EROSION AND SEDIMENT YIELD:

Some Methods of Measurement and Modelling

EDITED BY R. F. HADLEY D. E. WALLING

EROSION AND SEDIMENT YIELD:
SOME METHODS OF MEASUREMENT AND MODELLING

Edited by

R. F. HADLEY AND D. E. WALLING

Contributors

H. A. Elwell

W. W. Emmett

R. F. Hadley

H. G. Heinemann

C. A. Onstad

D. L. Rausch

D. E. Walling

P. R. B. Ward

published by:

Geo Books,
Regency House,
34 Duke Steet,
Norwich NR3 3AP,
England.

ISBN hardback 0 86094 158 2

ISBN paperback 0 86094 141 8

Printed in Great Britain at the
University Press, Cambridge

7.

Measurement of reservoir sedimentation

D. L. Rausch and H. G. Heinemann

Introduction

A reservoir sedimentation survey is an excellent method to determine the sediment yield from a watershed. This method has distinct advantages over other approaches. The measurements obtained are generally much more accurate than those obtained using sediment yield prediction procedures. In contrast with the streamflow measuring and suspended sediment sampling method, the sediment yield for past years can be determined with one survey--without waiting years for collection of streamflow data. The sedimentation survey can be made at a convenient time, whereas streamflow stations generally must be attended by stream gaugers periodically and whenever flow events occur, day or night. This method is usually cheaper than others, and once the ranges and the benchmarks are established, a reservoir can be resurveyed in only a few days.

There is a limitation to the type of survey where thickness of sediment deposition is determined with a spud or piston sampler. For reservoirs built on sandy sites and having sandy inflows, distinguishing between deposits and the original bottom in the upstream reservoir area is often difficult, if not impossible. Consequently, the original reservoir capacity cannot be computed accurately. Other data needed to determine sediment yield from reservoir surveys include the history of the reservoir, when the reservoir started to fill, and whether any sediment has been removed. Also, the sediment discharged through the spillways must be estimated. This can be done with trap efficiency values determined from Brune's (1953) or Heinemann's (1981) procedure.

This chapter describes an efficient method for making a good reservoir sedimentation survey and the procedure for determining the sediment yield from a watershed. The suggested method is based on considerable experience in making sedimentation surveys of small reservoirs up to 600 m wide and 10 m deep. Equipment and manpower needs, safety precautions, computational methods, suggested analyses of sediment samples,

---

Agricultural Engineer, Watershed Research Unit, ARS, USDA, Columbia, Missouri, and Hydraulic Engineer (deceased), Hydrology lab., SEA-AR, USDA, Beltsville, Maryland.

and other components to complete a sedimentation survey are described.

Another reference on this subject is the American Society of Civil Engineers Sedimentation Manual No. 54 (Vanoni, 1977) which covers sediment deposit measurement techniques and equipment used for both large and small reservoirs. Information for surveying small agricultural reservoirs is contained in articles by Rausch and Heinemann (1968); Heinemann and Rausch (1971); UDSA, SCS's National Engineering Handbook on Sedimentation (1973); and Rausch and Heinemann (1976).

Publications dealing primarily with the gamma probe for determining the sediment volume-weight include those by Timblin and Florey (1957), Heinemann (1962), McHenry (1962), McHenry and Dendy (1964), and by McHenry *et al.* (1971). One publication, Heinemann and Dvorak (1965), deals primarily with the volume computations.

General approach

Each survey should obtain enough data to accurately determine sedimentation rates with the most efficient surveying method or methods. In addition, the field survey should be documented with benchmarks to expedite future surveys.

Fieldwork

The fieldwork required depends upon the choice of surveying methods. It may include aerial and topographic mapping, locating ranges, cross sectioning with a level (above water) and by sounding (below water), and in situ measurements and sampling of sediment deposits. It is highly desirable that the original survey be made soon after construction is completed and a topographic map constructed. If a topographic map is not available, an accurate map must be constructed, because any error in the calculation of the original reservoir capacity will cause an equal error in the computed sediment volume.

Before starting the survey work, the topography in the surrounding area should be studied, including that directly downstream from the dam. The slopes leading into the reservoir should be examined to determine if they are continuous or if bench terraces or other irregularities exist. Such topographic features require adequate delineation during the fieldwork. Also, the method for computing the reservoir volume must be chosen so that compatible field data can be collected.

Surveying and computational methods

Three basic surveying methods, outlined by Eakin and Brown (1939), are (1) contour, (2) cross-sectional area or range, and (3) a combination of these two. In most surveys, a combination of the contour and cross-sectional area methods is used.

The contour survey method provides adequate information for the following methods of computing reservoir capacities as outlined by Heinemann and Dvorak (1965):

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

The cross-sectional area survey or range 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.

Care must be exercised when using an average-end area formula. A sizeable volumetric error usually occurs when there is a considerable size difference between the two areas being averaged. The error, however, is minimal if the areas are similar in size, have a similar width or depth dimension, or the reservoir segment is bowl-shaped.

The combination survey method is used advantageously on many reservoirs. The main body of the reservoir can usually be surveyed best by the cross-sectional or range method, because the topography is more uniform and its shape changes less between surveys than in deltaic areas. In contrast, the topography in exposed deltaic areas may not be uniform, or it may change considerably from survey to survey and it can best be surveyed by the contour method. This combination method is flexible and easily adapted to most reservoirs.

Accuracy

The accuracy needed in surveying sediment volume and density depends upon the intended use of the finding and the accuracy of the associated data. Changes in sediment volume between surveys are affected by sediment yield, average trap efficiency (TE) of the reservoir, removal of sediment, and/or change in the water level. Sediment yield and TE are not constants. They are affected by meteorological events, land use, and other conservation practices in the watershed. The sediment deposition rate cannot be accurately computed unless all the above data are available or can be closely estimated. Thus, if these data cannot be determined quite accurately, the survey itself may not need to be very accurate. However, if all sediment outflow has been measured since dam construction or a previous survey, then an accurate survey will also give an accurate measure of TE and sediment yield for the period.

Horizonal control of ± 0.5 m on any area exceeding 100 m square will give an areal accuracy better than $\pm 1\%$. Ground and sediment surface elevations are usually measured to within ± 3 cm and benchmarks are surveyed to within ± 0.3 cm.

For a reservoir that averages 2 m of water depth and 1 m of sediment depth, this gives an accuracy of ±1.5% for the water volume and ±3% for the sediment volume. These accuracies are not hard to obtain, and as areas and depths increase, the accuracies can be improved.

Manpower and communications requirements

Reservoir surveys can usually be divided into two parts: (1) land survey, and (2) water survey and sediment sampling. Each can be performed efficiently by a 2- or 3-man crew, either simultaneously or by two crews or sequentially by the same crew.

Small, hand-held, two-way radios speed the performance of crews, especially a new crew on a larger reservoir. They are also helpful on rough terrain where the instrument man can see the level rod but not the rodman.

Crew safety

Reservoir surveys present diverse hazards to each participant. Working in the boats can be hazardous. Walking surfaces on the boats should be non-skid, and a good life jacket should be worn at all times. Reflection off the water in addition to the direct sunlight makes the effect of the sun more intense and measures should be taken to protect personnel from sunburn, heat exhaustion, and stroke. In general, use common sense and caution in surveys on and about the water.

Poisonous snakes and insects are sometimes more numerous in or near bodies of water, and crew members should be aware of the hazards and take appropriate precautions. Snake bite kits should be available when working in areas too remote for medical help. Personnel allergic to insect stings should carry their appropriate medicine.

If a gamma density probe is used on the survey, personnel should be trained in its proper use. They should be required to wear film badges that record accumulated radiation received or dosimeters that given an immediate reading of accumulated radiation, or both.

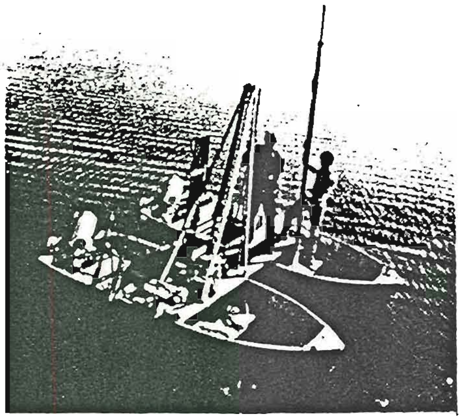
Surveying equipment

Boats

Two 4.2 m (or longer) aluminium boats with motors are used as a means of transportation and as a work platform when fastened together by two 5 cm x 25 cm x 4 m planks, as shown in Figures 7.1. and 7.2. Appropriate rafts might be substituted for the boats.

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 3 mm, 7- by 19-strand, galvanized, preformed aircraft cable or equivalent. The cable is stored



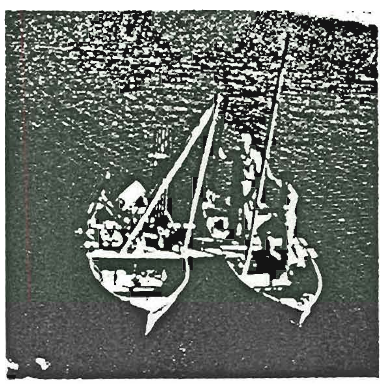


Fig 7.1. and 7.2. Side and front views of two boats fastened together by planks and equipped for reservoir sedimentation surveys.

and tightened by the reel shown in Figure 7.3. This reel will hold 600 m of cable.

Cable distance measurements

The distance across the reservoir is measured by using a commercially available cable-measuring meter with smooth, hardened-steel wheels that ride the cable. Similar devices may be constructed of various homemade designs. For small reservoirs a simple measuring tape or chain can be used, but a cable is much more convenient to handle.

Water depth

Water depth can be measured manually with a long, neutrally buoyant pole that is marked for length and which has a 12 cm disc on the bottom, or with a simple 2 kg sounding bell that is 12 cm in diameter and is attached to a

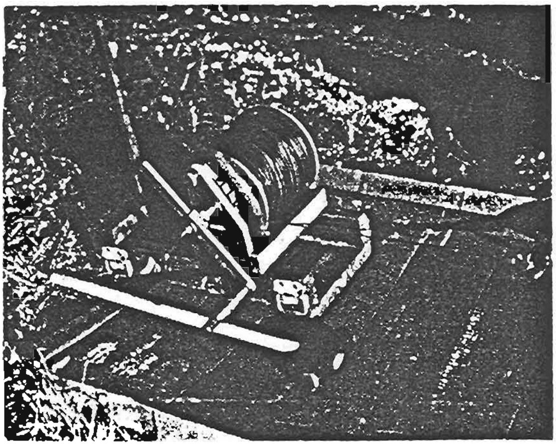


Fig 7.3. Reel holding cable which is stretched across reservoir to guide boat.

calibrated rope. These simple devices and techniques are recommended for small reservoirs (ponds). For larger reservoirs, however, use of a sonic depth recorder may be desirable. Depth recorders determine the depth of water by measuring the elapsed time between sending a high-energy acoustic signal downward and receiving the reflected signal off the bottom. Recorder adjustments permit 'zeroing' the chart at the water surface and varying the depth scale to compensate for differences in the speed of sound in the water.

Typical limits for the depth recorder are from 0.5 to 54 m. Depths as shallow as 0.5 m can be measured if the outboard transducer, or 'fish', is mounted 15 cm below the water surface instead of the recommended 60 cm (Figure 7.4.). The water depth versus time is recorded on a chart. Distance across the reservoir can also be recorded on the same chart if a switch is installed on the cable meter (Figure 7.5.) and wired parallel to the 'fix' switch on the recorder. The switch closes momentarily for every 'set' distance of boat travel and causes a vertical line to be marked on the chart (Figure 7.6.). This system has performed satisfactorily at boat speed up to 0.6 m.

Survey procedure

Base line

To provide accurate horizontal control for the survey, a base line is established along on side and approximately parallel to the reservoir (Figure 7.7.). Three or four permanent markers along this line enhance survey accuracy. Sometimes the base line has to be located on top of the dam. Steel pipes or rods driven to below the frost line and flush with the ground, or concrete monuments, serve as good permanent markers. They should be reflected by distance and direction to nearby permanent objects.

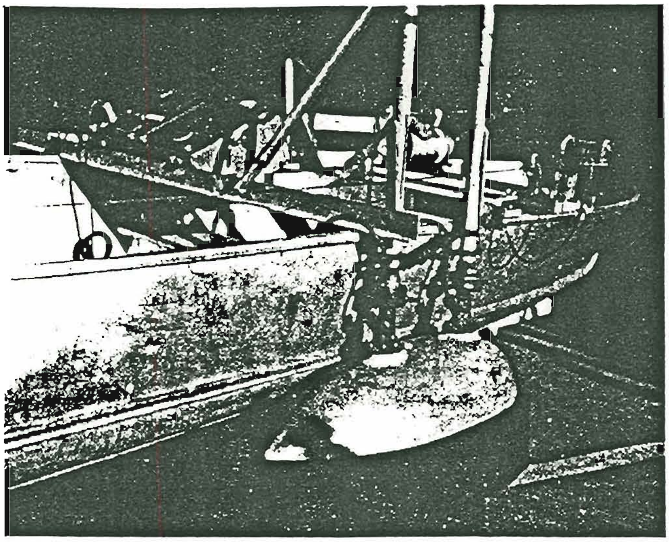


Fig 7.4. Mounting of sonic depth recorder transducer.

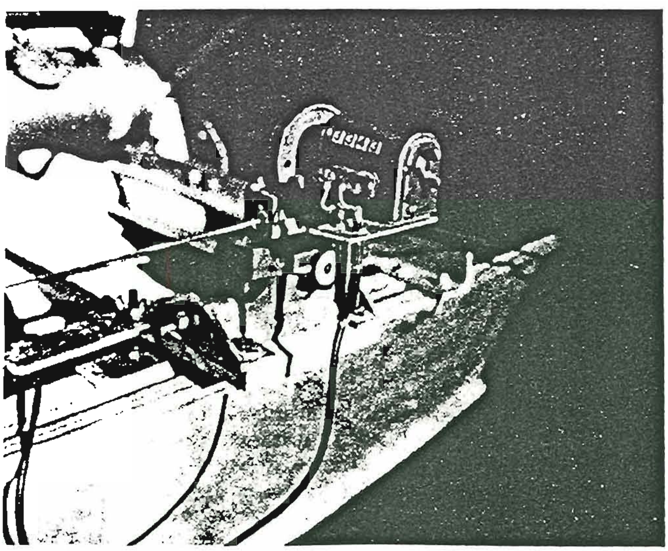


Fig 7.5. Switch on cable meter.

Benchmarks

At least two permanent elevation benchmarks should be established during the survey. This may include a designated point on a concrete spillway or similar object. It is sometimes convenient to have other benchmarks around the lake facilitate and check the level work.

Contour surveying

The contour surveying of a reservoir requires numerous elevation determinations of the reservoir topography and accurate location of these points so these 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 loate the elevation points such as transit, plane table and alidade, or range number and distance. A number of patterns can be used to systematically cover the area with elevations, such as a grid system or a 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 reservoir topography.

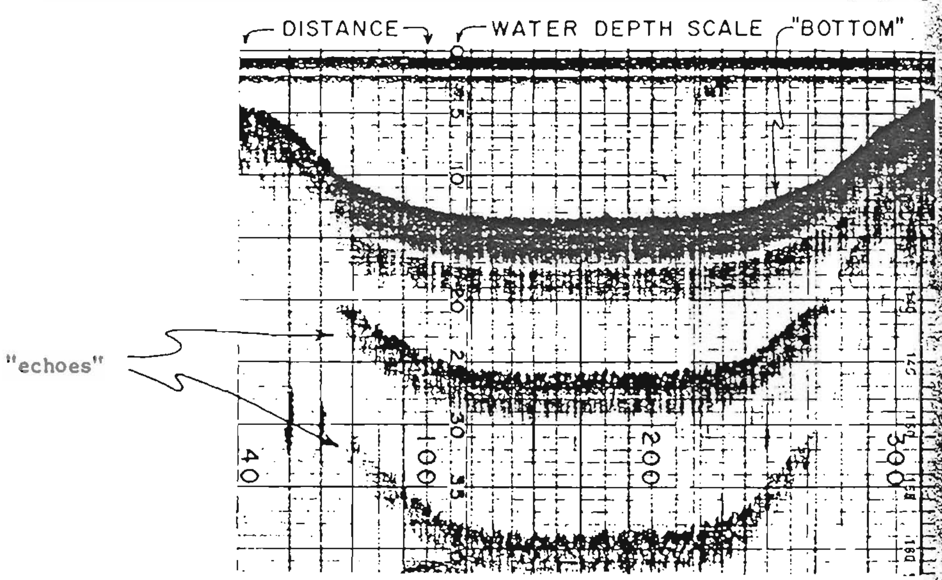


Fig 7.6. Depth recorder chart showing distance and water depth.

Experience has shown that a good reservoir contour map can be drawn from a field determination of the upper spillway contour, a selected lower contour such as the water surface elevation, and cross-sectional data from a number of properly located ranges. Information on the upper (emergency) spillway contour and a lower contour provide excellent areal control. The best elevation for the lower contour is about one-third of the total reservoir depth below the upper 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 may be 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 enhance its accuacy. If the reservoir has been surveyed previously and the shoreline has not changed, only the deltas need to be resurveyed by the plane table method. Experience has shown that a 0.5 m contour interval is usually adequate for small reservoirs. However, additional contour lines may be needed in the areas to accurately define this sediment deposit.

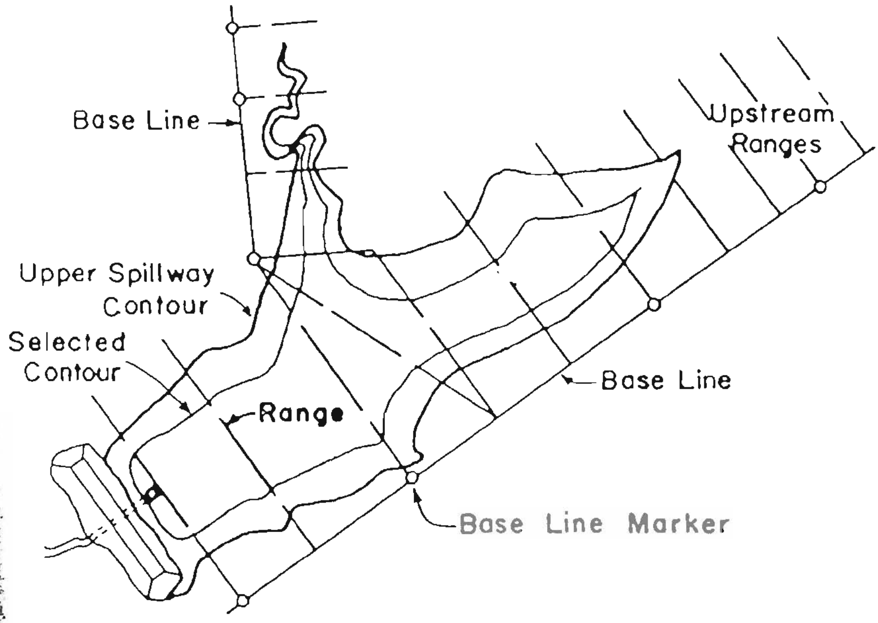


Fig 7.7. Suggested range layout for a typical reservoir.

Range layout

Cross sections or ranges should be placed generally perpendicular to the valley, and, if possible, perpendicular to the base line and parallel to each other because this speeds the survey and computations. Although such placement is not always possible, the location of ranges must always be selected carefully so that the data obtained along them accurately describe the topography. A suggested range layout is shown in Figure 7.7. Ranges on a small pond may be spaced as closely as 15 m. As the reservoir size increases, the interval between ranges may also increase without losing accuracy. For a reservoir with a 60 ha surface area, the spacing may be up to 150 m if the topography is uniform. The reservoir segment between any two ranges, however, should not be a disportionate part (more than 25%) of the reservoir capacity. Ranges must be locted so that they will yield maximum data for drawing contours. It is better to obtain more than adequate, rather than insufficient, data. Ranges should be extended if necessary, so that maximum elevations are at least 1 m above the highest spillway. If the exact topography of the upstream face of the dam is not known, at least one range should be located perpendicular to the axis of the dam to establish the presence or absence of a berm and also to locate the toe of the fill. If only a minimum number of ranges is used, one range must be located across the reservoir along the upstream toe of the dam.

When the range layout has been decided, the ends of the ranges are marked either temporarily or permanently and located by survey. Steel range markers driven flush with the ground can easily be located with a metal detector during succeeding surveys

Range surveying

Range cross sections are surveyed in the conventional manner, beginning at the base line or convenient range end and proceeding towards the water. If the base line is not above the upper spillway contour, the range line is extended in the opposite direction and cross sectioned until it is 1 m above the upper contour. 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 or range end. This distance is used to set the cable meter when the water portion of the range is surveyed from the boat. A similar stake is set on the opposite shore and marked with the distance based on the cable meter reading. The rest of the range is surveyed to 1 m above the upper contour elevation or to range end.

Water depth

Water depths can be measured manually with a sounding bell or pole, or automatically with a depth recorder. To guide the boat from which measurements are made, the cable is threaded through the cable meter and stretched across the reservoir. The boat containing the cable meter and depth recorder remains near the cable reel while the other boat pulls the cable across the reservoir and anchors it on the other shore.

Be cautious when tightening the cable. People should stand clear in case the cable breaks or the end anchors pull loose. Also, when loosening the cable, the operator should maintain firm control of the reel crank to prevent it from spinning free and possibly causing injury. Others on the lake should be warned that the cable is stretched across the reservoir so they will not strike it with their boats and motors.

When the cable is tight and the cable meter is set with the distance from the range end, the boat motor and depth recorder are started and the water depths across the reservoir are recorded. The distance lines are marked on the chart as it is being produced, as shown in Figure 7.6. The areas of each range too shallow for the depth recorder are sounded manually and recorded.

The notes should include range station or distance from range initial point, water depth, and depth to original bottom (initial survey only). Water level is recorded two or 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.

Sounding reservoir original bottom

If the original bottom has not yet been surveyed previously one of the following tools can be used to determine the original depth: a spud (Figure 7.8.), a smooth sounding pole,

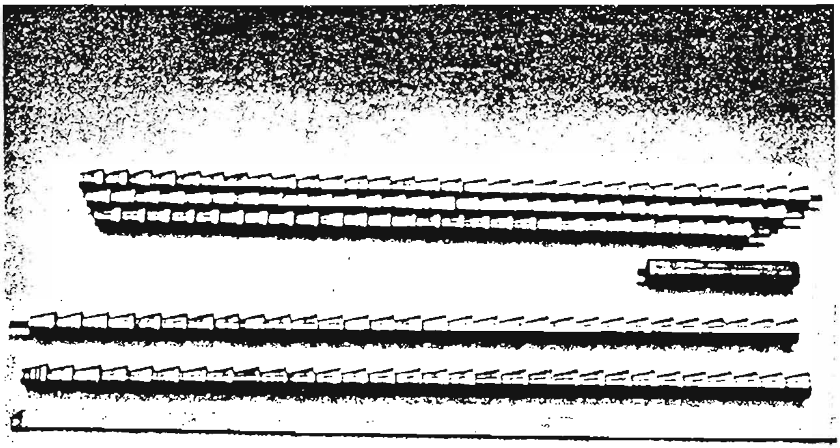


Fig 7.8. Sectional spud used to penetrate sediment and determine original bottom elevations, shown with meter stick and adapter for extension pipe.

a piston sampler, or any combination of these. Because the original soil surface is usually more cohesive than the sediment, it will adhere better to the triangular grooves in the spud. The spud is vertically into the sediment deposits and retrieved from deep water by the attached rope or from shallow water by an extension pipe.

When the sounding pole and other probes and samplers reach the original soil, penetration resistance usually increases suddenly, thus indicating 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 composition, structure, degree of aggregation, colour, and 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 from the elevation of the water surface. The original bottom shoul be probed about as often as the sediment surface is sounded, or, if, a depth recorder is used, about every 3 to 7.5 m, depending on range length and smoothness of the bottom.

It is sometimes quite difficult and strenuous to determine the original bottom of a reservoir. Therefore it is wise to survey reservoirs that may be used in sedimentation studies right after construction. Furthermore, ranges can be located and surveyed to provide maximum topographic data if the survey is made before the reservoir is filled. In addition, breaks in slopes, borrow areas, and other irregularities can be surveyed more easily and accurately.

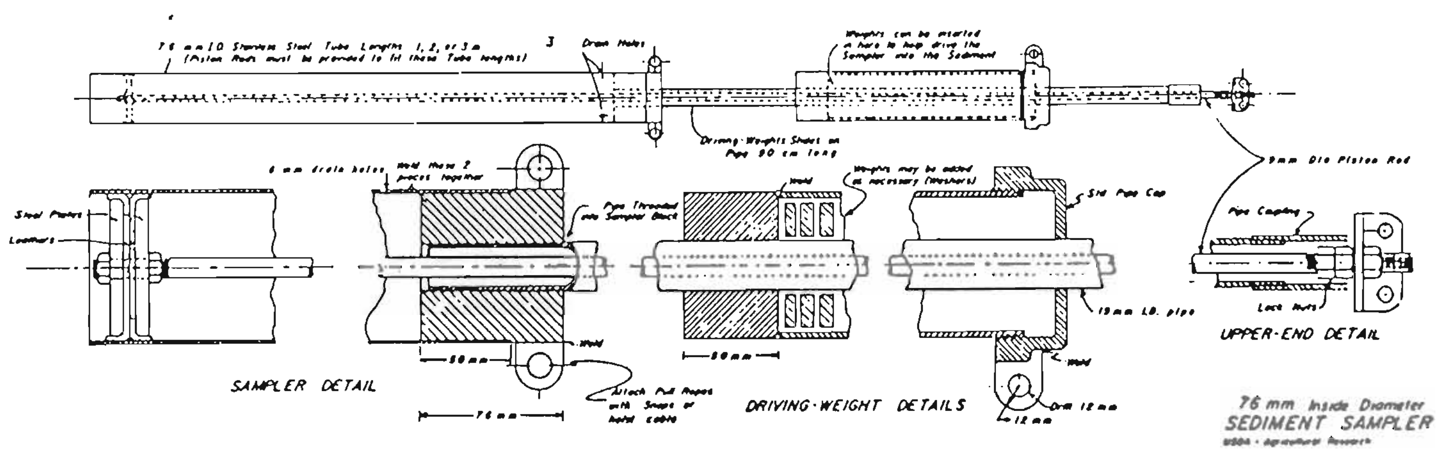


Fig 7.9. Drawing of ARS volumetric sediment sampler which is made out of standard plumbing pipe materials (Inside diameter is 7.6 cm).

SEDIMENT MEASURING EQUIPMENT

Sediment sampler

A piston-type sampler is used to take undisturbed volumetric samples of the deposited sediment. Figure 7.9. is a drawing of the Agricultural Research Service sampler. The barrels are interchangeable; they may be 1 m to 3 m long. The inside diameter is 7.6. cm and the wall is 1.6 mm thick. The barrel is made of high-strength stainless steel having a smooth interior surface. The nominal 7.6 cm inside diameter sampler samples unconsolidated deposits more accurately than samplers of small diameter (Hvorslev, 1948).

Gamma probe

Volume-weight of saturated sediment can be measured in place using a gamma probe that is properly calibrated in saturated material of similar specific gravity. This probe has a radioactive source (3 millicuries of radium 226) which emits gamma rays and a detector to pick up reflected radiation. The probe is connected electrically to a scaler by a coaxial cable (Figure 7.10.). The scaler readout is the total count for the time of measurement period (usually 1 minute). Extension pipes are threaded onto the gamma probe so that it can be shoved into sediment and removed. The 1.8 m aluminum extension pipes have a 38 mm outside diameter and a 6.35 mm wall thickness. The gamma probe has been used to penetrate as much as 4 m of sediment and to a total depth of 12 m. Additional extension pipes and coaxial cable would allow greater total depths. A yoke made from "vice-grip" clamps holds the extension pipe tightly and helps to remove it from the sediment (Figure 7.11.). The gamma probe, its accessory equipment and use and described in detail by McHenry (1962), Heinemann (1962), and McHenry and Dendy (1964).

A-frame and reel

An A-frame and a reel (US Geological Survey type B-50) are mounted on one of the boats for lowering and raising the gamma probe and sediment samplers (Figures 7.1. and 7.2.). The dial on the reel is used to indicate depth of the sampler. The A-frame is about 2.4 m tall and its top extends 0.3 m over the side of the boat. The hoist is used only when the two boats are fastened together by the two planks. A rack on the side of the A-frame holds the gamma probe extension pipes when they are not in use.

SEDIMENT VOLUME-WEIGHT DETERMINATIONS AND SAMPLES

Volume-weight determinations

Sediment volume-weight or dry bulk density can be determined by two methods; in place using a gamma density probe, or by removing an undisturbed sample of known volume and determining its dry weight. The gamma probe method is faster and more accurate but it can be used only in saturated sediment. Another disadvantage is that a few samples must

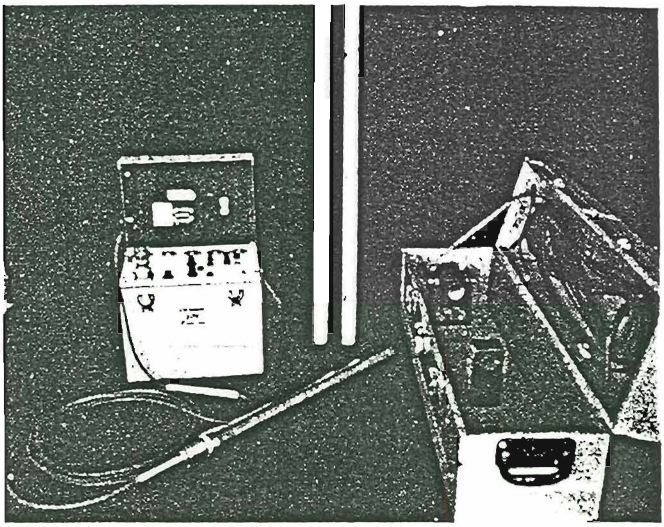


Fig 7.10. Scaler connected to gamma probe by coaxial cable, extension pipe, and case for probe.

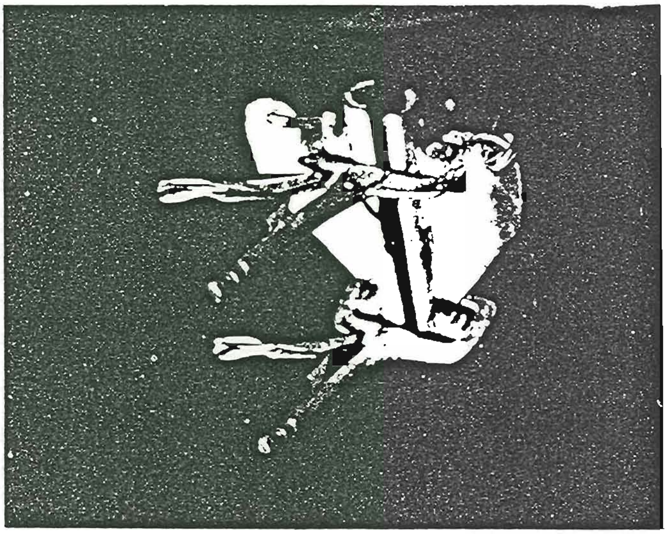


Fig 7.11. Yoke that clamps onto extension pipe. The cable on the yoke is attached to the hoist cable

still to be taken from each reservoir for particle size and specific gravity analyses.

Volume-weight measurements and sediment samples are taken at intervals along range lines. The number of samples and measurement locations depends on the accuracy desired and the variability of the sediment. The entire depth of sediment deposit must be sampled and its volume-weight measured to accurately determine sediment accumulation, because consolidation occurs with time throughout the sediment depth. Gamma probe measurements are limited to the depth the probe can be shoved into the deposited sediment, usually 4 m or less. Readings generally are taken at 0.3 m depth intervals.

Sediment samples

Undisturbed samples of sediment deposits are taken by lowering the piston-type volumetric sampler (with the piston flush with lower end) vertically to the sediment surface. With the piston held at the sediment surface with its rope, the sampler barrel is driven into the sediment by repeatedly dropping the driving weight. When the barrel has penetrated the sediment or is full, the sampler 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. With the sampler lying horizontally on the boat, relatively undisturbed samples can be obtained when the sediment is extruded from the barrel by pushing on the piston rod. The sampler is limited by the length of the barrel, usually 3 m or less. A 10 cm sample is taken from the core about every 0.3 m. Sample length and its depth in the deposit are determined by measuring the piston rod displacement. Samples are placed directly into plastic sample cartons, capped, and numbered. Sample numbers are recorded in a notebook and described as to reservoir, range, distance to range end, and depth. The rest of the core is observed closely for texture, air and water pockets, stratification, and organic matter. Such information along with total length of sediment in barrel, date, and daily weather conditions are also recorded in the notebook.

The sediment samples are usually analyzed in the laboratory for particle-size distribution, specific gravity, dry weight, and spectrographic data. Particle-size distribution may be determined by the hydrometer or pipette method before drying the samples. The specific gravity, measured using a pycnometer, is used to determine any shift in the calibration of the gamma probe. Spectrographic analyses may be performed on several samples to determine content of the elements adversely affecting absorption of gamma radiation from the gamma probe. These elements are iron, calcium, manganese, strontium and barium.

COMPUTATIONS

Capacity

After all the survey data have been gathered, a topographic map can be constructed. First, the intercepts of the contours and ranges are plotted. Contour lines are then drawn between ranges with the aid of other data such as point elevations of the sediment surface (deltaic deposits) and water elevation contour from the plane table sheet. This map is used for computing the present reservoir capacity. As mentioned earlier, there are several methods of computing reservoir capacity. Heinemann and Dvorak (1965) have shown that the stage-area curve is the most direct, simple, accurate, and uniformly adaptable method. The area inside each contour line is determined and plotted versus its elevation or stage. This is done for each segment (that portion of the reservoir between two or more ranges) and then for the total reservoir. In the stage-area curve method, the curve is integrated with a planimeter or an integrimeter with respect to stage. The instrument units are then converted to volume in cubic metres.

Other computational methods have also been compared and evaluated by Heinemann and Dvorak (1965). Some are almost as good as the stage-area curve method. The average-contour area method closely approximates the results of the stage-area curve method if small contour intervals are used and if 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 is easily programmed for computer use to quickly calculate 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 most accurate method for determining sediment volume, however, is to take the difference between the original capacity and any subsequent capacity. This can be 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 can be summed horizontally and vertically to give vertical and horizontal sediment distributions, respectively. The distribution of sediment is usually expressed as a 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). The sediment volume is also used with the sediment volume-weight to determine the true rate of sediment accumulation by weight.

Volume weight

If gamma probe readings are taken, they may be converted to wet densities using the calibration curve for the particular gamma probe and scaler involved. Volume-weight on a dry weight basis is then computed using the following formula:

$$\gamma_d = \frac{G_s(\gamma_w - 1.0)}{G_s - 1}$$

where γ_d is dry volume-weight in g/cm^3

γ_w is wet density in g/cm^3

G_s is specific gravity of sample at same location and depth; and

1.0 = weight of water in g/cm^3 at 0°C; use 62.4 for lbs/ft^3.

Volume-weight of the undisturbed samples can be determined by drying the sample or known portion thereof and the dividing the dry weight by the known sample volume.

Sediment weight

Sediment accumulation values should be reported on weight rather than a volume basis because the volume-weight of sediment varies within a reservoir and between reservoirs. The sediment also consolidates with time and with depth below the sediment surface. The increase in total weight of the reservoir sediment with time reflects the true rate of accumulation and, when adjusted for reservoir trap efficiency, is the sediment yield from the watershed.

The 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 that 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, which is weighted according to 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. Figure 7.12. and Table 7.1. show an example of these computations for a segment of the reservoir bounded by two ranges.

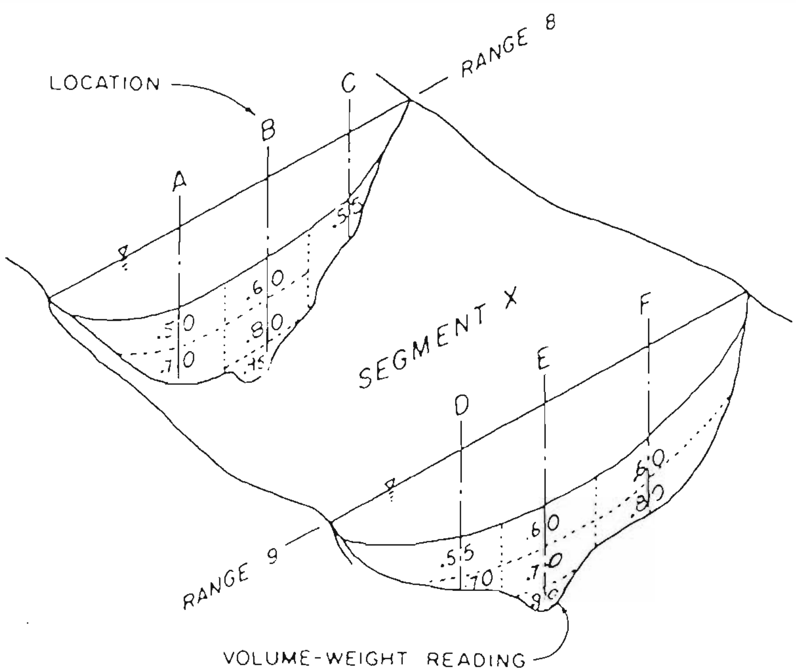


Fig 7.12. Possible volume-weights in a typical segment X, bounded by ranges 8 and 9.

Table 7.1. Example of weighted average volume-weight computations for one segment bounded by two ranges

Range Number	Location on range	Volume-weight Reading g/cm^3	Representative X-sectional area m^2	Product of Column 3 and Column 4
8	A	.50	20	10
		.70	10	7
	B	.60	20	12
		.80	20	16
		.95	10	9.5
	C	.55	15	8.25
			95	62.75
9	D	.55	20	11
		.70	5	3.5
	E	.60	20	12
		.70	10	7
		.90	5	4.5
	F	.60	20	12
		.80	10	8
			90	58

Weighted averages:

Range 8: 62.75 ÷ 95 = 0.660 g/cm^3

Range 9: 58.00 ÷ 90 = 0.644 g/cm^3

Segment (sum of Ranges 1 and 2): 120.75 ÷ 185 = 0.653 g/cm^3

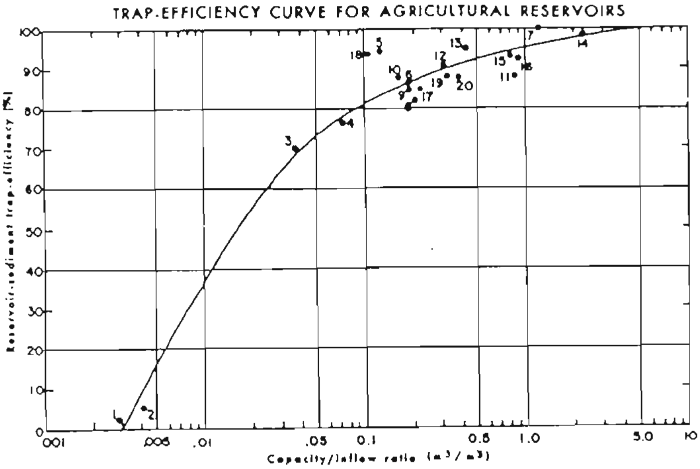
Sediment weight for segment = sediment volume x 0.653 g/cm^3 or 653 kg/m^3.

Sediment yield

In order to determine the average annual sediment yield from the contributing watershed, the weight of deposited sediment must be adjusted for reservoir sediment trap efficiency. This adjustment is needed because not all of the incoming sediment is trapped and deposited in the reservoir, usually some is passed through the spillway. By definition, trap efficiency is the portion of the incoming sediment (sediment yield) that is deposited or trapped in the reservoir, usually expressed in percent. Sediment yield, therefore, on a weight basis is calculated as:

$$\text{Sediment yield} = \frac{\text{Weight of Deposited Sediment x 100}}{\text{Trap Efficiency}}$$

The trap-efficiency value can usually be determined quite easily from Brune's (1953) or Heinmann's (1981) trap efficiency curves (Figure 7.13.). This requires knowledge of the average reservoir capacity up to the emergency spillway



1. Halbert Rock Res.#1, Tex.
2. Halbert Rock Res.#3, Tex.
3. Halbert Earth Res.#1, Tex.
4. Lexington, N.C.
5. Isaqueena, S.C.
6. T & P Reservoir, Tex.
7. H. Lage, Iowa
8. Third Ck. #7A, N.C.
9. N. Fork Broad R., #14, Ga.
10. Salem Fork #11A, W. VA.
11. Upper Hocking #1, Ohio
12. Plum Ck. #4, Ky.
13. Six Mile Ck. #6, Ark.
14. Escondido #1, Tex.
15. Double Ck. #5, Okla.
16. Brownell #1, Neb.
17. Highland Ck., Cal.
18. Ashland, Mo.
19. Callahan C-1, Mo.
20. Bailey, Mo.

Figure 7.13. Curve for predicting agricultural reservoir-sediment trap efficiency (from Heinemann, 1978).

level for the period included in the determination of the weight of deposited sediment and of the average annual inflow. The ratio of these two values, capacity/inflow, can then be used to obtain the trap efficiency value from the curves. The average annual sediment yield is the sediment yield thus calculated divided by the age of the reservoir and the watershed area. A reservoir survey will be more useful if a complete discription of watershed conditions that affected sediment yield are included.

SUMMARY

In summary, the general procedure for making reservoir sedimentation surveys has been described and the following items are emphasized.

1. Accuracy problems associated with many past reservoir sedimentation surveys can be avoided by systematic procedures and techniques outlined in this chapter.

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. Use of an engineer's level is suggested for vertical control.

4. A sonic depth recorder electrically pulsed by a switch on the cable meter can be used to automatically plot water depth versus distance as it is moved across the reservoir on each range. The transducer for the depth recorder is mounted so that water depths as shallow as 0.5 m can be measured. Optional manual sounding techniques may be used instead.

5. A gamma probe can be used to measure the volume-weight of the saturated deposited sediment in place. A piston type sampler can be used to also remove an undisturbed sample for further determination of its physical properties.

6. Reservoir capacity is best determined by the stage-area curve method - a direct, simple, and accurate method that is easily adapted to all reservoirs. Alternately, the average-contour method, which closely approximates the results of the stage-area curve method, 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 reservoir capacity and a subsequent capacity. The difference in volume between any two subsequent surveyed capacities will not accurately estimate additional sediment accumulation because earlier deposits 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.

9. Sediment yield can be determined from the deposited sediment weight by applying a reservoir sediment trap efficiency value to account for the sediment that passed through the reservoir.

REFERENCES

Brune, G.M., 1953, Trap efficiency of reservoirs, *Transactions, American Geophysical Union*, 34, 407-418.

Eakin, H.M., 1939, Silting of reservoirs, *US Department of Agriculture Technical Bulletin* 524.

Heinemann, H.G., 1981, A new sediment trap efficiency curve for small reservoirs. *Water Resources Bulletin*, 17, 825-30.

Heinemann, H.G., 1962, Using the gamma probe to determine the volume-weight of reservoir sediment, *International Association of Scientific Hydrology Publication* No. 59, 410-423.

Heinemann, H.G., and Dvorak, V.I., 1965, Improved volumetric survey and computation procedures for small reservoirs, *Proceedings of the Federal Inter-Agency Sedimentation Conference, 1963*, Miscellanous Publication 970, Agricultural Research Service, US Department of Agriculture, Washington, D.C., 845-856.

Heinemann, H.G., and Rausch, D.L., 1971, Discussion of chapter III, Sediment measurement techniques: reservoir deposits, by J. Lara, *Proceedings, American Society of Civil Engineers, Journal of the Hydraulics Division*, 97, 1551-1561.

Hvorslev, M.J., 1948, Subsurface exploration and sampling of soils for civil engineering purposes, *US Army Corps of Engineers, Research Report.*

McHenry, J.R., 1962, Determination of densities of reservoir sediments in situ with a gamma probe, *US Department of Agriculture Report* ARS 41-53.

McHenry, J.R., and Dendy, F.E., 1964, Measurement of sediment density by attenuation of transmitted gamma rays. *Soil Science Society of America Proceedings*, 28, 817-822.

McHenry, J.R., Hawks, P.H., Harmon, W.C., Kelly, W.J., Gill, A.C., and Heinemann, H.G., 1971, Determination of sediment density with a gamma probe: a manual of theory, operation, and maintenance for technical operations model 497, *US Department of Agriculture Report* ARS 41-183.

Rausch, D.L., and Heinemann, H.G., 1968, Reservoir sedimentation survey methods, *University of Missouri Agricultural Experimental Station, Research Bulletin* 939.

Rausch, D.L., and Heinemann, H.G., 1976, Reservoir sedimentation survey methods in *Hydrological techniques for upstream conservation, FAO Conservation Guide* No.2, 29-43.

Timblin, L.O., and Florey, Q.L., 1957, Density measurement of saturated submersed sediment by gamma ray scattering, *Chemical Engineering Laboratory Report* No. SI-11.

US Department of Agriculture, Soil Conservation Service, 1973, *National Engineering Handbook,* Section 3 (Sedimentation), Chapter 7, Field Investigations and Surveys.

Vanoni, V.A. (ed), 1975, *Sedimentation Engineering, American Society of Civil Engineers Manuals and Reports on Engineering Practice* No. 54.