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Reservoir Sedimentation Survey Methods

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COLUMBIA, MISSOURI

CONTENTS

Reservoir Sedimentation Survey Methods

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INTRODUCTION

Hundreds of small reservoirs are surveyed each year by various agencies and organizations to obtain information on the remaining capacity and on the sediment that is occupying space in these reservoirs. Some want to know how much water can be stored and others want to study the accumulated sediment and use the information as a guide in the design of similar reservoirs. The latter group obtain (1) sediment yield information from the sediment volume and its volume-weight, (2) sediment distribution from the location of the deposits in relation to vertical and horizontal distances, (3) physical properties of the sediment by direct measurement and laboratory analyses of samples of the deposited sediment, and (4) reservoir trap efficiency (percent of the sediment yield entering the reservoir that is deposited in it).

The problem is one of inadequacies and inconsistencies in many of the surveys. Frequently, it would cost no more in time, effort, or money to make a complete and accurate survey than it does to obtain insufficient and inaccurate data. A systematic survey procedure is needed so that the survey can form the basis for obtaining additional information at a later date. A standardized procedure also permits comparison of information on one reservoir with that on others. Furthermore, it assures obtaining all necessary data.

The purpose of this bulletin is to outline procedures and techniques that have proven highly satisfactory in making detailed sedimentation surveys of small reservoirs. Several mechanical and electrical innovations are also reported that facilitate greater accuracy and shorten the survey time.

GENERAL METHODS

Initial Basic Considerations

The outline of the reservoir and the topography of the reservoir bottom and of the surrounding area, together with consideration of the method contemplated for computing reservoir capacity, dictate the type of survey that should be made and the data that are needed. The presence of trees and other objects will

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[1] Contribution from the North Central Watershed Research Center, Corn Belt Branch, Soil and Water Conservation Research Division, Agricultural Research Service, U.S. Department of Agriculture, in co-operation with the Agricultural Engineering Department of the Missouri Agricultural Experiment Station, Columbia, Missouri.

limit the location of a base line and the usability of parallel ranges across the reservoir along which data are obtained. The water depth limits the type of equipment that must be used in collecting data.

The simplest reservoir to survey is one having only one water course in a rather straight line, in an area of smooth or uniform topography. Here, the base line should be located along one side of the reservoir, and all ranges (cross-sections) should be parallel and extend across the reservoir at a 90° angle from the base line. Such a survey can be made quickly and accurately, and the computations will be simple. Variations from the ideal sometimes necessitate the use of specific types of survey procedures, as presented on page 10.

Basically, there are three survey methods, as outlined by Eakin and Brown.[2] These methods are (1) cross-sectional area or range, (2) contour, and (3) a combination of these two. In most surveys, a combination of the cross-sectional area and contour methods is used.

The cross-sectional area survey method provides adequate data for the following methods of calculating reservoir capacities:

1. Eakins range end formula.
2. Cross-sectional area versus distance from dam—curve.
3. Simpson's rule using cross-sectional areas.
4. Average-end area formula.

The contour survey method provides adequate information for the following methods of computing reservoir capacities:

1. Stage-area curve.
2. Modified prismoidal formula.
3. Simpson's rule using contour areas.
4. Average-contour area formula.

These computational methods, as well as those enumerated under the cross-sectional area survey method, were discussed, compared, and evaluated by Heinemann and Dvorak.[3]

The combination survey method is used to advantage on many reservoirs. Frequently, part of the needed data can be obtained best by one method, while circumstances in other parts of the reservoir may lead to the selection of another method. The main body of the reservoir can usually be surveyed best by the cross-sectional method, since the topography is more uniform and its shape changes less from survey to survey than delta areas. On the other hand, the topography in exposed delta areas may not be uniform, or it may change considerably from survey to survey and can best be surveyed by the contour method. This combination method is very flexible and easily adapted to most reservoirs.

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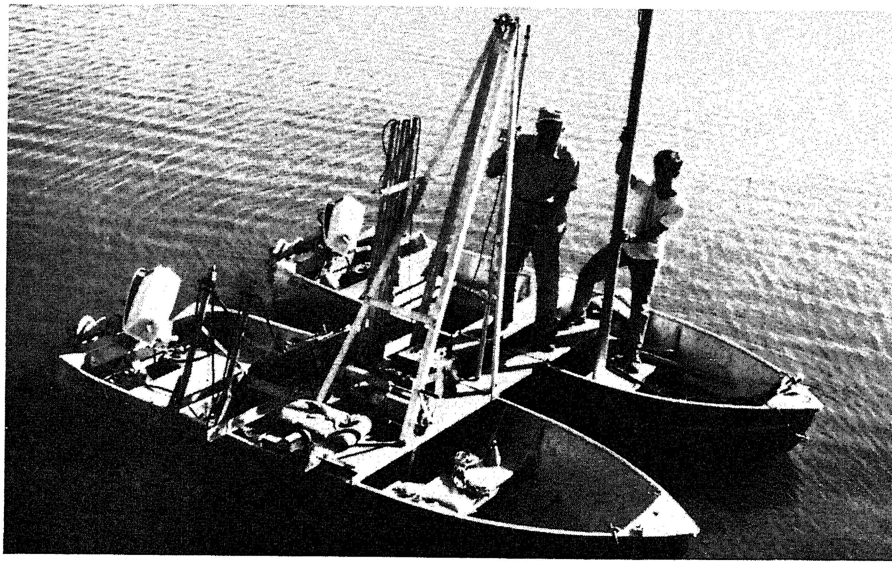
[2] "Silting or Reservoirs," by Henry M. Eakin, Technical Bulletin No. 524, USDA; revised by Carl B. Brown, U. S. Government Printing Office, Washington, D. C., 1939.

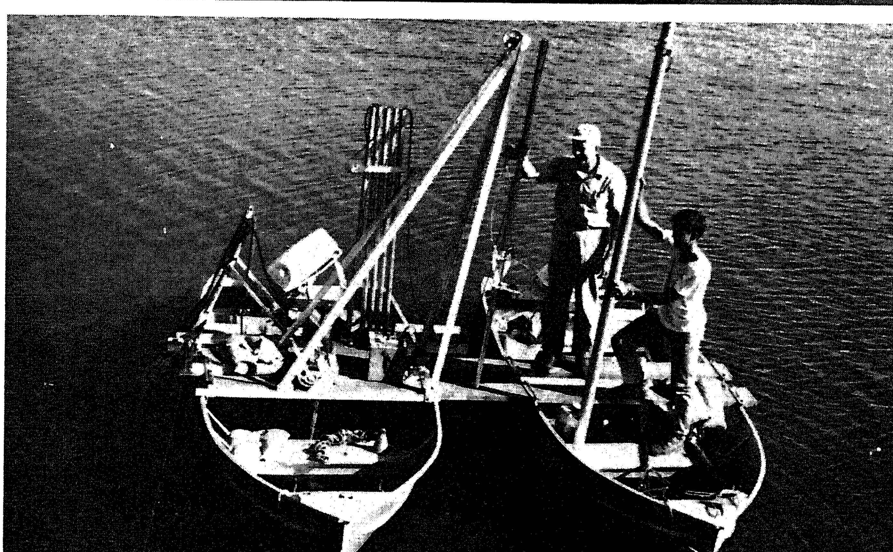
[3] "Improved Volumetric Survey and Computation Procedures for Small Reservoirs," by H. G. Heinemann and V. I. Dvorak, Proceedings of the Federal Inter-Agency Sedimentation Conference. U. S. Dept. Agr. Misc. Pub. 970, p. 845-856, June, 1965.

SURVEY EQUIPMENT

Boats

Two 14-foot aluminum boats with motors are used as a means of transportation and as a work platform when fastened together by two 2″ x 10″ planks, as shown in Figures 1 and 2.





Figures 1 and 2. Side and front view of two boats fastened together by planks and equipped for reservoir sedimentation surveys.

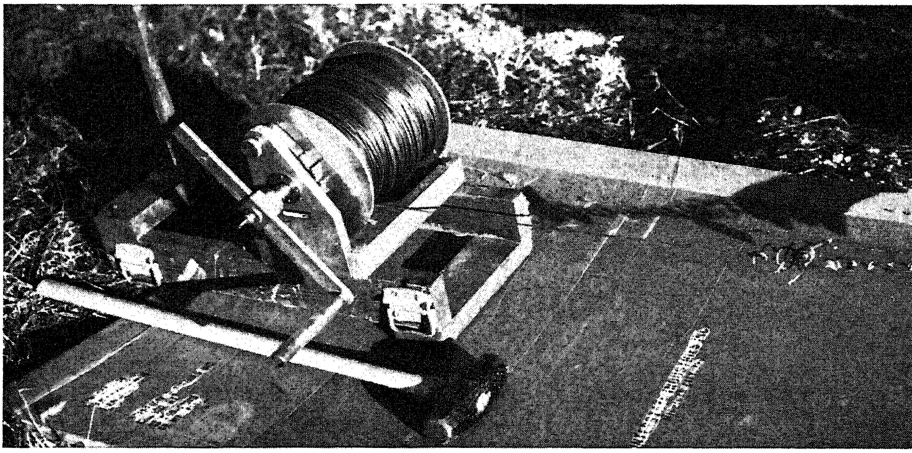


Figure 3. Reel holding cable which is stretched across reservoir to guide boat.

Cable and Reel

To make sure that all measurements along a range across the reservoir are on line, a cable is stretched along the range. The cable is a ⅛-inch 7- by 19-strand, galvanized, preformed, aircraft cable. The cable is stored and tightened by the reel shown in Figure 3. This reel will hold 2,000 feet of cable.

Productometer

The distance across the reservoir is measured by a cable-measuring device or a productometer. The productometer should have smooth, hardened-steel wheels when used with the cable.

Fathometer

Water depth can be recorded automatically with a depth recorder or fathometer. The fathometer determines the depth of water by measuring the time between sending a high-energy acoustical signal downward and receiving the reflected signal off the "bottom." Adjustments permit a compensation of differences in the speed of sound in the water and for "zeroing" the recorder. The depth limitations are from 1.5 to 180 feet. Depths as shallow as 1.5 feet can be measured if the outboard transducer—or "fish"—is mounted 6 inches below the water surface instead of the recommended 2 feet (Figure 4). The water depth versus time is recorded on a chart. Distance across the reservoir can also be recorded on the same chart if a microswitch is installed on the productometer as shown in Figure 5. This microswitch is connected electrically, parallel to the "fix" switch on the recorder. The microswitch closes momentarily every 10 feet and causes a vertical line to be marked on the chart (Figure 6). This system has performed satisfactorily at boat speeds up to 2 feet per second.

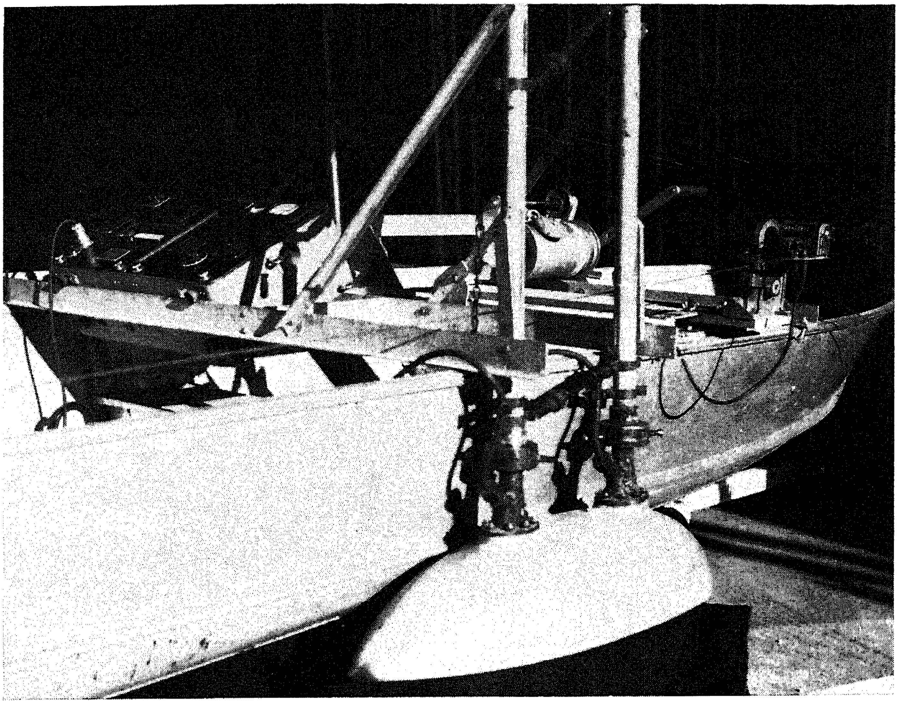


Figure 4. Mounting of fathometer transducer.

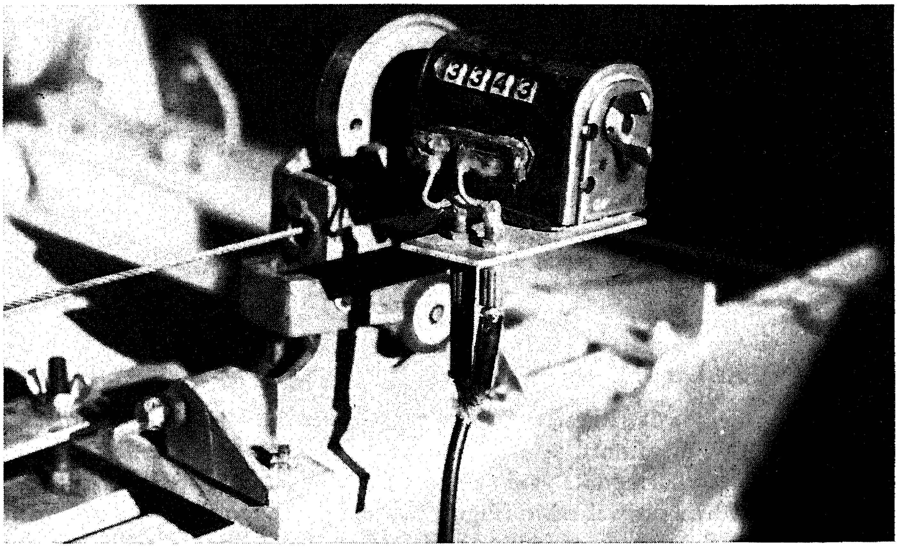


Figure 5. Microswitch on productometer.

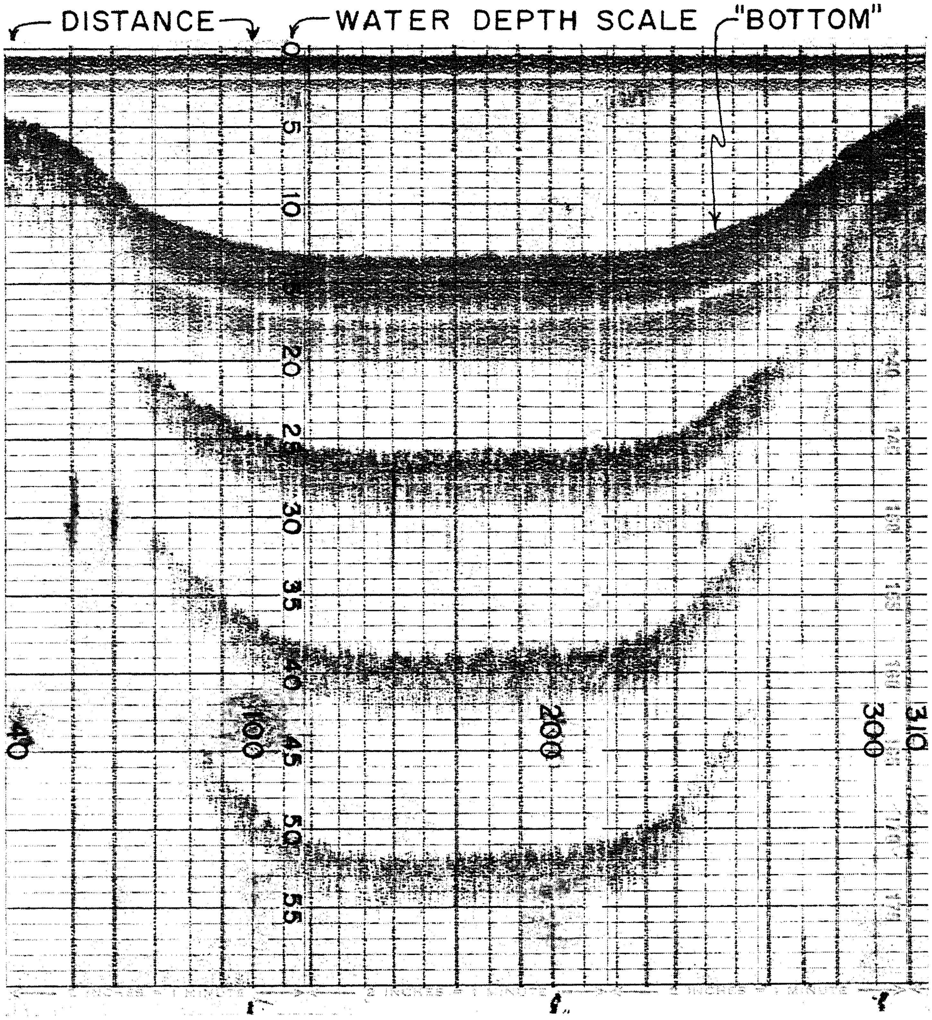


Figure 6. Fathometer chart showing distance and water depth.

Gamma Probe

Volume-weight of saturated sediment can be measured in place using the sediment density, or gamma, probe. The gamma probe gets its name from the radioactive source which emits gamma radiation. The probe is connected electrically to a scaler by a coaxial cable (Figure 7). The readout from the scaler is in total counts for the time of measurement. Extension pipes are attached to the gamma probe so that it can be shoved into sediment and removed. The 6-foot

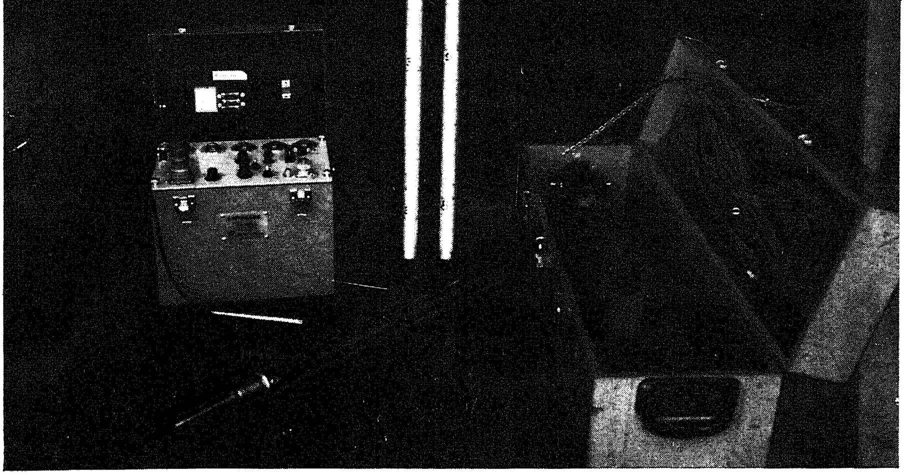


Figure 7. Scaler connected to gamma probe by coaxial cable. Also showing extension pipe and case for probe.

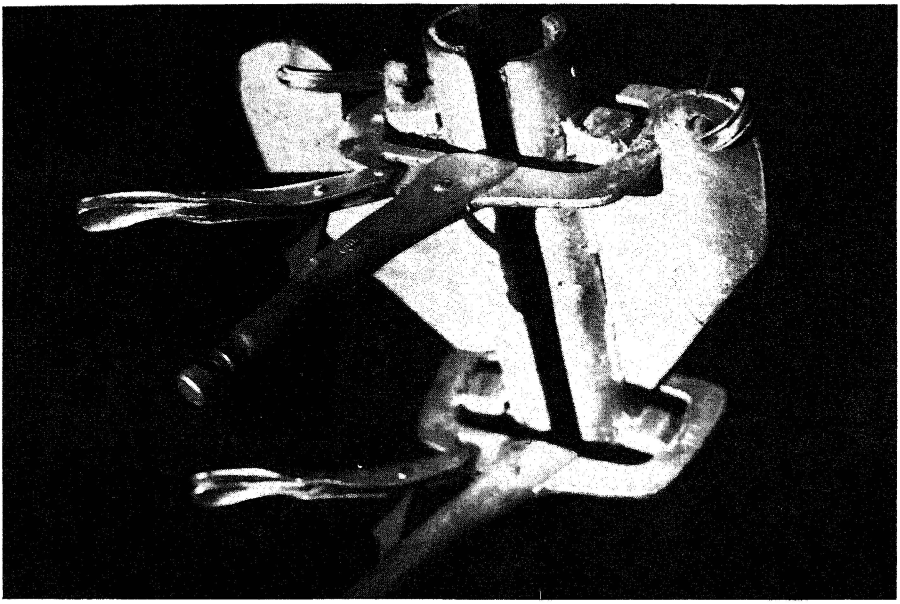


Figure 8. Yoke which clamps onto extension pipe. Cable on yoke is attached to hoist cable.

aluminum exension pipes have a 1.5-inch outside diameter and a 0.25-inch wall thickness. A yoke made from "vise-grip" clamps holds the extension pipe tightly and aids in removing it from the sediment (Figure 8). The gamma probe and its accessory equipment are described in detail by Heinemann[4] and McHenry.[5]

[4] "Using the Gamma Probe to Determine the Volume-Weight of Reservoir Sediment," by Herman G. Heinemann, Publication No. 59 of the IASH Commission of Land Erosion, p. 411-423.
[5] "Determination of Densities of Reservoir Sediments *in Situ* With a Gamma Probe," by J. R. McHenry, USDA, ARS 41-53, 1962.

A-Frame and Reel

An A-frame and a USGS B-50 reel are mounted on one of the boats to form a hoist for lowering and raising the gamma probe and sediment samplers (Figures 1 and 2). A dial on the reel indicate depth of the probe or the sampler. The A-frame is approximately 8 feet tall and the top extends 1 foot over the side of the boat. The hoist is used only when the two boats are fastened together by the two plants. A rack on the side of the A-frame holds the gamma probe extension pipe.

Sediment Sampler

An ARS piston-type sampler is used to take volumetric samples of the deposited sediment. A drawing of the sampler is shown in Figure 9. The barrels are interchangeable; they may be either 3 feet or 9 feet long. The inside diameter is 2.995 inches and the wall thickness is 0.065 inch. The barrel is made of high-strength stainless steel with a smooth interior surface. The nominal 3-inch I.D. sampler has proved to be more accurate sampling unconsolicated deposits than samplers of smaller diameter.[6]

SURVEY PROCEDURE

Base Line

To provide accurate horizontal control for the survey, a measured base line is established along one side and parallel to the reservoir, where possible. Three or four permanent markers along this line enable excellent survey accuracy. Sometimes the base line has to be located on top of the dam. A pipe or steel rod driven to below the frost line and flush with the ground or a concrete monument will serve as a good permanent marker. It should be referenced by distance and direction to nearby permanent objects.

Range Layout

Cross sections or ranges located perpendicular to the base line and parallel to each other speed surveys and computations. This is not always possible, of course; nevertheless, the location of ranges must always be selected carefully so that data obtained along them can accurately describe the topography. A typical range layout is shown in Figure 10. Ranges on a small pond my be spaced as close as 50 feet. As the reservoir size increases, the interval between ranges may also increase without losing accuracy. For a 150-acre surface area reservoir, the spacing may be up to 500 feet if the topography is uniform. No one range, how-

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[6] "Subsurface Exploration and Sampling of Soils for Civil Engineering Purposes," by M. Juul Hvorselv, U. S. Corps of Engineers, Research Report of ASCE, November, 1948.

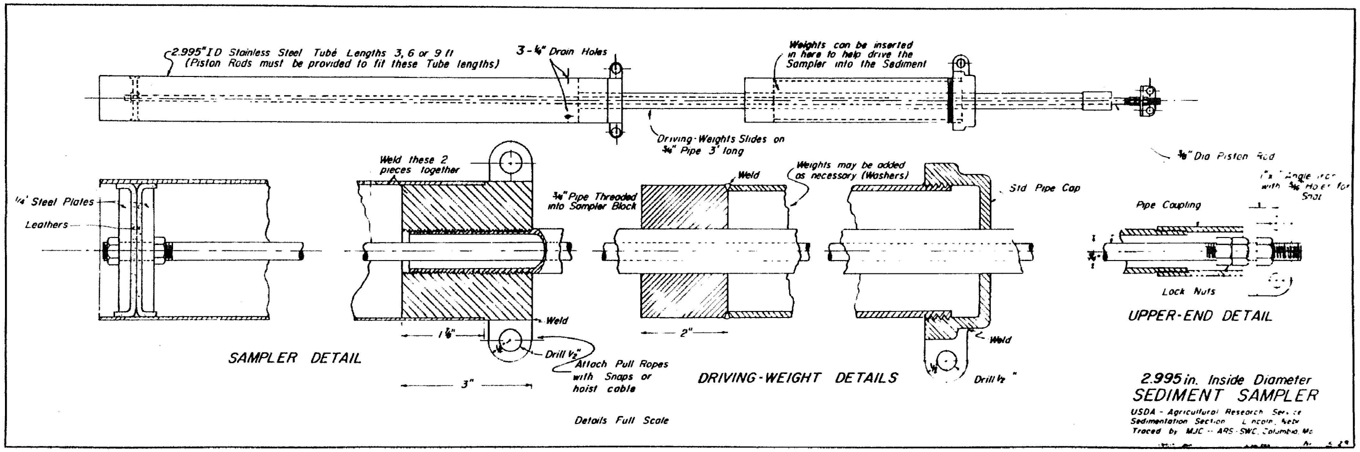

Figure 9. Drawing of ARS volumetric sediment sampler.

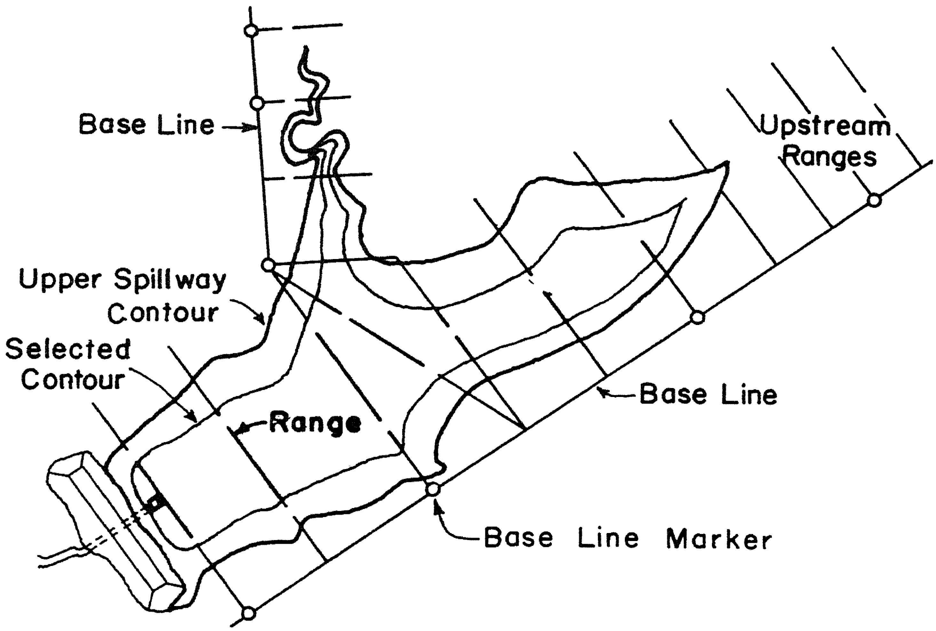

Figure 10. Suggested range layout for a typical reservoir.

ever, should represent a disproportionate part of the reservoir capacity. Ranges must be located so that they will yield maximum data for drawing contours. It is better to obtain more than adequate, rather than insufficient, data. When the range layout has been decided, the ends of the ranges are marked either temporarily or permanently and located by survey.

Bench Mark

A permaent bench mark should be established, to reference elevations during the survey. This may be a designated point on a concrete spillway or similar object. It is sometimes convenient to have a second bench mark some distance around the lake to facilitate and check the level work.

Contour Surveying

The contour surveying of reservoirs requires establishment of numerous elevations of the reservoir topography and accurate location of these points so that they can be plotted. The number of soundings or elevations needed varies with the irregularity of the topography. Various methods and equipment can be used to locate the points of known elevation—such as transit, plane table and alidade, or the distance along a range. A number of patterns can be used to systematically cover the area with elevations, such as a grid system or certain distance between points along ranges. When an adequate number of specific point elevations are obtained and plotted, contour lines can be drawn to reflect the topography.

Experience has shown that a good reservoir contour map can be drawn from a field determination of the spillway contour, a selected lower contour such as the water line, and data from a number of ranges that are properly located. Information on the upper (emergency) spillway contour and a lower contour provide excellent areal control. The selected lower contour is of most value when it can be located about one-third of the total reservoir depth down from the spillway. Both contours provide much information on the topography between ranges, and data from these two contours provide strategic points on a stage-area curve. The plane table and alidade are used to map these selected contours and range ends and to accurately define the volume of exposed deltaic deposits. Maintaining vertical control with an engineer's level while locating the points with the alidade will speed the plane table work and make it more accurate. If the reservoir has been surveyed previously and the shoreline has not changed, only the delta areas need to be surveyed by the plane table method. Experience has shown that a 2-foot contour interval is usually adequate for small reservoirs. However, additional contour lines may be needed in the delta areas to accurately define this sediment deposit.

Range Surveying

Range cross sections are surveyed in the conventional manner, beginning at the base line or convenient end and proceeding toward the water. If the base line is not above the upper spillway contour, the range line is extended and cross sectioned in the opposite direction also until the upper contour is reached. When the range has been surveyed down to the water, a stake is set at the water line and marked with the distance from the base line. This distance is used to set the productometer to read the actual distance from the base line when working from the boats. A similar stake is set on the opposite shore, based on the productometer reading for the location, which is the distance from the base line. The remainder of the range is cross sectioned up to the upper contour line on this side.

Water Depth

Water depth can be measured manually with a sounding bell or pole—or automatically with a fathometer. To guide the boat from which measurements are made, the cable (described earlier) is threaded through the productometer and stretched across the reservoir. The boat containing the productometer and fathometer remains near the cable reel while the other boat pulls the cable across the reservoir and anchors it on the other shore. It is important to be cautious when tightening the cable. Personnel should stand clear in case the cable breaks or the end pulls loose. Also, when loosening the cable, care should be taken that the crank on the reel does not slip and injure personnel. Others on the lake should be warned that the cable is stretched across the reservoir so they do not strike it with their boats and motors. When the cable is tight and the productometer is set for the distance from the base line, the fathometer is started and the water depths across the reservoir are recorded. Every 100 feet, the distance is marked on the chart as it is being produced, as shown in Figure 6.

Water level is recorded two to three times daily during the survey and referenced to the bench mark, to provide good vertical control for range cross sectioning. Water depths can then be converted to elevations and plotted.

If the original bottom has not been surveyed previously, one of the following can be used to determine the original depth: a spud,[7] a smooth sounding pole which can be shoved through the sediment, a sediment sampler which will penetrate the sediment, or any combination of these. Because the original soil surface is usually more cohesive than the sediment, it will adhere better to the spud. The original soil will resist penetration by the sounding pole and other probes and samplers and will, therefore, indicate the location of the original bottom. The sediment sampler may be used to obtain a sample of the original bottom, and the interface between sediment and original soil can be determined based on degree of aggregation, color, coarseness of material, and accumulation of leaves, twigs, and other organic matter. The easiest method is to use the sounding pole and periodically check the results with the spud or sediment sampler. By having distances marked on the sounding pole and other devices, one can easily convert a given depth below the water surface to an elevation by using the elevation of the water surface. The original bottom should be sounded approximately as often as the present bottom is sounded—or, if a fathometer is used, every 10 to 25 feet, depending on range length and smoothness of the bottom.

Communications

The use of the two-way radios speeds the survey where vegetation, topography, or distance limit the use of visual and voice signals. Quite often, the instrument can see the rod but not the rodman, or the rodman cannot see the instrument man. Two-way radios are useful also in keeping the boat on line when stretching the cable across a range. It is also easier to train a new crew when aided by two-way radios.

SEDIMENT SAMPLES AND VOLUME-WEIGHT MEASUREMENTS

Sediment volume-weight or dry bulk density can be measured by two methods—in place, using a gamma density probe, or by removing a sample of known volume and determining its dry weight. The first of these methods is more accurate[8] but the gamma probe is limited to saturated sediment. Another disadvan-

[7] USDA, SCS, Engineering Division, "Reservoir Sedimentation Surveys," Technical Release No. 22, Geology, August 1964.

[8] "Using the Gamma Probe to Determine the Volume-Weight of Reservoir Sediment," by Herman G. Heinemann, Pub. No. 59 of the IASH Commission of Land Erosion, p. 411-423.

tage is that it does not obtain a sample for particle-size and specific gravity analyses.

Volume-weight measurements and sediment samples are taken along range lines. The number of sample and measurement locations depends on the accuracy desired and the variability of the sediment. The entire depth of sediment deposit needs to be sampled and its volume-weight measured to accurately determine sediment accumulation. Consolidation continues to occur throughout the entire sediment depth.

Volume-Weight Measurements

To use the gamma probe, the coaxial cable is threaded through the desired number of extension pipes, depending on the maximum depth to be measured, and connected to the probe and scaler. The scaler is turned on and allowed to warm up for 30 minutes before use or until the counts per minute for the gamma probe in water agrees with the calibration data. Extension pipes are added to the probe assembly as it is lowered into the water and sediment without disconnecting the coaxial cable or turning off the scaler. The first volume-weight measurement is taken when the tip of the probe is 12 to 18 inches below the sediment surface. Additional readings or measurements are taken in 1-foot increments through the depth of the deposited sediment or until the probe cannot be shoved any deeper.

For safety reasons, dosimeters or film badges must be worn by personnel in the boats when working with the gamma probe. If direct-reading dosimeters are used, the reading should be recorded at the beginning and end of each day's use.

Sediment Samples

Physical specimens are taken of the sediment, using the piston-type volumetric sampler. To take a sample, the sampler is placed in a vertical position, with the piston held at the sediment surface while the barrel is driven into sediment by repeatedly dropping the driving weight. When the sampler has penetrated the sediment or the barrel is full, it is withdrawn from the sediment, using the reel and A-frame on the boat, making sure the piston does not move in relation to the sampler. Relatively undisturbed samples can be obtained when the sediment is extruded from the barrel by shoving on the piston rod. A 4-inch sample is taken from the core approximately every foot. Sample length and its depth in the deposit are measured on the piston rod. Samples are placed directly into plastic sample cartons, capped, and numbered and their description and location recorded in a separate notebook. The remainder of the core is observed closely for texture, stratification, and organic matter.

The sediment samples are analyzed in the laboratory for particle-sized distribution, specific gravity, dry weight, and spectographic data. Particle-size distribution is determined by the hydrometer or pipette method before drying the samples. Specific gravity is measured using pycnometer bottles. Spectographic analysis is performed on several samples to determine content of the elements affecting absorption of gamma radiation from the gamma probe. These elements are iron, calcium, manganese, strontium, and barium.

COMPUTATION

Capacity

When all the survey data have been gathered, the point elevations of the sediment surface along each range can be plotted on the plane table sheet or topography map. Contour lines can then be drawn for the entire reservoir and can form the basis for computing the reservoir capacity. As mentioned earlier, there are several methods of computing reservoir capacity.

Heinemann and Dvorak[9] have shown that "The stage-area curve is the most direct, simple, accurate and uniformly adaptable way to determine the capacity of a reservoir." The area inside each contour line is plotted versus its elevation or stage. This is done for each segment (that portion of the reservoir between two or more ranges) and for the total reservoir. In the stage-area curve method, the area under the curve is manually integrated with a planimeter or an integrimeter with respect to stage. The units are then converted to acre-feet.

Other computational methods have also been evaluated and compared. Some are almost as good as the stage-area curve method. The average-contour area method closely approximates the area under the stage-area curve when small contour intervals are used and the areas being averaged are not widely different. The average-contour area method uses a straight line approximation for integrating each increment of depth. This method can be easily adapted to computer use for quickly computing reservoir capacities, sediment volumes, and sediment distribution from stage-area data.

Sediment Volume and Sediment Distribution

There are also several methods of computing sediment volumes. Sediment volume may be computed directly from cross-sectional areas of sediment by the methods described earlier. The easiest and most accurate method, however, is to take the difference between the original capacity and any subsequent capacity. This is usually done for each increment of elevation in each segment of the reservoir.

The sum of all sediment volume increments is the total sediment volume. The increments of sediment volume are summed horizontally and vertically to give vertical and horizontal sediment distributions, respectively. The distribution of sediment is usually expressed in percentage of the total sediment volume for a percentage of original depth (vertical distribution) or for a percentage of total distance from the dam (horizontal distribution).

[9] "Improved Volumetric Survey and Computation Procedures for Small Reservoirs," by H. G. Heinemann and V. I. Dvorak, Proceedings of the Federal Inter-Agency Sedimentation Conference, U. S. Dept. Agr. Misc. Pub. 970, p. 845-856, June, 1965.

Volume-Weight

Gamma probe readings are converted to wet densities using the calibration curve for the particular gamma probe and scaler involved. True volume-weight is computed using the following formula:

$$w/v = G \frac{(D_w - 62.4)}{G-1}$$

where w/v is volume weight (lb./ft.^{3}),
D_w is wet density (lb./ft.^{3}), and
G is specific gravity of sample at same location and depth.

Total Weight

Sediment accumulation values must be based on total weight (especially for fine-textured sediment). Because the volume-weight of sediment varies within a reservoir and from reservoir to reservoir, sediment accumulation values cannot be based on volume alone. The sediment will also consolidate with time and with an increase in depth below the sediment surface. The increase in total weight of the reservoir sediment with time will give a true rate of accumulation and, when adjusted for reservoir trap efficiency, is the sediment yield from the watershed.

The total weight of sediment in a reservoir is computed from sediment volumes and weighted averages of volume-weights. A weighted average is computed for each range, based on the cross-sectional area each volume-weight reading represents. The weighted average volume-weight for each *segment* is then based on the weighted average volume-weight of each bounding *range* and the cross-sectional area of each range represented in the segment. The weighted average volume-weight for each segment times the sediment volume in each segment equals the weight of sediment in each segment. The total weight of sediment in the reservoir is then the sum of all segment weights. An example of these computations is given in Table 1 and Figure 11 for a segment of the reservoir bounded by two ranges.

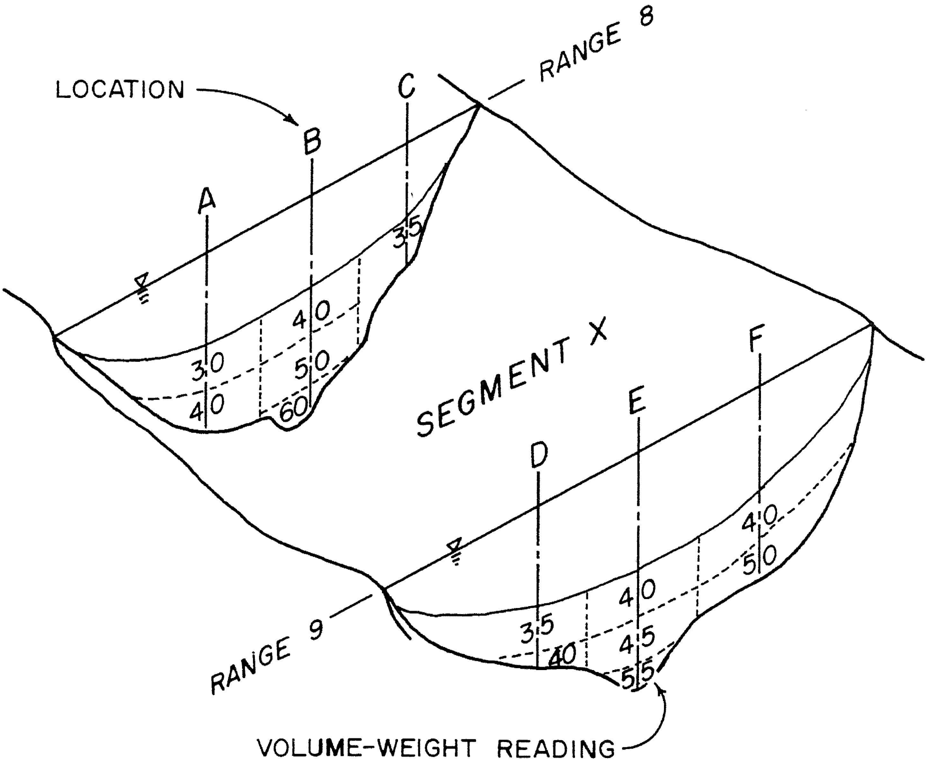

Figure 11. Illustration of possible volume-weights in typical segment X, bounded by ranges 8 and 9.

TABLE 1--EXAMPLE OF WEIGHTED AVERAGE VOLUME-WEIGHT COMPUTATIONS FOR ONE SEGMENT BOUNDED BY TWO RANGES.

Range Number	Location on Range	Volume-Weight Reading lb./ft.^{3}	Representative X-Sectional Area ft.^{2}	Product of Col. 3 & Col. 4 lb.
8	A	30	200	6,000
		40	100	4,000
	B	40	200	8,000
		50	200	10,000
		60	100	6,000
	C	35	150	5,250
			950	39,250
9	D	35	200	7,000
		40	50	2,000
	E	40	200	8,000
		45	150	6,750
		55	50	2,750
	F	40	200	8,000
		50	100	5,000
			950	39,500

Weighted Averages:

Range 8: 39,250 ÷ 950 = 41.3 lbs./ft.^{3}
Range 9: 39,500 ÷ 950 = 41.6
Segment (Sum of Ranges 1 and 2): 78,750 ÷ 1,900 = 41.4 lbs./ft.^{3}

Sediment weight for segment = sediment volume x 41.4 lbs./ft.^{3}

SUMMARY

1. The problem of inadequacies and inconsistencies in many reservoir sedimentation surveys can be solved by systematic procedures and techniques outlined in this bulletin.

2. Each reservoir must be considered individually and its base line and range layout carefully planned before the survey begins.

3. A plane table and alidade can be used to map readily and accurately the exposed deltaic deposits, spillway, and shoreline contours and range ends. An engineer's level is used for vertical control.

4. A fathometer electrically connected to a microswitch on the productometer will automatically plot water depth versus distance as it is moved across the reservoir on each range. The transducer for the fathometer is mounted so water depth as shallow as 1.5 feet can be measured.

5. The gamma probe can be used to measure the volume-weight of the saturated deposited sediment in place, while the ARS volumetric sampler can be used to remove an undisturbed sample for further determination of its physical properties.

6. Reservoir capacity is determined by the stage-area curve method which is direct, simple, accurate, and easily adapted to all reservoirs. The average-contour method closely approximates the stage-area curve method and can be easily adapted to computer use to determine capacities and sediment volumes and distribution.

7. Sediment volume is computed as the difference between the original capacity and a subsequent capacity. The difference between any two subsequent capacities will not give the sediment accumulation between surveys because earlier deposits will continue to consolidate.

8. Sediment accumulation should be expressed as a total weight of sediment. The total weight of sediment is computed from the sediment volume and its weighted average volume-weight.

Reservoir sedimentation surveys made with these systematic procedures and techniques, together with available equipment adapted to reservoir use, will provide complete and accurate data on reservoir sedimentation and capacity.