totally compensated for by a decrease in surface areas at lower elevations. The difference may be due either to compaction of sediment, movement of sediment downstream of the surveyed range line, or transport of fine sediment through the dam. If sediment inflow and outflow records are obtained for the period between surveys, it may be possible to roughly differentiate between the sediment accumulation due to inflow and that due to bank changes. If the bank changes are localized, not continuous through a segment of the reservoir, and the volume of material involved is relatively small, the bank changes may be voided in the analyses. The sediment yield rate developed for the drainage basin above a reservoir, where significant bank changes occur, will usually include those bank materials and should be explained in the report. The use of the contour method includes the capacity changes due to bank erosion and is the preferred method for a resurvey.

The trap efficiency of the reservoir may be determined when sediment inflow and outflow records are available for the period between surveys, but, in the United States, these data usually are not available for most reservoirs. When the records are available, the trap efficiency for the period between surveys should be computed and compared with predictive methods. Another useful and more common analysis tool is the sediment deposition profile plot extending the full length of the reservoir. Figure 9.22 shows the profile plot based on the original, 1948, 1963, and 2001 resurveys of Lake Mead. The deposition profile is useful in displaying delta growth and depth of sediment near the dam. The longitudinal profile may also be displayed in a dimensionless plot of percent distance from the dam versus percent reservoir depth, as is shown on figure 9.23 for Lake Powell. This plot permits the comparison of reservoir deposition profiles without scale interference.

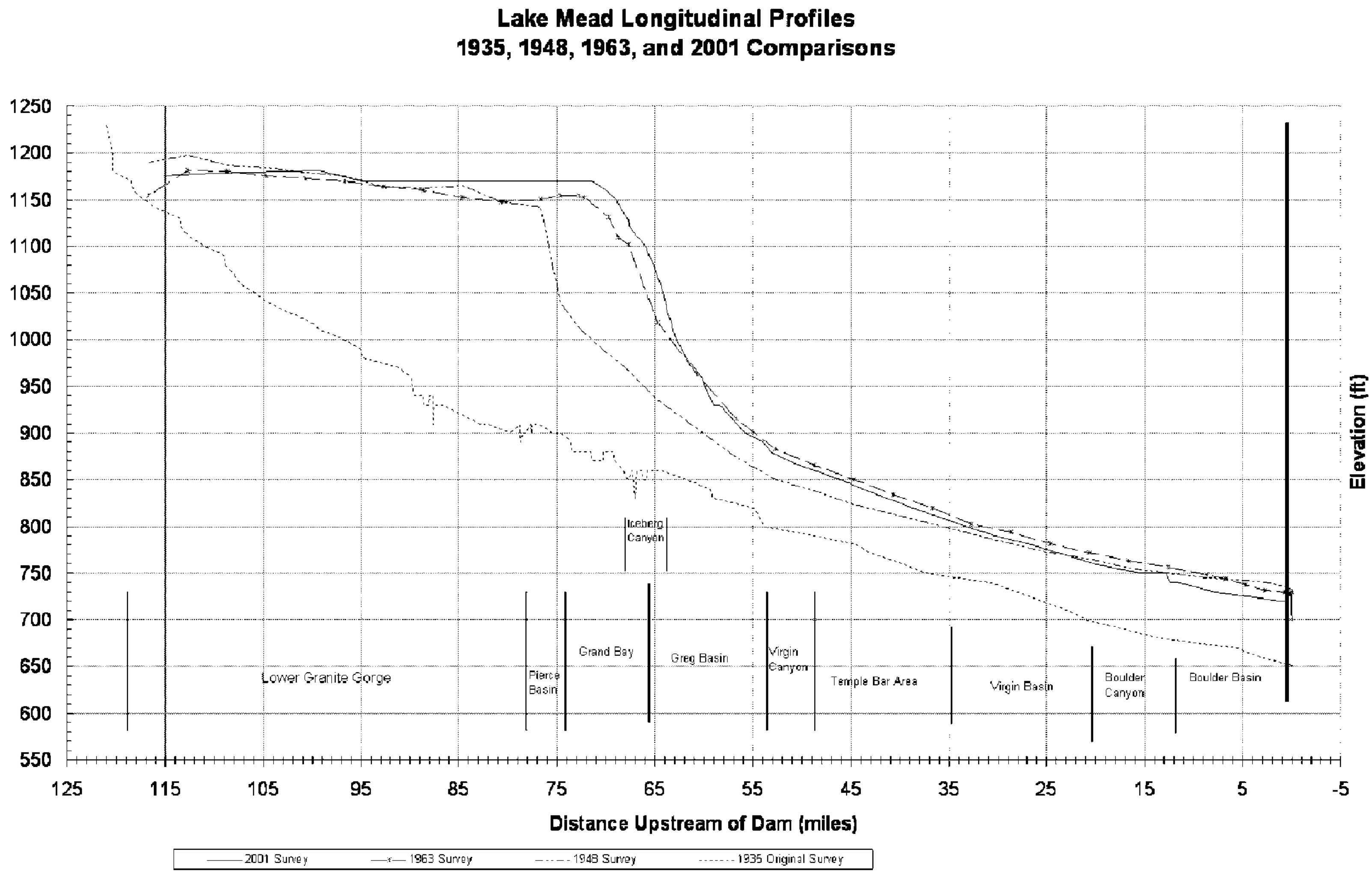

Figure 9.22 Colorado River profiles through Lake Mead.

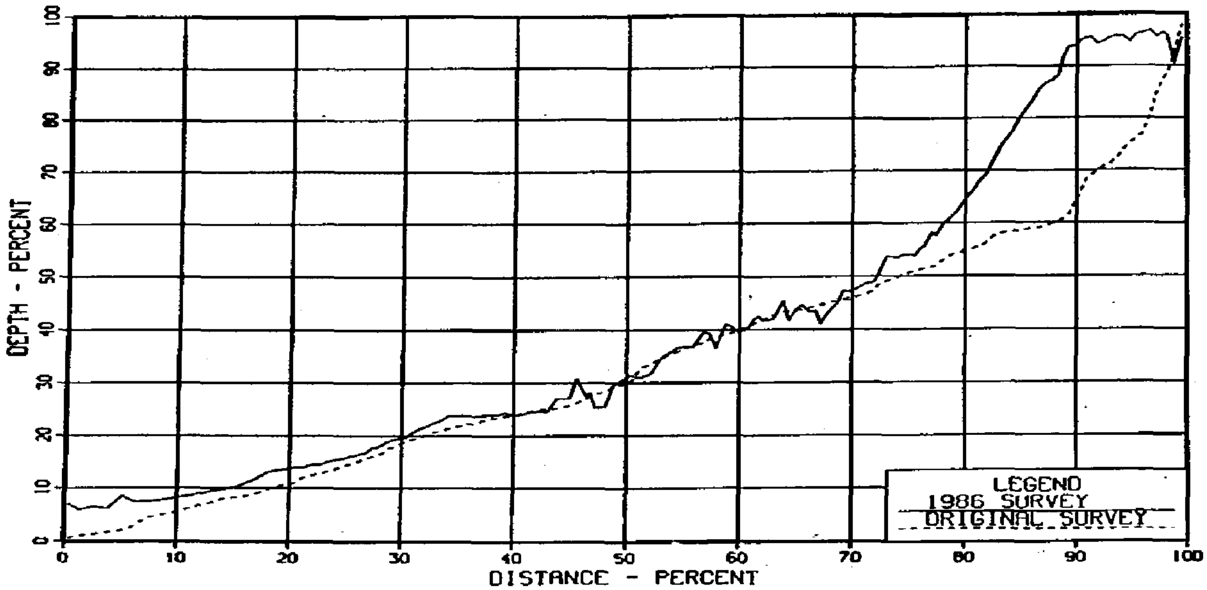

Figure 9.23 Dimensionless plot of Lake Powell sediment deposition profiles (Ferrari, 1988).

9.15.1 Report

An important feature of any reservoir survey is the report of results, so that others may benefit from the time and effort expended in the investigation. The information gathered during a detailed survey helps define the sedimentation characteristics of the contributing drainage basin as well as the reservoir. A well-prepared report serves the interests of the Federal, state, city, and county governments; water districts; and other engineers and scientists not involved in the investigation.

The report should be as inclusive as necessary to document the survey and provide the information useful for future surveys. The items included in individual reports may vary according to the problems and circumstances encountered. Some of the important items that may be included in a report are:

- General information on the dam, reservoir, and drainage basin.
- Information on all surveys, past and present, conducted on the reservoir.
- Description of the survey and sampling techniques for the present survey and the special equipment used.

- A reservoir map showing the location of all range lines. In many cases, the original range line survey map is sufficient. For contouring studies, a plot showing the areas surveyed would be beneficial, along with the newly developed contour map of the reservoir.

- A description of all major survey controls with a table listing horizontal and vertical information. Note: It is highly recommended that control datum used for the survey be reported. Include information such as WGS84, NGS datums used and year established, geoid model used (i.e., geoid99), and state plane coordinate used (i.e., NAD83 Colorado central).

- A plot or table showing the reservoir stage fluctuation or stage duration curve.

- Profiles of all reservoir and degradation ranges showing the latest survey superimposed on the original profile and, in some instances, plots from other surveys.

- Graphs of sediment distribution in a longitudinal profile, a percent depth versus percent sediment volume, and a percent depth versus percent distance from the dam plot

- Data in tabular and graphic form describing sediment densities and particle sizes

- Revised area and capacity tables and curves resulting from the new survey

- Any data on sediment inflow and outflow that may be available for estimating trap efficiency

- A completed reservoir sedimentation data summary sheet. The Subcommittee on Sedimentation, Interagency Advisory Committee on Water Data, provides some examples with instructions for filling out the form given in ASTM D4581 (ASTM, 2005).

Although a formal report is not essential for development of new area and capacity tables and curves, it does provide an excellent document for future surveys and for other reservoir sediment investigations. Figure 9.24 shows an example of a reservoir sediment data summary table.

RESERVOIR SEDIMENT
DATA SUMMARY

Bully Creek Reservoir
NAME OF RESERVOIR

1
DATA SHEET NO.

DAM	1. OWNER Bureau of Reclamation	2. STREAM Bully Creek	3. STATE Oregon
	4. SEC 12 TWP. 18S RANGE 43 E	5. NEAREST P.O. Vale	6. COUNTY Maiheur
	7. LAT 44 ° 00 ' 55 " LONG 117 ° 23 ' 45 "	8. TOP OF DAM ELEVATION 2529.0	9. SPILLWAY CREST EL 2494.0 [1]

RESERVOIR	10. STORAGE ALLOCATION	11. ELEVATION TOP OF POOL	12. ORIGINAL SURFACE AREA, AC-FT	13. ORIGINAL CAPACITY, AC-FT	14. GROSS STORAGE ACRE-FEET	15 DATE STORAGE BEGAN / 16 DATE NORMAL OPERATIONS BEGAN
	a. SURCHARGE	2523.0		7,300	38,950	15: 2/63
	b. FLOOD CONTROL					
	c. POWER					
	d. JOINT USE	2516.0	993	30,000	31,650	16: 2/63
	e. CONSERVATION					
	f. INACTIVE					
	g. DEAD	2456.58	137	1,650	1,650	
	17. LENGTH OF RESERVOIR 3.4 MILES			AVG. WIDTH OF RESERVOIR 0.47 MILES		

BASIN	18. TOTAL DRAINAGE AREA 547 SQUARE MILES		22. MEAN ANNUAL PRECIPITATION 9.1 [2] INCHES
	19. NET SEDIMENT CONTRIBUTING AREA 547 SQUARE MILES		23. MEAN ANNUAL RUNOFF 9.27 [3] INCHES
	20. LENGTH MILES	AVG. WIDTH MILES	24. MEAN ANNUAL RUNOFF 270,490 [4] ACRE-FEET
	21. MAX. ELEVATION	MIN. ELEVATION	25. ANNUAL TEMP, MEAN 52 °F RANGE -27 °F to 106 °F

SURVEY DATA	26. DATE OF SURVEY	27. PER. YRS	28. PER. YRS	29. TYPE OF SURVEY	30. NO. OF RANGES OR INTERVALS	31. SURFACE AREA, AC.	32 CAPACITY ACRE - FEET	33 C/I RATIO AF/AF
	2/63			Contour (D)	5 - ft	983 [5]	31,590 [5]	0.12
	5/00	37.2	37.2	Contour (D)	5 - ft	911 [6]	24,380 [6]	0.09

26. DATE OF SURVEY	34. PERIOD ANNUAL PRECIPITATION	35. PERIOD WATER INFLOW, ACRE-FEET a. MEAN ANN.	35. b. MAX. ANN.	35. c. TOTAL	36 WATER INFLOW TO DATE, AF a. MEAN ANN.	36. b. TOTAL
5/00		182,855 [7]	270,490	5,811,350	182,855	6,811,350

26. DATE OF SURVEY	37 PERIOD CAPACITY LOSS, ACRE-FEET a. TOTAL	37. b. AVG. ANN.	37. c. /MI.^{2}-YR.	38. TOTAL SEDIMENT DEPOSITS TO DATE, AF a. TOTAL	38. b. AVG. ANN.	38. c. /MI.^{2}-YR.
5/00	7210 [8]	193.6	0.364	7210	193.6	0.364

26. DATE OF SURVEY	39 AVG. DRY WT. (#/FT^3)	40. SED. DEP. TONS/MI.^{2}-YR a. PERIOD	40. b. TOTAL TO DATE	41. STORAGE LOSS, PCT. a. AVG. ANNUAL	41. b. TOTAL TO DATE	42 SEDIMENT INFLOW, PPM a. PER.	42. b. TOT.
5/00				0.613 [9]	22.8 [9]		

26. DATE OF SURVEY	43. DEPTH DESIGNATION RANGE BY RESERVOIR ELEVATION									
		2460-2425	2470-2460	2480-2470	2490-2480	2500-2490	2510-2500	2516-2510		
	PERCENT OF TOTAL SEDIMENT LOCATED WITHIN DEPTH DESIGNATION									
5/00		11.7	7.2	8.0		24.3	22.9	8.0		

26. DATE OF SURVEY	44. REACH DESIGNATION PERCENT OF TOTAL ORIGINAL LENGTH OF RESERVOIR													
	0-10	10-20	20-30	30-40	50-60	60-70	70-80	80-90	90-100	100-105	105-111	110-115	115-120	120-125
	PERCENT OF TOTAL SEDIMENT LOCATED WITHIN REACH DESIGNATION													

Figure 9.24. Reservoir sediment data summary for Bully Creek Reservoir (page 1 of 2).

45. RANGE IN RESERVOIR OPERATION [7]

YEAR	MAX. ELEV.	MIN. ELEV.	INFLOW, AF	YEAR	MAX. ELEV.	MIN. ELEV.	INFLOW, AF
				1963	2,491.2	2,452.2	32,720
1964	2,505.7	2,417.2	111,050	1965	2,515.3	2,476.0	253,410
1966	2,509.1	2,464.0	166,370	1967	2513.5	2,463.1	168,500
1968	2,510.2	2,478.3	168,040	1969	2,516.0	2,477.4	184,780
1970	2,515.5	2,483.4	228,580	1971	2,515.9	2,498.8	220,460
1972	2,513.4	2,481.4	163,060	1973	2,506.1	2,479.2	113,060
1974	2,516.0	2,488.1	205,950	1975	2,516.0	2,489.4	213,610
1976	2,512.5	2,498.1	188,960	1977	2,499.4	2,486.5	105,000
1978	2,518.9	2,461.0	183,050	1979	2,516.2	2,487.5	183,720
1980	2,514.4	2,504.2	221,990	1981	2,515.4	2,487.8	225,980
1982	2,516.8	2,486.5	256,000	1983	2,516.8	2,500.1	270,490
1984	2,516.3	2,494.1	243,930	1985	2,516.2	2,484.2	212,580
1986	2,516.0	2,480.8	195,110	1987	2,510.1	2,458.1	152,430
1988	2,497.1	2,458.5	52,960	1989	2,516.8	2,458.7	164,590
1990	2,500.1	2,458.7	105,630	1991	2,489.3	2,458.4	52,930
1992	2,496.6	2,458.8	61,230	1993	2,517.5	2,458.9	180,990
1994	2,507.0	2,458.8	154,430	1995	2,517.0	2,458.8	211,420
1996	2,516.4	2,493.3	237,570	1997	2,515.5	2,492.1	237,960
1998	2,517.2	2,491.1	251,390	1999	2,516.5	2,497.7	260,840
2000	2,516.3	2,495.4	170,330				

46. ELEVATION - AREA - CAPACITY - DATA FOR **2000 CAPACITY** [10]

ELEVATION	AREA	CAPACITY	ELEVATION	AREA	CAPACITY	ELEVATION	AREA	CAPACITY
2440.4	0	0	2445	15.0	38	2450	51.6	204
2455	89.3	556	2460	117.2	1,073	2465	141.0	1,718
2470	191.0	2,548	2475	244.1	3,636	2480	279.8	4,946
2485	319.9	6,445	2490	375.4	8,183	2495	466.8	10,289
2500	557.7	12,850	2505	635.2	15,832	2510	767.0	19,338
2515	889.9	23,480	2516	911.0	24,300	2520	995.7	28,194
2523	1,032.0	31,236	2525	1,056.9	33,325	2530	1,116.9	38,759

47. REMARKS AND REFERENCES

[1] Top of sluice gates, elevation 2,516.0.
[2] Bureau of Reclamation Project Data Book, 1981.
[3] Calculated using mean annual runoff value of 270,490 AF, item 24, 2/63 - 5/00.
[4] Computed annual inflows from 2/63 through 5/00.
[5] Original surface area and capacity at el. 2,516.0. For sediment computation purposes the original capacity was recomputed by the Reclamation ACAP program using the original surface areas.
[6] Surface area and capacity at el. 2,516.0 computed by ACAP program.
[7] Inflow values in acre-feet and maximum and minimum elevations in feet by water year from 2/63 through 5/00. Some months of missing records. Elevation data for 1963 through 1970 from USGS water records.
[8] Computed sediment volume at elevation 2516.0.
[9] Storage losses at elevation 2516.0.
[10] Capacities computed by Reclamation's ACAP computer program. At elevation 2,456.58 (dead capacity elevation) the calculated surface area was 98 acres with a capacity of 704 acre-feet.

48. AGENCY MAKING SURVEY Bureau of Reclamation
49. AGENCY SUPPLYING DATA Bureau of Reclamation DATE March 2001

Figure 9.24. Reservoir sediment data summary for Bully Creek Reservoir (page 2 of 2).

9.16 Reservoir Survey Terminology

Accuracy: Refers to how close a measurement is to the true or actual value.

Almanac: Data transmitted by a GPS satellite, which includes orbit information on all the satellites, clock correction, and atmospheric delay parameters. These data are used to facilitate rapid satellite acquisition. The orbit information is a subset of the ephemeris data with reduced accuracy.

Analog depth recorder: A graphical recording echo sounder showing profile view of channel section.

Anti-spoofing: For the NAVSTAR system, anti-spoofing is the process whereby the P code used for the precise positioning service is encrypted. The resulting encrypted code is called the Y code. The encryption data can only be decoded by GPS receivers with DOD-authorized special decryption circuitry that guards against fake transmissions of satellite data.

Automated hydrographic survey processing system: A computer system that combines positional and depth measurements into a single database.

Bar: A metallic channel, I-beam, pipe, plate, or ball that reflects sound waves produced by the fathometer.

Bar check: A method for calibrating a fathometer by setting a sound or acoustic reflector (bar) below a survey vessel to a known depth below a sounding transducer.

Baseline: The primary reference line for use in measuring azimuth angles and positioning distances.

Base station (master or reference station): A location that is known. For GPS, a receiver is located over and programmed with known coordinates and calculates error from satellites. With differential corrections, the rover (mobile) GPS position accuracy is improved.

Bathymetric survey (bathymetry): A survey of the underwater portion of the study area.

C/A code: The Coarse/Acquisition (or Clear/Acquisition; civilian or S code) modulated onto the GPS L1 signal. This code is a sequence of 1023 pseudo random binary biphase modulations on the GPS carrier at a chirping rate of 1.023 megahertz, thus having a code repetition period of 1 millisecond. This code was selected to provide good acquisition properties.

Carrier: A radio wave having at least one characteristic (such as frequency, amplitude, phase), which may be varied from a known reference value by modulation.

Carrier frequency: The frequency of the unmodulated fundamental output of a radio transmitter. The GPS L1 carrier frequency is 1575.42 megahertz.

Clock offset: Constant difference in the time reading between two clocks.

Cross section: Survey line normally run perpendicular to the flow direction in the original river channel.

Density: The mass of a substance per unit volume. It is usually expressed as ρ in kilograms per liter or kilograms per cubic meter. Use ρ_s for density of solid particles, ρ_w for water, ρ_d for dry sediment with voids, ρ_{sat} for saturated sediment, ρ_{wet} for wet sediment, and ρ_b for submerged sediment (buoyant weight).

DEM: Digital elevation model.

Depth: Vertical distance between a reference water surface elevation and grade below water.

Differential GPS (DGPS): Differential GPS is a technique for improving GPS solution accuracy. Determining the error at a known GPS location, then subtracting that error from the solution at an unknown GPS location to reduce error.

Differential (relative) positioning: Determination of relative coordinates of two or more receivers which are simultaneously tracking the same satellites.

Dilution of Precision (DOP): A mathematical quality description of the satellite geometry with Position Dilution of Precision (PDOP) the most common used with best-case value of 1. Standard precision terms used for GPS:

GDOP:	Geometric (three position coordinates plus clock offset in the solution)
PDOP:	Position (three coordinates)
HDOP:	Horizontal (two horizontal coordinates)
VDOP:	Vertical (height only)
TDOP:	Time (clock offset only)
RDOP:	Relative (normalized to 60 seconds)

Drainage basin: The area tributary to or draining to a lake, stream, or measuring site.

Draft (transducer draft): Vertical distance from the bottom of the transducer to the surface of the water.

Draft: Vertical distance from water surface to bottom point of survey vessel.

Dynamic positions: A position determined while in motion (kinematic positioning).

Electronic Distance Measurement (EDM): Measurement of distance using pulsing or phase comparison systems.

Electronic Positioning System (EPS): A system that receives two or more EDM signals to obtain a position.

Elevation: Height above mean sea level.

Elevation mask angle: That angle above the horizon below which it is not recommended to track satellites. Normally set to 15 degrees to avoid interference problems caused by buildings, trees, atmospheric, and multipath errors.

Ellipsoid height: The measure of vertical distance above the ellipsoid. Not the same as elevation above sea level. GPS receivers output position fix height in the WGS84 datum.

Ephemeris: The predictions of current satellite position that are transmitted to the user in the data message.

Erosion: The wearing away of the land surface by detachment and movement of soil and rock fragments through the action of moving water and other geological agents.

Fathometer: An electronic device for registering depths of water by measuring the time required for the transmission and reflection of sound waves between a sonic transducer and the lake or river bottom.

Fix: Instant the position of survey vessel is observed.

Fluff (suspended sediment): Lightweight particles in suspension.

Fundamental frequency: The fundamental frequency used in GPS is 10.23 megahertz. The carrier frequency's L1 and L2 are integer multiples of this fundamental frequency.
L1=1575.42 megahertz
L2=1227.60 megahertz

Gauging station: A selected cross section of a stream channel where one or more variables are measured continuously or periodically to index discharge and other parameters.

Geodetic surveys: Global survey to establish control networks for accurate land mapping.

GDOP: Geometric Dilution of Precision. The relationship between errors in user position, time, and satellite range.
$GDOP^2 = PDOP^2 + TDOP^2$

Global Positioning System (GPS): A satellite EDM system used in determining Cartesian coordinates (x, y, z) of a position by means of radio signals from NAVSTAR satellites.

GLONASS: Global Navigation Satellite System. Russian GPS.

HDOP: Horizontal Dilution of Precision.

Horizontal control: A series of connected lines whose azimuths and lengths have been determined by triangulation, trilateration, and traversing.

Hydrographic survey: A reservoir resurvey involving both above water and underwater surveys.

Ionosphere: A band of charged particles 80 to 120 miles above the earth's surface that changes the signal speed or causes a refraction as it passes through.

Kinematic surveying: A form of continuous differential carrier-phase surveying requiring only short periods of data observations. Operational constraints include starting from or determining a known baseline, and tracking a minimum of four satellites. One receiver is statically located at a control point, while others are moved between points to be measured (dynamic positioning).

Latitude: Angular distance, measured in degrees, north or south from the equator.

Longitude: Distance east or west on the earth's surface, measured as an arc of the equator in degrees between the meridian passing through Greenwich, England.

Multipath: Interference similar to "ghosts" on a television screen, which occurs when GPS signals arrive at an antenna having traversed different paths. The signal traversing the longer path will yield a larger pseudo range estimate and increase the error. Multiple paths may arise from reflections from structures near the antenna.

Multipath error: A positioning error resulting from interference between radio waves which have traveled between the transmitter and the receiver by two paths of different electrical lengths. Usually caused by path being reflected from surrounding objects.

Multibeam system: Channel sweep systems employing a single transducer.

Multiple transducer system: Channel sweep system using multiple, vertically mounted transducers.

NAVSTAR: Name given to United States GPS satellite system standing for Navigation Satellite Timing and Ranging.

NAD27: North American Datum of 1927. Older horizontal datum of North America using an approximate shape of Earth designed to fit only the shape of the United States.

NAD83: North American Datum of 1983. Official horizontal datum of North America that relies on the precise Geodetic Reference System of 1980 (GRS 80).

NAVD88: North American Vertical Datum of 1988. A fixed reference adopted as a standard geodetic datum for heights in North America.

NGVD29: National Geodetic Vertical Datum of 1929. NGVD is not the same as mean sea level (msl).

P code: Precise or protected code. A very long sequence of pseudorandom, binary biphase modulations on the GPS carrier at a chirp rate of 10.23 megahertz, which repeats about every 267 days. Each 1-week segment of the code is unique to one GPS satellite and is reset each week. This code is made available to U.S. Department of Defense authorized users only.

PDOP: Position dilution of precision measuring geometrical strength of the GPS satellite configuration.

Position: Latitude, longitude, and altitude of a point.

Postprocessed differential GPS: GPS where the base and rover receiver have no real-time data link between them. All GPS receiver data will be stored for differential correction processing at a later time.

Precision: Refers to how closely a set of measurements can be repeated. The amount by which a measurement deviates from its mean.

Pulse wave system: An electronic positioning system in which the signal from the transmitting station to the reflecting station travels in an electromagnetic wave pulse.

Range: Distance to a point measured by physical optical or electronic means.

Range line: An imaginary, straight line extending across a body of water between fixed shore markings.

Range line markers: Site poles or other identifiable objects used for positioning alignment on a range line.

Reservoir: An impounded body of water or controlled lake where water is collected and stored.

Real-time differential GPS: GPS where a base station computes, formats, and transmits corrections through a data line, such as VHF radio or cellular telephone, for each GPS observation. The rover or mobile GPS unit requires a data link to receive the transmitted correction where it is applied to the current satellite observation.

Reconnaissance survey: Minimal survey effort to determine approximate conditions of a study area.

RINEX: Receiver Independent Exchange format that is a standard to promote free exchange of GPS data from any manufacturer's GPS receiver. The format includes definitions for time, phase, and range.

RTK: Real Time Kinematic.

Satellite configuration: State of the satellite constellation at a specific time, relative to the user.

Satellite constellation: Arrangement of satellites in space.

Selective availability (S/A): Intentional degradation of the performance capabilities of the NAVSTAR system for civilian use by the U.S. military by creating a clock error in the satellites.

Sediment yield: The total sediment outflow from a drainage basin in a specific period of time. It includes bedload as well as suspended load.

Shore markings: Any object, natural or artificial, that can be used as a reference for maintaining boat alignment or establishing the boat's position as it moves along its course.

Site poles: Metal or wood poles used as a sighting rod.

Sounding: Subsurface depth measured by an acoustic device, echo sounder, or sounding pole.

Specific gravity: Ratio of the mass of any volume of a substance to the mass of an equal volume of water at 4°C.

Stadia: Telescopic instrument equipment with horizontal hairs used for measuring the vertical intercept on a graduated vertical rod held in front of the instrument at some distance.

State Plane Coordinate System: A reference coordinate system used by various states of the United States of America.

Thermocline: The middle layer of a water body, separating the upper warmer portion from the lower colder portion.

Total station: An electronic surveying instrument that digitally measures and displays horizontal distances and vertical angles to a distant object. Fully automated self-tracking or manual tracking total stations will digitally measure a moving target.

Transect: A sample area, cross section, or line chosen as the basis for studying one or more characteristics of a particular assemblage.

Transducer: A device for translating electrical energy to acoustical energy and acoustical energy back to electrical energy.

Triangulated Irregular Network (TIN): A linked network of x, y, z data points in a digital terrain model (DTM) from which volumes can be computed using the triangular prismoidal elements.

Universal Transverse Mercator (UTM) coordinate system: Worldwide metric military coordinate system.

WGS84: World Geodetic System 1984. Rotational ellipsoid reference model/datum whose surface is used to compute GPS coordinates. The WGS84 and the GRS80 use the same earth center, which makes NAD83 adjustment coordinates essentially the same.

Y-code (see anti-spoofing): Classified code similar to P-code with restricted access.

9.17 Summary

This chapter presents methodology used by the Bureau of Reclamation's (Reclamation) Sedimentation and River Hydraulics Group (Sedimentation Group) of the Technical Service Center (TSC) to measure reservoir topography for monitoring sediment deposition. The Sedimentation Group has monitored reservoir sediment[1] over the last century with closure of several dam structures in the early 1900s. The monitoring methodology has varied between reconnaissance to detailed field collection and analysis with the goal of accurately updating sedimentation and reservoir capacity information in a timely and cost-effective manner.

The Sedimentation Group continuously upgrades their technical procedures to reflect ever-changing technology. The majority of the techniques provided are from experience gained by Reclamation personnel in the planning and conducting of numerous reservoir and river surveys. Available publications with detailed descriptions such as hydrographic survey manuals by the U.S. Army Corp of Engineers (USACE, 2004), American Society of Testing and Materials (ASTM, 2005), International Hydrographic Organization (IHO, 2005), and manufacturer specifications should be used in conjunction with this guide.

The information presented is intended to assist in the planning and design of a data collection and analysis program. No deliberate endorsement of any particular procedure or manufacturer's equipment is either expressed or implied. The procedures and equipment presented have been utilized for numerous reservoir surveys by different U.S. Federal and state agencies, as well as various private companies. There are many worldwide vendors available with high-quality collection equipment and computer programs that should be reviewed prior to any selection.

All safety issues associated with hydrographic surveying are not discussed or addressed. It is the responsibility of the collection team and agency to establish appropriate safety and health guidelines, but the ultimate responsibility belongs to the individuals in the field who are using the equipment and executing the data collection procedures. Thorough evaluation of field conditions and available equipment, along with sound practical judgment, must be used in ensuring the safety and well-being of the personnel and equipment. Some safety decisions are made during the selection of equipment, such as the survey boat, that also determine the conditions in which crews can safely conduct surveys.

[1] The definition of numerous terms, such as "sediment," "sediment yield," "hydraulic height," "structural height," etc. may be found in manuals such as Reclamation's *Design of Small Dams, Guide for Preparation of Standing Operating Procedures for Dams and Reservoirs*, the American Society of Civil Engineers' (USASCE) *Nomenclature for Hydraulics, and ASTM D19 on water standards.*

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