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THIRD SESSION - RESERVOIR SEDIMENTATION

E. N. Munns* Presiding

RESERVOIR SEDIMENTATION SURVEYS - OBJECTIVES AND METHODS

by Albert S. Fry**

Investigations with respect to reservoir sedimentation are of significant importance wherever storage reservoirs are an integral part of water conservation and utilization projects. This is true whether the reservoirs be for domestic water supply, flood control, irrigation, hydro-power development, navigation improvement, or other related or corollary uses.

The importance of reservoir sedimentation in the economic life of any project obviously varies according to those factors which influence the rate of silting. These factors vary throughout the world. Where conditions are favorable to silting, reservoir sedimentation is of much greater importance than where silting is comparatively light. However, under any conditions, in small reservoirs where the ratio of reservoir capacity to drainage area is small, the useful life of the reservoir may be so restricted by sedimentation as to affect the economics of the project.

But irrespective of the economic or operational significance of reservoir sedimentation, it is important in any region to determine the facts with regard to sedimentation progressively throughout the life of a reservoir. For example, within the Tennessee Valley area, the TVA has a system of 26 water storage reservoirs. The gross storage capacities of these reservoirs vary from 14,000 to 6,000,000 acre-feet. The water-shed of the Tennessee Valley is slightly more than 50 percent forested and, although the average rainfall varies from 40 to 85 inches, the region as a whole is not one where heavy silting occurs. However, even under these conditions which exist in the Tennessee Valley, it is essential to have concrete data with regard to reservoir sedimention so that the true situation may be known and so that inaccurate statements lacking factual basis may be answered and disproved. It is, therefore, as necessary in this region of relatively light silting to make reservoir sedimentation investigations as it is in the more heavily silting regions such as those of watersheds in the western United States.

Objectives

The broad objective of any reservoir sedimentation survey is to provide positive information upon which to base estimates of the number of years that will be required, first, to cause silting sufficient to interfere with operations and second, to fill each reservoir to an elevation where its useful life will be ended. The most obvious direct objective is the measurement of the volume of material filled into any reservoir. It is also important to know where the deposits occur within a reservoir and particularly whether in live or dead storage. It is of interest to study the movement of silt from the place of original deposition as it is redistributed within a reservoir to its ultimate resting place and to study the effect of the operation cycle of water levels upon the deposition and movement of silt. Volumetric measurements further furnish a check on computations of reservoir silting made from suspended sediment investigations prior to the creation of a reservoir.

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The determination of the density of the deposited material may or may not be a part of the sedimentation survey. This, however, is important in the conversion of volumes of material into weight and in determining the state of consolidation of deposits in terms of ultimate consolidation.

Considering the large number and importance of reservoirs both large and small throughout the country, the over-all magnitude of reservoir sedimentation determinations is sufficient to justify the development and use of methods which will give desired results both accurately and economically.

Methods for sediment measurement in reservoirs are necessarily predicated upon soundings. In reservoirs of considerable capacity and extent, soundings are made along predetermined ranges. In small reservoirs, ranges may be spaced sufficiently close so that bottom contours may be drawn. In some small reservoirs, ranges may be dispensed with and independent sounding surveys made whenever desired to develop bottom contours. The reservoirs with which this paper is chiefly concerned are relatively large where the most feasible and practical method for sediment surveys is by ranges. The methods and equipment described are those which the Tennessee Valley Authority has found best for this work.

Layout of Ranges

After the plans for a reservoir have been completed and before the reservoir is filled, a paper location of silt ranges is made in sufficient number and in proper locations so that subsequent soundings on these ranges will furnish the necessary data for computation of silt volumes. The ranges should be located giving consideration to important local tributaries and the drainage areas of these tributaries and their probable sediment characteristics. A closer spacing of ranges is usually desirable in the upper and shallower end of the reservoir than in the lower and deeper portion. The width of reservoir should be given consideration. If there is a system of reservoirs on one stream such as those on the Tennessee River, the location in the system with respect to protection from upstream reservoirs may also be significant. In tributary reservoirs subject to considerable draw-down, closer spacing of ranges within the draw-down reach is desirable as the deposition and movement of silt throughout this range is greater than in other parts of the reservoir. For example, in Douglas Reservoir which is subject to draw-down, ranges are spaced two miles apart in the lower and extreme upper ends of the reservoir and 1 to 1.5 miles in between.

Since the location of deposited material cannot usually be completely forecast, it is desirable to include more ranges in the initial base survey than are actually needed. This permits more accurate data to be obtained on resurveys which can be guided with respect to which ranges are sounded by the location of deposited materials as developed during the survey.

Survey of Ranges

Following the paper location of ranges, elevations must be taken along each range. The ends of the proposed ranges are first monumented in the field with a permanent type of monument which also may be a part of the horizontal and vertical control network established around a reservoir. The monuments should be adequately referenced so that they can be found several years later without too much difficulty. Experience indicates that finding silt monuments in the field after vegetation has overgrown them is a costly time consumer.

In canyon type reservoirs such as those of Norris and Hiwassee Reservoirs in the Tennessee Valley where the sides of the valley are steep and the water depth is great, an accurate profile should be taken by surveying along each range prior to the filling of the reservoir. This base profile along a range before reservoir filling is preferable to a profile by echo sounding immediately after filling. Ground surveying develops the sides of the section where echo equipment might not prove feasible. However, in certain reservoirs of very rugged topography, echo sounding might be the only feasible method for obtaining the original section. If there is timber along the line of the silt range, this should be cleared if it is intended to sound with a lead line in the future. This has been done on TVA reservoirs because at the time of establishing silt ranges echo sounding methods had not been seriously considered. Where echo sounding equipment is to be used, the clearing is probably not essential but it would still seem desirable that large timber not be left directly along the silt range. TVA practice has been to clear a width of 50 feet along the silt range free of timber. This has been reduced to 25 feet in reservoirs now under construction where it is known that echo sounding equipment will be used for resurveys. Range monuments should not be located on the point of a sharp hill or abrupt change in reservoir

direction. At such places the elevation of the ground may show a variation within a relatively few feet of the center line of the range so that the resounding, which may vary a few feet off the center line, may lead to erroneous results with regard to deposition.

In the comparatively shallow reservoirs with depths usually less than 100 feet, such as those on the main Tennessee River, ranges are longer than those on the tributary reservoirs and may be two or three miles wide. The topography is also less steep and the depth less than in the canyon type reservoirs. In these cases, it is much more economical to wait until the reservoir is filled and then determine the profile along the silt range by soundings than it is to do so by ground survey work prior to filling. In the Kentucky Reservoir, for example, which includes 225 river miles of main river and tributaries, a very appreciable economy was accomplished by this method. It may be necessary in these cases to supplement the sounding surveys by bank work along the ends of the range to develop the section above the existing stage of water when the sounding is done.

Subsequent Reservoir Surveys

The surveys either prior to or immediately after the filling of a reservoir furnish the base for future determination of the volume of reservoir sedimentation and the manner in which the sediment is deposited and moves through the reservoir. Resurveys are made after an appropriate interval of years following closure of the reservoir. In the Tennessee Valley, surveys are made at intervals of 5 to 10 years.

The methods used in such resurveys embrace one form or another of sounding. For very shallow water depths, a sounding pole equipped with a base plate may be used. Beyond the range of a sounding pole, the general practice until the past few years has been to make soundings by conventional lead line methods. A rope lead line may be used directly or a piano wire may be used on a sounding wheel of the type developed by the Corps of Engineers. Although the lead line will still be useful for surveys of reservoirs where more modern methods are not available or justified economically, on large projects or reservoirs, future soundings will probably be made by supersonic equipment.

Supersonic Sounding Equipment

The development of echo sounding equipment represents an important forward step in reservoir sedimentation surveying. The general principle of this equipment is not particularly new as fathometers have been in use for more than 25 years. However, this type of equipment was improved and developed during World War II so that it is now the most practical and economical equipment for use in making soundings in reservoirs or other bodies of water. This equipment determines water depths by utilizing supersonic sound pressure waves and precision timing. There are two principal units and essential accessories. One unit is a projector, the function of which is to transmit the sound pressure waves to the reservoir bottom and to receive the reflected waves. The second unit is a recorder electrically connected with the projector which, by electronic and mechanical means, gives a permanent and continuous record on a calibrated chart of the depths of water through which the sound waves are sent. A 12-volt storage battery powers the equipment. Total power consumption approximates 120 watts.

There are three principal manufacturers of echo sounding equipment and the recording chart and detailed operation varies somewhat with each manufacturer. The equipment may be obtained either non-portable or portable. The latter is the better adapted to reservoir surveys. The basic principles are the same for both types of equipment.

With this equipment, rapid, automatic determination of depths of water and observations of the configuration of the bottom of the reservoir are obtained. In operation, the power switch is turned on, sending electrical impulses at a frequency in the supersonic range to the transmitting projector where each impulse is converted to a sound pressure wave. This is projected downward through the water to the bed of the reservoir, from where it is reflected upward to the receiving projector. The reflected sound pressure wave is converted in the receiving projector to an electrical impulse, which in turn records on the chart. The wave is very accurately timed in units of depths for the round trip. The elapsed time interval is converted into feet or fathoms on the basis of the velocity of sound in water for direct recording of depths of water on the charts. The chart speed is one inch per minute. For the type of equipment being used in the Tennessee Valley, depths of water are recorded in feet up to 200 feet and beyond that depth in fathoms up to 200 by a change in scale of the equipment. Soundings in feet are recorded at the rate of 200 per minute and in fathoms at the rate of 33-1/3 per minute. Soundings are recorded on rectilinear or curvilinear charts, depending on the design of the equipment. Both types of charts have their advantages.

On reservoir investigations, the echo sounding equipment is operated from a boat suitable for carrying the equipment and operating personnel.

Hydrographic Party

The hydrographic party for reservoir sedimentation investigations consists of four to five men specially trained for their duties on this particular kind of work. These are a chief hydrographer, an instrumentman, a boat operator, a sounding recorder operator, and a distance wheel operator. It is desirable for the recorder operator or some other man in the party to have some knowledge of radio and electronic circuits.

Equipment

Equipment is designed to provide complete mobility and permit the entire outfit to move readily from a reservoir in one part of an area to that in another perhaps a hundred or more miles distant. Automobile equipment consists of one sedan, a 3/4-ton covered truck with 4-wheel drive, and a boat trailer. The boat which carries the equipment is 20 feet long with a beam of 5 feet and a draft when loaded of about one foot. The boat is especially fitted with a well in the center through which the sound wave projector operates. Three outboard motors are used, two of 16 H. P. each and one of 10 H. P. The latter has a long shaft and is reversible. The two large motors are used during travel between ranges and whenever moving but not sounding. The 10 H. P. motor is excellent for maneuvering and is used in sounding up to 1,000 feet. The motor is speeded up by the operator as the distance increases until full power is developed at 1,000 feet. Beyond that distance one 16 H. P. motor is used in addition to the 10 H. P. On long ranges where the distance wire is not used, the 10 H. P. motor is used with a trolling plate to reduce speed to about 3 miles per hour. Fire extinguisher, life preserver jackets, and miscellaneous tools are included in the boat's equipment.

An auxiliary small boat is used on long range surveys but is obtained where needed and is not carried as regular party equipment.

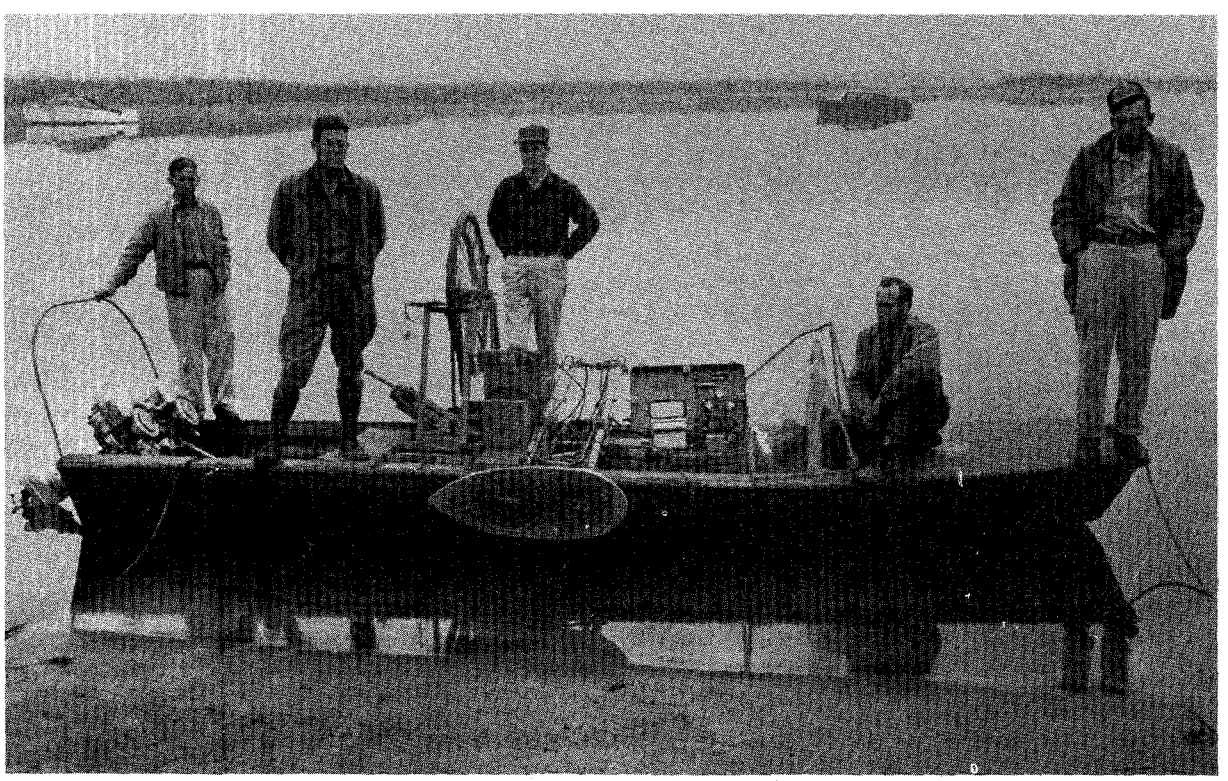

Figure 1. RESERVOIR ECHO-SOUNDING INVESTIGATIONS BOAT

Later improvements moved the projector unit to a well in the center of the boat and changed the type of distance wheel as shown in Figure 3.

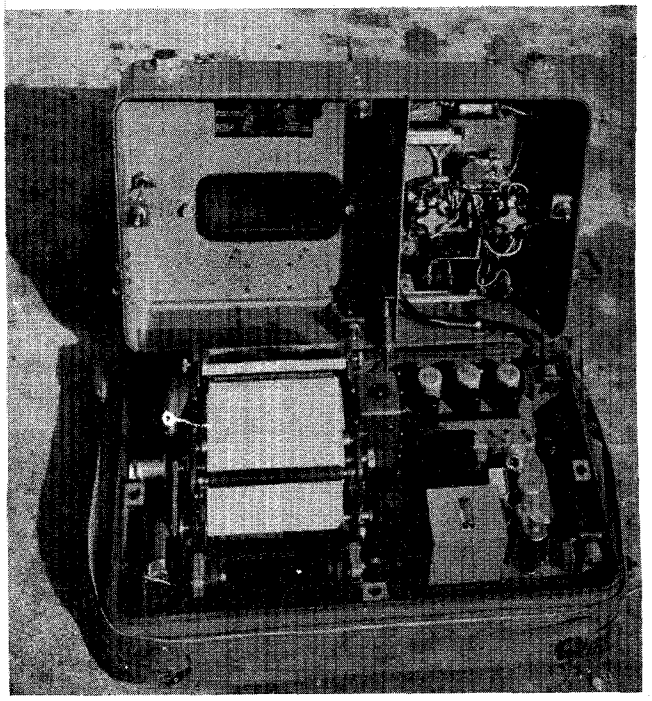

Figure 2. ECHO-SOUNDING RECORDER

The echo sounding equipment includes the sounding recorder, projector, storage batteries, and depth checking bar. The projector is of the outboard type, which is designed to be operated by being swung over the side of the boat and positioned below the water line for observations. However, with a boat of the size used for purposes of mobility, it has been found to be desirable from the standpoint of the most satisfactory and safest loading of the boat to operate the projector from a well centered in the hull. A simple lowering device positions the projector at the operating depth of one foot below the water surface. The heavy storage batteries, weighing about 165 pounds, are charged in place on the boat by a small motor generator.

One of the chief pieces of equipment is the distance measuring wheel devised by chief hydrographer E. H. McCain. This is an improved modification of the circumferential type wheel developed by the Corps of Engineers. The distance measuring apparatus consists of the drum of a Ford automobile wheel upon which is wound 2,500 feet of piano wire 0.039 inch in diameter.

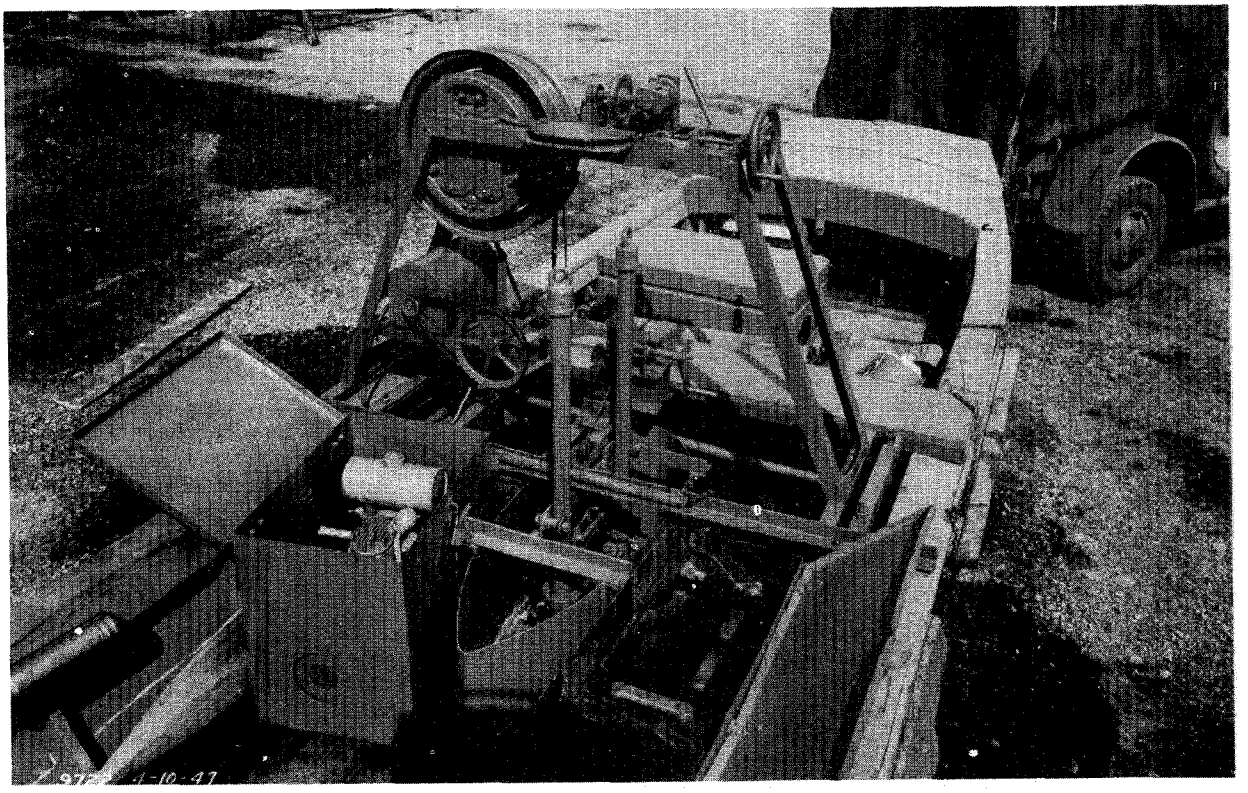

Figure 3. INTERIOR OF BOAT SHOWING PLACEMENT OF EQUIPMENT

The projector operates from the center well. The improved distance wheel is shown. Motor for rewinding is in metal box under drum. Motor generator set is at left of projector well, batteries are to right. Echo recorder is beyond the cross board.

The wire leads from the drum over two sheaves to a fixed pivot point on the bank from which measurements are taken. The second sheave is made of case-hardened steel to maintain a fixed rim diameter and operates a 3-digit counter which indicates the distance that the boat is from the pivot point. The rim of this sheave is accurately machined so that the circumference through the center of the encircling piano wire is exactly one foot. Two horizontal guide sheaves countersunk into top and bottom plates maintain the wire in position on the counter sheaves as the boat turns or moves about. The drum is fitted with a brake which the operator uses during the sounding process in order to control the reeling out of the piano wire. The apparatus includes a one-sixth H. P. motor to rewind the piano wire after a range has been sounded. The motor is operated by the motor generator set, which also is used to charge the storage batteries. The wire is purchased in 2,500 feet lengths as it is difficult to unreel piano wire from larger sized rolls. An iron bar bent in a loop over the rear end of the boat prevents the distance wire from fouling the outboard motors.

The party is equipped with transit, plane table, 200 feet steel chain, chainman's plumb bobs, signal flags, Abney level or clinometer, machete, hand axes, and iron pins.

One of the most useful pieces of equipment has proven to be a Walkie-Talkie radio which enables the boat party and the instrumentman on the bank to maintain conversational contact with one another, thereby eliminating hand signals and misunderstanding. The equipment used is former Army Signal Corps "Radio Receiver and Transmitter BC-611 F" and operates on a frequency band of 3,885 kilocycles. Four of these are carried as essential party equipment. For satisfactory use on long ranges, the voltage for these units was increased to use a $1\frac{1}{2}$-volt standard dry cell A-battery and 112 volts in B-batteries. These additional batteries are housed in an auxiliary box which may be placed on the ground or in the boat near where the radio unit is being used. Head phones are provided for the use of the boat operator. Some interference has been experienced when operating the radio set near the recorder but this is overcome by keeping the set a few feet away from the recorder.

Sounding Range

The operation of sounding a range using the equipment described is essentially as follows.

The ranges which are to be sounded should have been previously located and marked by a red or white flag about 2 feet square on a stick behind the silt range monument. Red is used where the background is light, white where it is dark as seen from the water. An additional flag should be set up near the water's edge when the monument flag is some distance away and can not be readily seen from the boat. Flagging the ranges ahead of the main party saves the time of the sounding party and materially reduces the over-all cost.

Assuming that the party moves up to a range in the boat, the boat lands on one bank. The distance from the monument to a point on the shore is measured with the steel tape and the angle taken from that point to the range monument by the hand clinometer. The transit is set up over the point so located. The boat with the other members of the party then cross to the opposite bank in order that, during sounding, the boat operator will be facing the instrumentman. Here a point is set on range about 5 to 8 feet above the water where an iron pin is driven into the ground. The distance from this pin to the range monument on that bank is measured and the angle taken. The distance from the pin to the distance wheel on the boat is then measured. The end of the distance wire is secured to the iron pin and the counter set to read the distance from the pin to the wheel. The projector is lowered, the chart operator turns on the sounding recorder and the boat moves across the river on the range at a speed of about 3 miles per hour. The transitman keeps the boat on range by giving directions over the Walkie-Talkie to the boat operator, who wears head phones connected to the radio on the boat. At the end of the run, the distance is taped from the boat to the instrument.

The recorder is equipped with a fix button which, when pressed by the operator, prints a line on the moving chart. At intervals of approximately 25 or 50 feet, the distance wheel operator calls out the distance, the chart operator pushes the fix button and notes the distance on a sheet of paper. These distances are transferred to the chart immediately on the completion of the range, thus serving as a check on the fix markings and distances. With these known distances indicated by fix markers on the chart, interpolation for other distances can be done accurately because the speed of the boat for any distance of 50 feet is likely to be uniform. If the movement of the boat were entirely uniform across the range, it would be possible to eliminate the measuring of distance and the noting of fixes. However, the operation of keeping on range accurately and the effect of current in the main channel where this exists are significant enough so that distances based on a straight line interpolation from one end of the range to the other

are not sufficiently accurate.

Upon the completion of the sounding of a range, the instrumentman boards the boat and the boat retraces the range in order to rewind the piano wire. The rewinding is done by the small motor at 400 feet per minute. At the bank, the end of the wire is released, the iron pin is pulled, and the party heads for the next range.

The temperature of the water must be taken into consideration in the operation of echo sounding equipment. The speed of the motor in the echo sounder can be adjusted to give correct depths where a constant temperature of water exists. This condition is seldom found in deep reservoirs which stratify with temperatures ranging from possibly 50 to 80 degrees Fahrenheit. Hence it is not practical to adjust the sounder to read correct depths. At the beginning of a day's run and at other periods if there is much change in depths of the reservoir, a check is made with the sounding recorder by submerging a steel bar hung from chains on either end to known depths below the water surface and recording the echoes therefrom. Successively lowering the bar by known intervals of 10 feet gives the depths which are recorded on the chart and the corrections which must be made to reduce the chart depths to true depths. The bar check is considered accurate to a depth of about 100 feet. For greater depths, corrections are made based on water temperatures. For example, in a survey of Hiwassee Reservoir, temperatures at 100 feet of depth were 42 degrees Fahrenheit and soundings were corrected for this condition. Corrections for salinity must be made where this exists.

It is desirable on reservoir work to use echo sounding equipment on which base line corrections may be automatically made on the recording chart for the depth of the projector below the water. This saves office work in making such corrections later.

In sedimentation surveys the accuracy of echo sounding equipment is considerably better than that formerly experienced with the best lead line methods and expert leadsmen. In water 100 feet deep, lead lines can not be considered to have an accuracy greater than one or two feet depending on whether a wire or a rope is used for sounding. If there is a current, the error may be more due to bowing of the lead line by the moving water. With echo sounding equipment of the type such as the TVA has used, an accuracy of one-half foot is accomplished at the same depth of 100 feet. The echo sounding method is much faster and hence more economical than lead line. Soundings are made in deep water as readily as in shallow water and in practically the same time. Echo sounding is obviously a labor saver as sounding with a lead is hard work.

In surveying Norris Reservoir last summer, an excellent check on the equipment was found on parts of ranges where there had been no silting. In numerous cases, the echo soundings checked the ground topography determined before the reservoir was filled practically flat.

As in any type of sounding, there is the problem of what is the character of the surface of the bottom where the soundings are taken. The possible unconsolidated nature of relatively new deposition introduces difficulties of interpretation and application of the soundings. The solution for this problem lies in methods for determination of density of materials in deep water which are separate from the soundings themselves.

Echo sounding equipment does not work satisfactorily close to the vertical face of a dam or cliff or very steep hillside which provides an opportunity for a reflecting echo. This effect is most evident in water greater than 100 feet deep.

The operation of the distance wheel requires a degree of skill but can be acquired by any one who has the feel for the job. The piano wire requires careful handling in order to avoid breaking and kinking.

Determining Position on Range

For ranges up to a length of 4,000 feet, position on range is determined with the McCain distance wheel. For ranges longer than 2,000 feet, the party works first from one bank and then the other up to a distance of about 2,000 feet. In establishing ranges initially where the length exceeds 2,000 feet and on resurveys for ranges longer than 4,000 feet, location on range is determined by cutting angles with a plane table from the bank.

Some of the reservoirs on the main Tennessee River have wide expanses of water of as much as two to three miles. These are beyond the limit of the distance wheel for position measurement. For ranges of this long length, two instruments are used on the bank. One is a transit to keep the boat on range and the other is a plane table to locate the soundings by cutting in horizontal

angles. The plane table point is located as far from the end of the range as the range is wide or maybe on an island in the lake if there is an available island. Plane table points for a day's sounding are always chosen before beginning the day's work. For this type of work, the Walkie-Talkie radio instrument has proven itself invaluable to increase efficiency of the party and speed up the work. Both men on the bank are equipped with Walkie-Talkies and a third instrument is used on the boat. Since the distance wheel is not used on long ranges, the wheel operator becomes the radio man on the boat. To obtain best radio conditions, he takes a position on the bow of the boat removed from the recorder mechanism and motors. The transitman uses his Walkie-Talkie to keep the party on range. The plane table man follows the sounding boat through the alidade and cuts in position at each sounding by horizontal angle on the plane table sheet whenever the sounding operator indicates a fix by the waving of a flag. Flags are alternated, using four white flags and one red, which provides a check for the plane table man in observing position and plotting these on his sheet. After the boat has completed its run to the opposite bank, contact with the plane table man by Walkie-Talkie makes sure that he has obtained all the necessary data. The plane table man in this case has a separate small boat and proceeds independently to the plane table point from which he will cut in sounding positions for the next range. Meanwhile the main party also proceeds to that range. Contact is again established on the Walkie-Talkie before starting the new range. It is possible to carry on work in this way perhaps for a whole day without the main sounding party even catching more than a glimpse of the plane table man.

Surveys of Deltas or Other Areas

In some detailed surveys in reservoirs where it is desired to study the deposition of material brought in by tributaries and deposited as a delta, or to determine accurate bottom contours for several hundred feet immediately above or below a dam, a detailed survey of such areas is best made by a radial sounding method. An expert boatman is essential on this type of work as the boat must be held closely in position and must be handled skillfully in order not to break the distance wire. In this case a pivot point is located on the bank adjacent to the area to be surveyed and a plane table is set up over this point. The distance wheel is initially set at a fixed distance from the pivot point of 25 feet. The pivot point is placed high enough above the water to keep the wire out of the water and for distances up to 300 feet, correction for the inclination of the wire is set on the distance wheel.

Starting at the bank, the boat swings in an arc, keeping the distance wire taut until the boat reaches the bank 50 feet distant from the starting point. The distance wire is then extended another 25 feet to a total of 50 feet from the pivot point and a reverse arc is run if operating in still water. If sounding where there is appreciable current, the soundings must all be made in arcs swinging with the current. As the boat proceeds along each arc, the chart operator presses the fix button and at the same time indicates to the plane table man his position by dropping a flag, using the red and white flag system previously described. By successively increasing the radial distance, the desired area is covered completely and accurately. The plane table man prepares the plane table sheet before setting up by drawing arcs at 25 feet intervals. As he follows the sounding boat around each arc, he marks the position on each arc on the plane table sheet where a sounding fix is indicated.

Prior to the advent of the present echo sounder, radial sounding surveys have been made with equipment developed by the Corps of Engineers. This uses a large sounding wheel with piano wire passing around the calibrated circumference to a lead sounding weight. Excellent results have been obtained with this equipment but echo sounding is superior.

Deep Reservoirs

In the experience which we have had so far in the Tennessee Valley, the maximum depth sounded has been about 200 feet in Norris Reservoir. However, depths in Fontana Reservoir will reach a maximum of about 450 feet. The soundings in such reservoirs where there is a seasonal draw-down should be made whenever possible at the time of maximum draw-down in order that the maximum length of reservoir may be sounded using the chart operating on a foot scale. Where depths greater than 200 feet must be sounded, the equipment is operated so that the chart reads fathoms.

Possible Succeeding Equipment Developments

The advances which have been made in the utilization of electronic principles in engineering equipment during World War II have opened up many possibilities in the way of future improvements in engineering equipment for engineers. The echo sounding equipment is an excellent example of

something that has been accomplished. The utilization of the distance wheel for ranges up to 4,000 feet in length is an advance in techniques. So also is the use of the Walkie-Talkie radio. However, there is still a fertile field for the development of better methods for determining positions of reservoir soundings. Radar immediately suggests itself but equipment that might be used is bulky and costly at the present time. If research is made with a specific objective in mind, however, radar should offer an excellent possibility for providing position determining equipment with satisfactory accuracy and an over-all cost that would make the equipment feasible for practical use. Engineers should not be satisfied that the ultimate has been reached but should be ever alert to the possibilities of further advances either through electronics or otherwise.

DISCUSSION

Harold W. Murray.* Mr. Fry has requested me to expand his remarks on the nature of echo soundings. For the purpose of this meeting, consideration will be given briefly to a few definitions and appropriate illustrations depicting graphic recorder phenomena. The accompanying illustrations were obtained from fathogram records of the U. S. Coast and Geodetic Survey.

True depth. A true vertical depth is obtained only when the reflecting surface under the sounding vessel is parallel to the water's surface. This definition is quite rigid but does not detract from the overall accuracy, efficiency and practicability of echo sounding.

Superimposed echoes. A fathogram recording of two or more reflecting surfaces usually provides a trace of the bottom under the sounding vessel and a distinct superimposed trace received from a secondary feature lying off to one side of the vessel (Fig. 1). Examples occur when passing near a sunken rock, shoal, or near the foundation of a bridge pier.

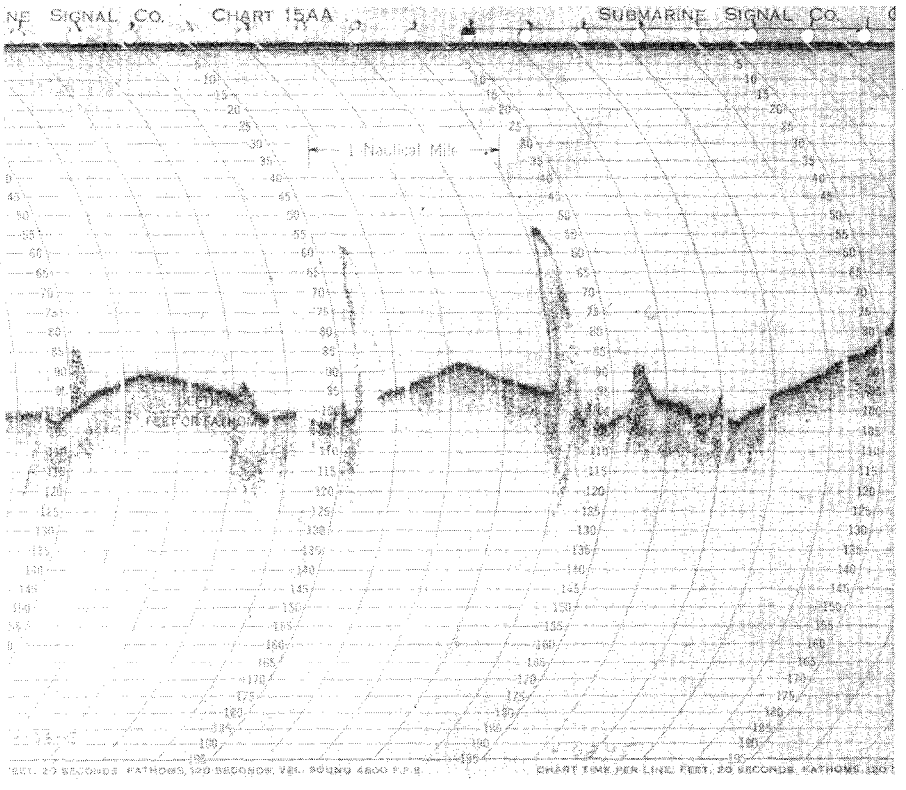

Figure 1. Type NJ3-Fathogram showing a distinct superimposed side echo received from a shoal lying off to one side of the sounding vessel. All indicated shoals in this illustration were received from the same feature.

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Strays. Intermittent recordings resulting from fish swimming under the vessel, plankton, flotsam, oscillation in the amplifying unit, or to other temporary causes. Strays resulting from electrical oscillation are the most annoying but can usually be eliminated by proper fathometer operation (Fig. 2).

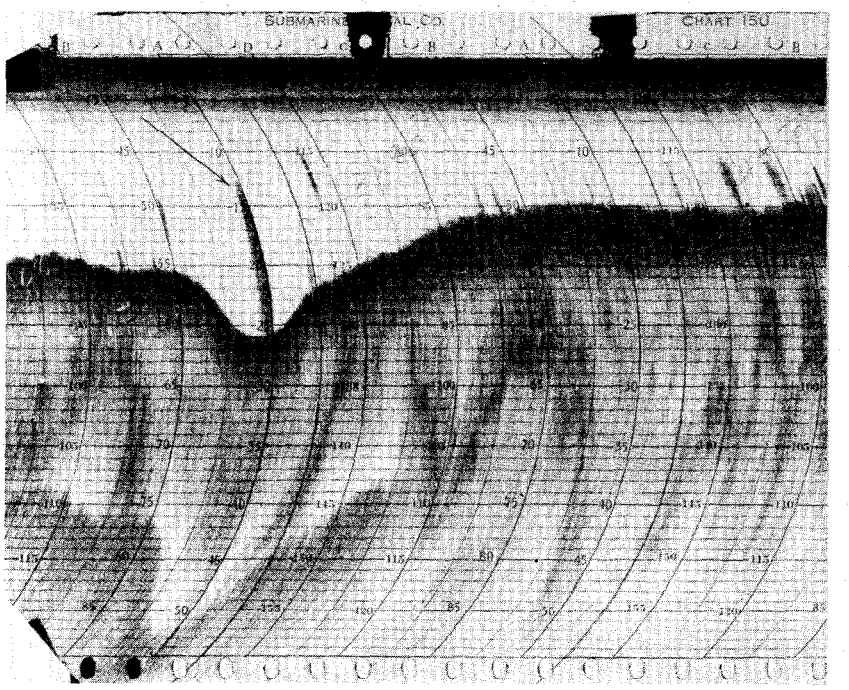

Figure 2. Type 808-fathogram showing several strays. The prominent stray marked by a leader was disproved by a special investigation.

Pseudo-features. Unusual shapes not formed by nature but caused by movement of the sounding vessel or improper fathometer operation. Examples are momentary increase or decrease in the speed or gain of the fathometer (Fig. 3), vertical motion or roll of the sounding vessel caused by waves or swells (Fig. 4), and change in course of the sounding vessel (Figs. 4 and 5).

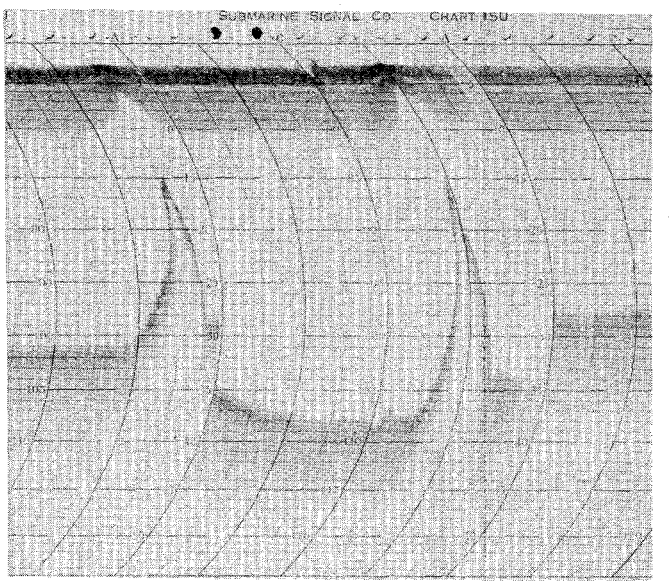

Figure 3. Type 808-fathogram showing pseudo-shoals caused by a temporary slowing of the fathometer speed.

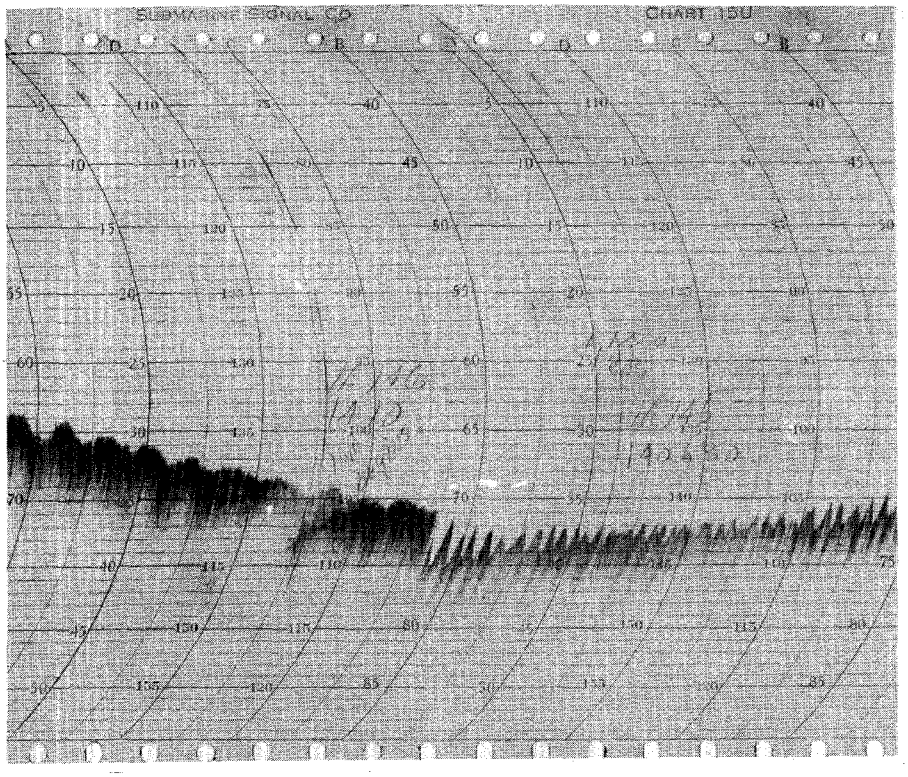

Figure 4. Type 808-fathogram showing pseudo-sand wave patterns caused by a ground swell raising and lowering the sounding vessel.

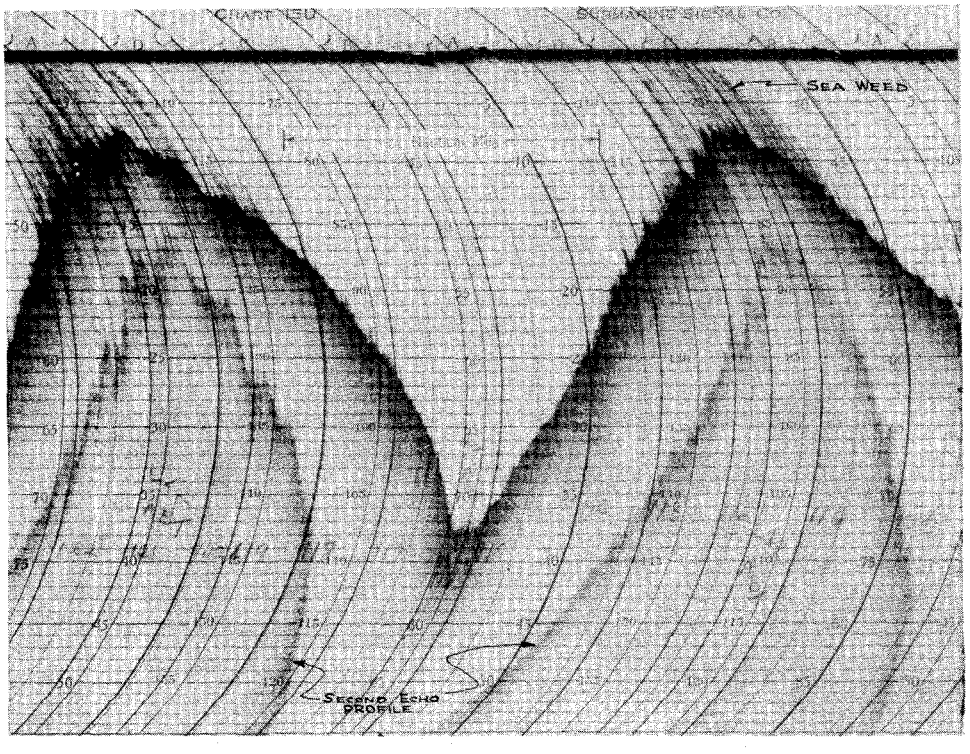

Figure 5. Type 808-fathogram showing an apparent submarine valley caused by a sounding vessel reversing its course while sounding over a descending slope.

Referring to the pseudo-sand wave patterns in Figure 4, the waves of a rolling sea consist of a series of alternate crests and valleys. However, neither the crests nor the valleys of the waves represent the mean water level. When sounding under such conditions, the fathogram profile resembles a non-existent sand wave bottom. In addition, the patterns recorded are just the reverse of the actual wave patterns raising or lowering the sounding vessel. It can be appreciated that when the sounding vessel is momentarily riding the crest of a wave, the vessel has risen above the mean water level. Consequently, the echo returns received during this brief period are too long and are recorded on the fathograms as the bottom of the valley shapes. Conversely, when the vessel lies in the trough of a wave, the vessel is below the mean water level. In this instance, the echo returns are too short and are recorded as the crests of the waves shapes. When recordings of the above pseudo-features are made, soundings should be scaled from the means of the crests and valleys. This can best be accomplished by sketching a continuous pencil line along the mean and then scaling soundings directly from the pencil line at the desired time intervals.

The shapes of the pseudo-features on the left and right portions of the fathogram (Fig. 4) are contrasting. In the latter portion, the patterns resemble the sharp teeth of a carpenter's saw because the vessel is heading directly into the oncoming waves. In other words, the direction and velocity of both the waves and the vessel are opposed. Consequently, the period of the recorded pseudo-wave with respect to the movement of the vessel is at the minimum. In the left portion of the illustration, the patterns are gently undulating because both the vessel and the waves are traveling in the same direction. Consequently, the periods of the pseudo-wave patterns are approximately double the periods shown in the right half of the illustration.

The valley pattern in Figure 5, is termed a pseudo-valley because, at first glance, it mistakenly resembles a submarine valley. This fathogram was obtained in a locality where the vessel's sounding courses consisted of a pattern of parallel lines laid normal to and over a sloping bottom area. When the vessel reverses its course while over the lower portion of the slope, the apex of the bottom of the valley pattern is formed. The flat portion of the valley pattern is caused by the vessel momentarily running at right angles to the descending slope while making a U-shaped turn to obtain position on the next parallel sounding line. Similarily, while reversing the course of the vessel when over the upper portion of the bottom slope, an apparent shoal pattern is formed. It is evident, therefore, that the resemblances to shoal and valley patterns in this illustration are purely superficial. The fathogram, however, portrays a correct echo profile of the bottom with respect to the course of the sounding vessel.

Conversion to true depth. When the slope of the bottom is determined with sufficient accuracy, echo soundings received from the bottom slope can be converted to true depth by use of the formula:

$$h = e / \cos \theta$$

in which h represents the depth under the vessel, e is the echo depth received from the slope, and θ is the angle between the slope and the horizontal.

Measuring sediment. One of the advantages of supersonic equipment is its ability to penetrate and measure deposits of soft mud bottom (Fig. 6). These deposits vary as to content and

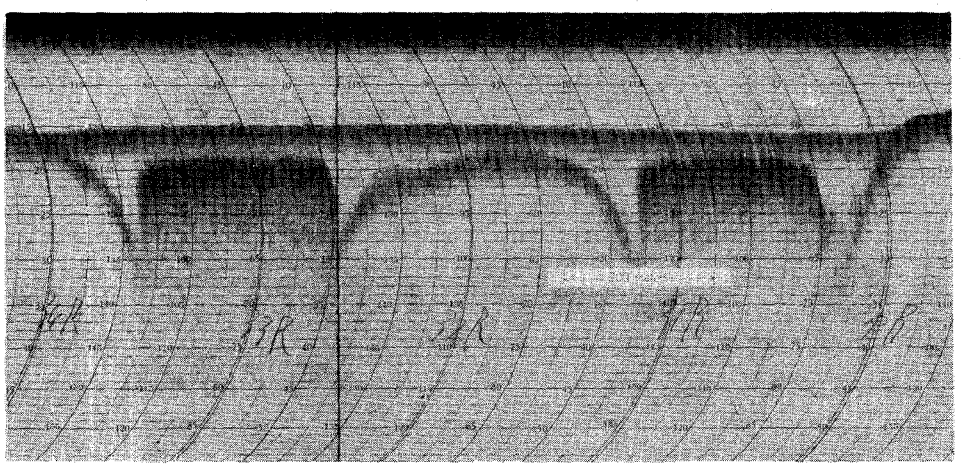

Figure 6. Type 808-fathogram showing soft mud bottom in the Choptank River, Maryland. The maximum thickness of the sediment is about 14 feet. Soundings are read on the 0-to 55-foot scale.

range from material in suspension to material with a high degree of compaction. The maximum thickness of such deposits measured by the U. S. Coast and Geodetic Survey is about 90 feet.

The velocity of sound in areas of sedimentation has not been determined and will vary with the nature of the particles comprising the sediment. Because of the increased density of the sediment, the velocity is assumed to be greater than in sea water, and therefore the sediment thickness will be slightly greater than that recorded.

JOHN A. MORRISON.* I would like to preface my remarks with two clarifying statements. In the first place I lay no claim to being a sedimentation man, nor am I a civil engineer or a topographic or hydrographic surveyor, so that I am but ill prepared to discuss the general scope of Mr. Fry's excellent paper. However, I am an electrical engineer and my career in that field has included many years both in commercial organizations and in the Government service in the design of electrical instruments. In the second place I want to make it perfectly clear that while I have, as a Government employee, worked with all of the commercial concerns which are currently engaged in the production of sounding machines, and have had no small part in the design of nearly all models now in service, including that used by Mr. Fry, I hold no brief whatever for any manufacturer. Therefore, if I indicate a preference for the product of one manufacturer, that preference is based upon merit and upon the ability of the machine to out-perform all others for the application under consideration. The preference is based upon extensive design and field experience, and the facts are presented to you in order that all of you may be spared the expense and the growing pains which are ever the lot of the pioneer.

The use of sound in either the audible or inaudible ranges, or as they are technically termed, the sonic or supersonic ranges, in the measurement of depths of water, when reduced to its fundamentals becomes simply a matter of measuring time intervals. The fact that these measurements must be quite precise is necessitated by two factors, namely the rapidity with which sound travels in water, and the relatively short distances involved in river, harbor and reservoir surveys.

Both factors lead to split seconds in terms of time. There are several reasons for employing supersonic frequencies rather than those in the sonic range, but sound velocity is not one of them, for the velocity does not vary with frequency. However, sound velocity does vary measurably with water temperature, to some extent with dissolved solids in the water (often termed salinity), and slightly with pressure. Extreme variations may amount to as much as 200 ft/sec between warm fresh water and cold sea water (roughly 4,750 to 4,950 ft/sec).

Assuming a velocity of 4,800 ft/sec, then in one-hundredth of a second a distance of 48 feet will be covered, so that time errors of that magnitude may not be tolerated. Therefore, an accuracy of 6 inches when converted to time units represents a time interval of 1/10,000 of a second. This is really splitting a second, and yet in sounding for dredging operations and for sedimentation surveys, accuracy and precision are of vital importance if a reliable picture of conditions is to be presented.

In the larger harbors, where great volumes of water are involved, perhaps the water temperature may not vary widely, but in reservoirs, especially where depths are shallow and water velocities are low, the temperature factor may loom large, indeed it may exceed the allowable accuracy. For this reason alone an accurate means of temperature compensation is imperative.

The Corps of Engineers has since 1938 spent much time upon the investigation of the various phenomena connected with supersonic methods as applied to hydrography. Considerable time and effort have been applied to the design of recording instruments for shoal water applications, which fall into the same category as those of reservoirs. These applications are quite different from those of navigation, of the fisheries, and others of the deep seas where the greater accuracies are not required. The deep sea market is much larger and therefore more attractive to the manufacturer, but the limited shoal water market is the one to test his skill and ingenuity.

The three portable recorders known as NK-2, ES-114 and ES-123, manufactured by Bludworth Marine of New York, have been designed, in cooperation with Corps of Engineers personnel, specifically for the survey field, involving rivers, harbors and reservoirs, and they meet the exacting requirements of that service. An accuracy of plus or minus six inches in depths to 50 feet is

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* Philadelphia District, Corps of Engineers, Department of the Army, Philadelphia, Pa.

guaranteed. Models NK-2 and ES-114 are no longer available, but the ES-123 is currently available from stock. The use of a pointer type of tachometer, rather than one of the vibrating reed type, has much to do with the superior accuracy of this recorder, for not only has this tachometer considerably greater sensitivity, but it positively will not react to extraneous vibrations, such as those of the propulsion motor. The six inch accuracy guarantee is twice that of any model which is currently available.

In conclusion, the Corps of Engineers continues a lively interest in the design of supersonic equipment in the field of shoal water hydrography, and constant liaison is maintained with every manufacturer in the industry. Advice, cooperation and assistance in this type of hydrography are always available upon request.

CHARLES W. THOMAS.* The objectives of reservoir sedimentation surveys have been presented in an excellent manner by the author, and he has very ably described the method currently employed by his agency in the conduct of the surveys. Mr. Murray and Mr. Morrison have contributed greatly to the subject by describing other methods with particular reference to echo-sounding equipment.

Considerable thought should be devoted to one paragraph in the original paper, particularly, by individuals who are concerned with conducting reservoir sedimentation surveys.

"Considering the large number and importance of reservoirs both large and small throughout the country, the over-all magnitude of reservoir sedimentation determinations is sufficient to justify the development and use of methods which will give desired results both accurately and economically."

In other words, the problem is of such magnitude that it merits the concerted cooperative effort of all concerned, even to the extent of joint purchase of equipment.

Further development of presently employed methods is dependent upon improvement of present equipment, production of new equipment, and the possibility of adapting to the problem equipment designed for other uses.

Hydrographic surveys are three dimensional. A sounding represents a vertical dimension which might be located in the horizontal plane by two coordinates. Hence, in addition to the sounding, there must also be position finding, or horizontal control of the survey. In recent years, depth measurements have been made with supersonic equipment. The operation of this equipment has been described previously. The continuous graphical recording of depth by electronic sounders has greatly increased the need for some means of automatically determining position. However, the development of such equipment has not been consistent with the development of sounding devices.

Horizontal control for hydrographic surveys now being generally employed may be divided into two categories: (1) established methods utilizing mechanical survey and navigation instruments, and (2) experimental methods employing electronic equipment. The positioning of soundings is ordinarily accomplished by a direct, or indirect measurement of angles and distances, using instruments normally employed in topographic surveys, or navigation. The methods of application have necessarily been modified.

The electronic methods of horizontal control now being used to a limited extent in hydrographic survey work were designed principally for war or aeronautical use, but the basic principles upon which they operate permit conversion to civil use. Since applications to war effort differ from peace-time applications, new procedures must be established for securing and interpreting the data. These procedures have been established to a limited extent, and preliminary applications indicate greater accuracy may result than that attained by purely mechanical means.

Methods of position finding, depending on visual means are not operational during inclement weather and periods of poor visibility. This causes considerable loss of time to survey parties working in coastal areas, but should be a somewhat lesser problem on reservoirs located inland. One particular advantage of the electronic devices is that they will remain operational in fog and during other periods of low visibility.

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Essentially, all of the electronic position finders now applied to hydrographic surveys are still in the development stage, although Shoran and search-type radar are being employed extensively by the major oil companies on underwater geologic surveys. The cost of such equipment, although justifiable on large surveys, would probably be out of proportion for our ordinary reservoir sedimentation surveys.

Among the electronic systems being used at present is the SCR-584 radar developed by the Army for detecting and tracking hostile aircraft. This equipment has a certain degree of mobility but is mounted on trucks and trailers; hence, is heavy and bulky and not adaptable to movement over rough terrain. It was used on the hydrographic surveys in Galveston Harbor very successfully and accurate results were obtained. The system employes ultra-high frequencies and, therefore, operates on "line-of-sight." The bulk of the equipment is located on shore and a target, or radar beacon, is mounted on the survey boat. The cost of the equipment is approximately $150,000. The availability is questionable, since all radar equipment has been frozen for the needs of the Army. However, it may be possible for Federal agencies to arrange for a loan of the necessary apparatus for experimental purposes. Trained crews are prerequisite for successful operation.

Another type of equipment that has been used on off-shore surveys conducted for oil exploration, is the S08 Navy radar. This equipment is mounted on the survey vessel. The location of the vessel is accomplished by resection from previously located points as viewed on the PPI scope. The accuracy is somewhat less than the shore-based radar, but the equipment is not bulky and is easily installed. This apparatus is available only from Navy surplus or War Shipping Administration, and the cost varies considerably, depending on the condition of the equipment. Highly trained operators are not required.

Shoran, a war development for the control of airborne aircraft, is being used for off-shore surveys and other similar work where relatively long distances are involved. This equipment consists of two or more fixed stations and one mobile station normally located on the airplane or ship. It employs radar frequencies and accomplished measurement of distance by timing the signal for the round trip over the course from craft to ground station. The equipment is very compact and well designed. The accuracy is excellent for long distances. The percentage of error is greater when measuring short distances being in the order of 15 yards. The cost of the equipment, two ground stations and one airborne station, is approximately $30,000.

The British Decca system is, generally speaking, suitable only for large bodies of water. The fixed stations are more of a permanent nature, but the mobile station is quite simple and readily moved about. The cost, including duty, is approximately $160,000.

Other methods employed to a lesser degree are variations of the radio direction finding principle. This type of equipment was not designed to give a high degree of accuracy, but further development might permit adaptation to reservoir surveys.

Photogrammetric methods of position finding are undergoing rapid development, and some system based on this principle may be available in the future.

Probably the most promising equipment for use on reservoir surveys is a recently developed electronic device known as "Raydist." This equipment was developed for determining ground speed of aircraft in flight. It is a highly accurate and sensitive electronic distance measuring system and is applicable to many problems requiring precise determination of position. The system measures relatively short distances accurately and is capable of detecting a 1-inch movement of a small transmitter. It is also capable of measuring the longer distances and is not limited to line-of-sight measurements.

The method accomplishes the equivalent of setting up standing radio waves in space and enables the number of these waves set up within a given distance to be counted. In setting up for the measurement of linear distance between any two points, equipment is placed at two stations located conveniently adjacent to the distance to be measured. A continuous wave transmitter is then moved over any convenient path from a point at one end of the distance to be measured to a point at the other end. A second transmitter heterodynes the moving transmitter and is held at a fixed point in such a way that the heterodyned signals can be received at both ends of the distance to be measured. The signal received at one receiver is then retransmitted to the other point so that the two signals can be mixed. Each beat between these two signals represents a distance traveled by the moving transmitter equal to one-half wave length of its transmitted frequency.

For sedimentation surveys, the pure range system of Raydist may be utilized. In this system, two instruments are required and a continuous indication of distance between the two sets is obtained. If one instrument were located on the end of the range line and the recording instrument carried in the craft, continuous indication of distance along the line could be had.

The contemplated accuracy of this system is 1 inch in a mile, a little better than one part in 50,000. Actual measurements have been made where the error was consistently less than 1 foot in a mile.

The equipment is completely housed in suitcase-type cabinets. The heaviest single unit weighs 32 pounds. The cost of the presently developed Raydist is approximately $20,000, but this should be somewhat less after exact needs are known and production increases.

In closing, I wish to again point out that there is a definite need for an accurate continuous means of position finding. I have reviewed briefly some of the methods of effecting this position finding by electronic devices.

HAROLD W. MURRAY. With respect to horizontal control of surveys by electronic means, the U. S. Coast and Geodetic Survey is using two Shoran installations for control of offshore hydrography. The localities are in the Gulf of Maine and near the western end of the Aleutian Islands, Alaska. The results obtained are most gratifying.

J. W. JOHNSON.* It may be worth mentioning at this time that, in many reservoir surveys, the use of photography in establishing a horizontal control may be more convenient and less expensive than the more conventional methods of triangulation. This method proved extremely valuable in the atomic bomb tests at Bikini in that it permitted the accurate determination of the various ship locations at the moment that the bomb was exploded. Conventional means of locating the vast number of ships was not possible due to the fact that the ships were continuously swinging on their anchor chains. Aerial cameras, of 40-inch focal length, were mounted on towers on the various islands of the atoll and aimed in a horizontal direction towards the approximate center of the explosion. Although the cameras were intended for other purposes than for determining ship location, they proved extremely valuable for this purpose; in fact, an error was discovered in the survey for horizontal control that was made by conventional triangulation methods. It was estimated that this method of surveying is accurate to within 1 in 8,000, which is accurate enough for many reservoir surveys.

COLONEL C. L. HALL.** In the Corps of Engineers we have done quite a lot of work on beach surveys, which is of course a branch of hydrographic surveying, and we have had some experience in the use of "ducks." The whole matter will be reported upon in a report when we finish our experiments. I don't want to go any further now than to say that we think we will produce something on the subject which will be interesting.

(QUESTION) Is that equipment capable of being moved on the highway?

Yes, we moved it from Washington to Pensacola and put it in the water and then went back to Washington with it. It was the same type duck that I saw in the Philippines. We moved it on the highways all right. It was not too wide. We even took the precaution of writing to the State Highway Commissioners of the States we were going through, asking if they wanted an escort on it to carry it through. No escorts were required and we went right along.

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** The Beach Erosion Board, Corps of Engineers, Department of the Army, Washington, D. C.

ANALYSIS AND USE OF RESERVOIR SEDIMENTATION DATA

by L. C. Gottschalk *

Introduction

Prior to 1934 about 40 reservoirs in the United States had been surveyed to determine rates of sedimentation. In that year the Soil Conservation Service began a nation-wide survey to evaluate the effects of accelerated soil erosion on reservoir sedimentation. To date detailed sedimentation surveys have been made on about 200 representative reservoirs and reconnaissance-type surveys on approximately 300 more. In addition, results from nearly 100 surveys made by other Federal, State, and local agencies are available. Thus, sedimentation data now exist on nearly 600 reservoirs in 36 States, more than 5 percent of the total number of larger reservoirs in the country.

Factors Considered in Analysis of Data

Since the beginning of its program, the Soil Conservation Service has been concerned with analyzing these data: First, to obtain a better understanding of the basic factors controlling rates of sediment transportation and deposition; and, secondly, to develop procedures for useful application of the data to determine sedimentation damages and methods of control of sedimentation in existing and proposed reservoirs. Much work still remains to be done. Different methods of analysis are still being tested. From the results so far obtained, however, certain conclusions can be drawn. It is the purpose of this paper to point out the relative effects of some of the more important factors that need to be considered in the analysis and interpretation of reservoir sedimentation data and to outline briefly methods for applying the results.

The rate of silting of a reservoir depends upon its capacity, the quantity and nature of sediment delivered to it, and its ability to retain sediment. Some watersheds produce an abundance of sediment, while others of equal size do not. In some cases, sediment remains in suspension for long periods of time and is carried entirely through the reservoir and over the spillway. In others, it may be deposited almost immediately near the head of the reservoir. Some sediment deposits compact readily whereas others compact slowly. Reservoirs of equal size but of different use may trap sediment at different rates.

In analyzing reservoir sedimentation data, such factors as period of record, nature of reservoir operation, occurrence of density flows, watershed characteristics, capacity-watershed ratio of the reservoir, nature and specific weight of sediment, and precipitation and runoff should be considered. It is desirable, of course, to have long periods of records. Estimated long-term rates from sedimentation records of less than ten years generally are not dependable unless adequate inflow or precipitation records are available for making adjustments.

It is essential that the period of record be continuous. If gates in a dam have been kept open for long periods of time or if the dam has been breached so that considerable sediment has been sluiced out of the reservoir, the sediment that remains will not give a reliable measure of the total amount of sediment brought into the reservoir. Some operators make it a practice to open bottom sluices during periods of heavy sediment inflow. Plans are being made at present to develop operating schedules at some reservoirs to vent the maximum quantity of density flows in order to reduce the rate of sediment accumulation. Some operators draw down their reservoirs completely in attempts to desilt them. This not only sluices sediment from the reservoir but also increases the specific weight of remaining sediment by exposing it to aeration. Normal reservoir operation and seasonal draw-down cause minor redistribution and exposure of sediment to aeration. This, however, does not appreciably increase the density of sediment except in delta areas. The results of sedimentation surveys of reservoirs from which sediment has been partially removed by desilting practices or breaching of the dam are not comparable to results from surveys of reservoirs where no sediment has been removed other than by normal spillway losses, and cannot be considered on the same basis unless adjustment can be made for the quantity of sediment removed.

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Density flows have been observed in a number of reservoirs in the United States, particularly in the Southwest. It is suspected that they occur in many reservoirs. Usually they are not taken into account in analyses because of lack of quantitative data. In some reservoirs the amount of sediment transferred out by density flows may represent a significant proportion of the incoming load.

The quantity of sediment delivered to a reservoir depends on the rate of gross or absolute erosion in the watershed and the ability of the stream system to transport eroded material to the reservoir. The rate of gross erosion depends on climatic conditions, nature of the soils, slopes, topography, and land use. The ability of a stream system to transport eroded material to a reservoir depends on the hydrophysical conditions of its watershed. Not all of the material eroded from upland areas in a watershed is delivered to the reservoir. Part of it comes to rest at the base of slopes, on the stream flood plains, in upstream reservoirs, in stream channels, and as above-crest deposits within the reservoir area itself. In the analysis of reservoir sedimentation data only the net erosion, or quantity delivered to the reservoir, is considered. This is determined by measuring the volume of sediment in the reservoir and measuring or estimating the amount lost over the spillway. The annual net erosion is popularly referred to as the rate of sediment production.

In most of the analyses made by the Soil Conservation Service, the data are grouped according to a problem area. This is done in an effort to keep soil, slope, and topography, which are difficult to measure, more or less constant. Generally it has been found that on this basis the two measurable factors, net drainage area and land use, are the most important watershed factors affecting rates of sediment production.

The net drainage area is the sediment-contributing area. Excluded are areas above upstream reservoirs that intercept the sediment load and the main reservoir area, which does not contribute sediment to the reservoir.

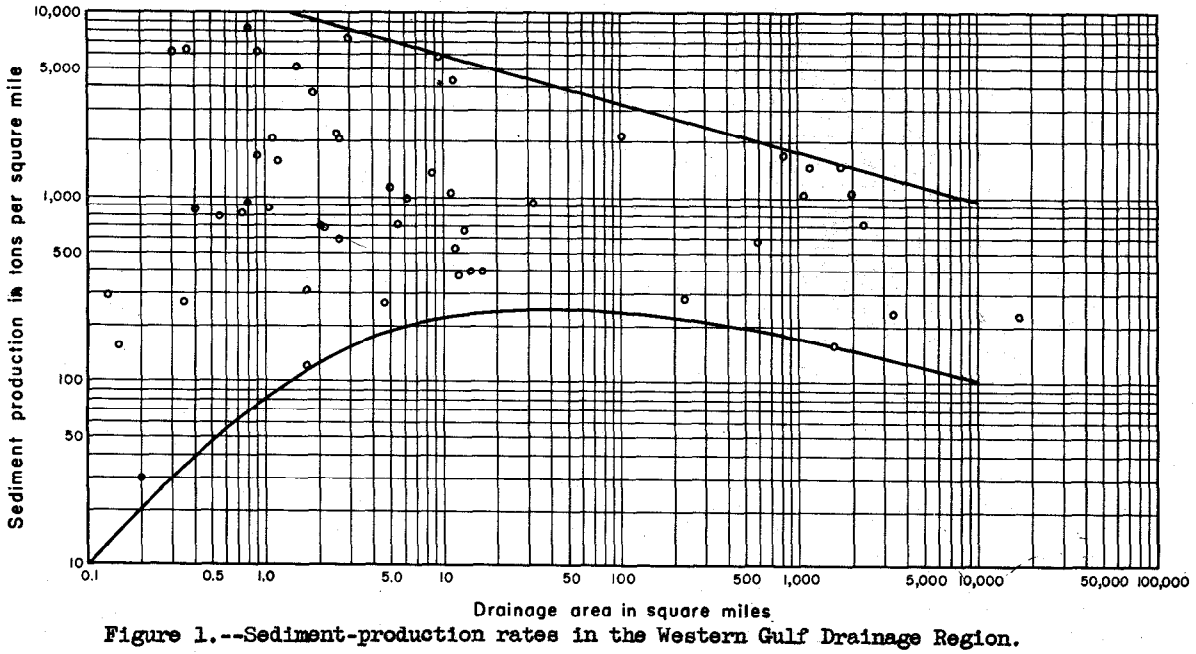

Figure 1.--Sediment-production rates in the Western Gulf Drainage Region.

Rates of sediment production per unit of area vary with the size of the net drainage area. As a general rule, the average rate of sediment production decreases as the size of the drainage area increases (See Figure 1). Also, the larger the watershed, the less is the variation between rates. The mean rate of sediment production decreases in much the same manner as runoff per unit of area decreases with increase in size of watershed. Also the larger the watershed, the greater the opportunity for deposition between the point of origin and the reservoir. Very high and very low rates of sediment production per unit area are found generally on very small watersheds. This is because a shorter distance of transportation gives lesser opportunity for deposition above the reservoir and because land use becomes increasingly important the smaller the watershed. A very small watershed may be entirely in forest or as much as 80 to nearly 100 percent in cultivation. The forested watersheds may produce extremely low rates of sediment production

while the cultivated watersheds may produce extremely high rates. In larger watersheds land use tends toward greater uniformity with less variation between rates of sediment production.

Not much study has been given to the effects of land use on sediment production from areas larger than plot size. Effects of land use on rates of silting show up in reservoir sedimentation data but are often masked by other factors and have not yet been critically evaluated. In order to evaluate these effects, resurveys are needed on a number of reservoirs where land use adjustments have been made in the watersheds since the original sedimentation surveys were made.

The ratio between the capacity of a reservoir and the size of drainage area has an important bearing on the rate of silting of a reservoir. It is obvious that with a given sediment volume, a reservoir having twice the capacity of another will have only half the rate of capacity loss due to sedimentation. The smaller the capacity-watershed ratio, the greater the rate of silting, all other conditions being equal.

The capacity-watershed ratio also provides a clue to the trap efficiency of the reservoir. The trap efficiency, or effectiveness of a reservoir to retain sediment, has been found to be one of the most important factors involved in sedimentation.

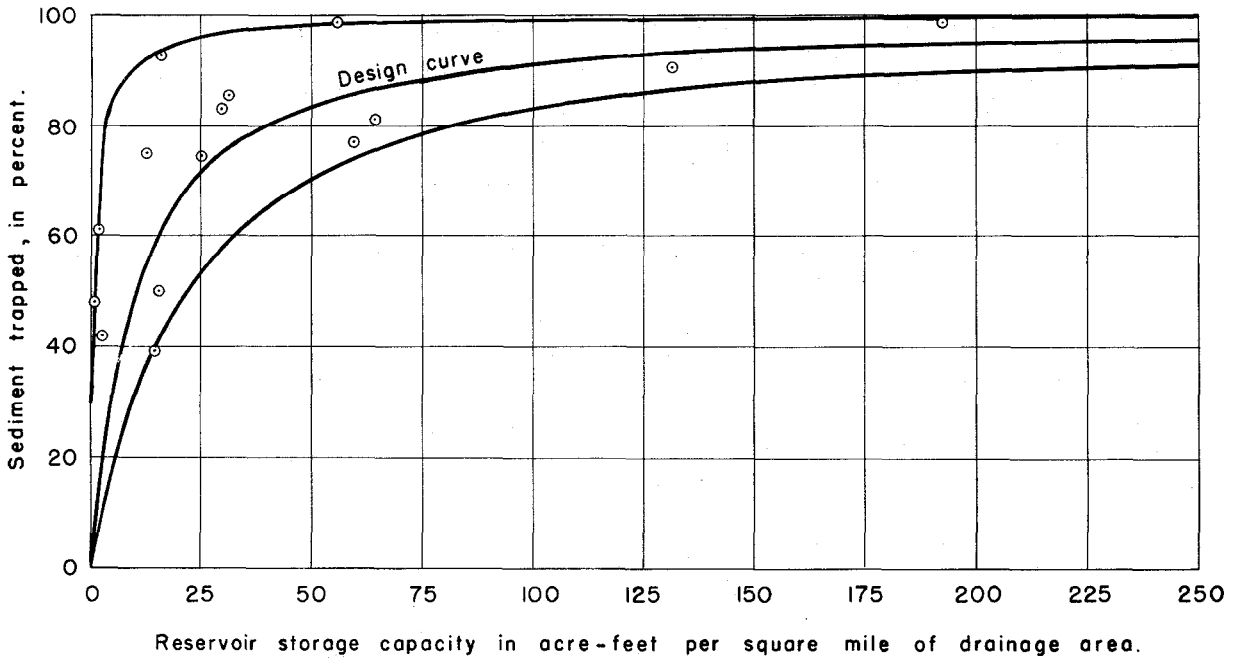

Figure 2.--Relation of reservoir trap efficiency to the capacity-watershed ratio.

By plotting all the measured soil-loss data in various watersheds against rate of silting of reservoirs in these same watersheds and by analyzing sediment-outflow records of various reservoirs, a general trap-efficiency curve has been developed which is useful for estimating the percentage of total sediment trapped in a reservoir, depending on its capacity-watershed ratio 1/. In general, a reservoir with a capacity-watershed ratio of 100 acre-feet or more per square mile will trap 96 percent or more of the incoming load. The trap efficiency gradually decreases in the range of 100 down to about 30 acre-feet per square mile, and from this point it diminishes rapidly to zero. On the average, a reservoir with only 30 acre-feet of storage per square mile will trap about 75 percent of the incoming load; one with 15 acre-feet per square mile will trap about 60 percent; and one with 5 acre-feet will trap only about 30 percent of the total incoming load.

The capacity-watershed ratio of a reservoir is used in place of capacity-inflow ratio because inflow data are usually available only for larger streams and major reservoirs. The assumption that the two are comparable is not strictly valid. For example, a reservoir in an arid or semi-arid region may have a low-capacity-watershed ratio yet not receive enough inflow in any one year to cause water to be discharged over the spillway. In contrast, the volume of mean annual

1/ See "References" at close of comments.

flow from a watershed of equal size in a humid area may be equivalent to 25 times that of a reservoir having the same capacity-watershed ratio. In the drier region 100 percent of the incoming sediment load is trapped, whereas in the humid area possibly only 70 percent is trapped.

Geology, topography, soil, and climatic conditions affect the nature as well as the quantity of sediment delivered to a reservoir. Where parent materials are shales or limestone, sand content of sediment is low. Where parent material is mainly sandstone, sand content may be high. Some igneous and metamorphic rocks produce fine sediment under some climatic conditions and coarse material under others. Sediments derived from Piedmont areas in the southeastern United States contain much clay and colloidal material. Sediments derived from loessal soils in the Midwest have a high silt content. The West Cross Timbers area of Texas, with sandy soils and poorly consolidated sandstone substrata, provides sediment with high sand content. Sand and silt settle out rapidly in reservoirs. Clay may settle out rapidly or be held in suspension for long periods because of the temperature or chemical nature of the water in which it is suspended. Its environmental origin has a definite bearing on the nature of the sediment transported to a reservoir, and the nature of the sediment has a direct bearing on the percentage of total load deposited in the reservoir and on the ultimate volume of deposited material.

The specific weight of sediment is an important factor in estimating the life of an existing reservoir and in estimating rates of sediment production which are generally expressed on a weight basis. Laboratory analyses have been made by the Soil Conservation Service to determine the specific weight of sediment in numerous reservoirs throughout the country. These analyses show variations in the dry weight of sediment ranging from 20 to 117 pounds per cubic foot, depending on the nature of the sediment and whether or not it had been exposed to aeration. Factors affecting the specific weight of sediment in a reservoir, including age, nature of sediment, and reservoir operation, have been discussed in detail by Lane and Koelzer 2/. In previous studies of the specific weight of sediment, sediment thickness as a factor has not been adequately evaluated because of lack of quantitative information. This is due mainly to lack of suitable equipment for taking undisturbed core samples of more than the upper two or three feet of sediment in a reservoir.

The relationship of the specific weight of sediment to depth is illustrated by an experiment conducted by the Soil Conservation Service at Greenville, S. Car., in 1939-1940. A measured quantity of sediment, about 2,700 grams, was allowed to settle in a $22\frac{1}{2}$-foot, transparent, calibrated, water-filled Lucite tube 6 inches in diameter. Each second or third day an equal portion was added and each successive layer separated from the preceding layer by a marker strata of fine sand. Over a period of 126 days, 36 separate layers of sediment were added to the tube, resulting in a total depth of sediment of nearly $13\frac{1}{2}$ feet. By knowing the approximate dry weight of each layer of sediment and measuring the volume occupied in the calibrated tube, the approximate specific weight of each layer could be determined. The relationship between specific weight and depth of sediment is shown in Figure 3. This relationship may be expressed by the empirical formula:

$$\rho = 22.05 + 1.09d + 0.00129e^{0.695d}$$

where ρ = specific weight of sediment, in pounds per cubic foot
d = Depth of sediment, in feet
e = Base of natural logarithms.

If the vertical distribution of the specific weight of sediment in a reservoir is similar to that in a Lucite tube, then determinations of the average specific weight of sediment in a reservoir based on analyses of samples taken from the upper two or three feet are erroneous.

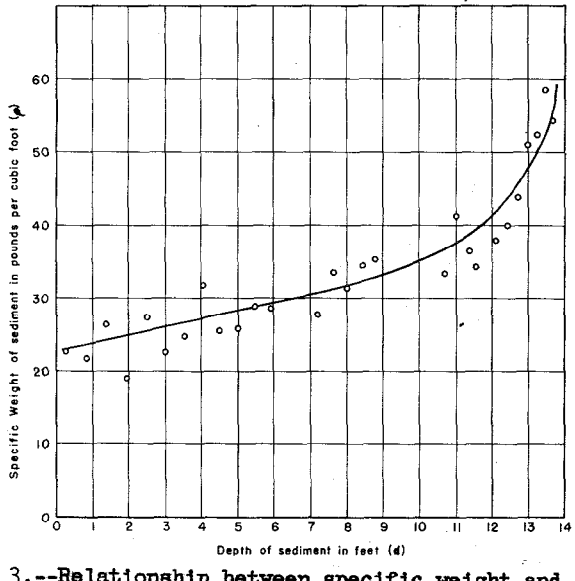

Fig. 3.--Relationship between specific weight and depth of sediment in 6-inch Lucite tube, Greenville, S. Car.

2/ See "References" at close of comments.

An analysis of reservoir sedimentation data, particularly where the period of record is short, should include an analysis of precipitation or discharge data to determine the adequacy of the sedimentation data for estimating long-term rates. If the period of record is short the results might be misleading, particularly if sedimentation occurred during a period when inflow was abnormal, either above or below average. Discharge records should be used when available. Accumulative-difference curves may be plotted to determine the position of the sedimentation record in relation to cyclic changes in discharge. Graphs showing departure of monthly discharge from the mean are helpful in estimating long-term rates since seasonal variations are readily apparent from these charts. Where discharge records are not available, it becomes necessary to use precipitation records instead. The use of either precipitation or discharge records for forecasting rates of sedimentation is only approximate, but they are helpful in extrapolating data from short records. Considerable work remains to be done in development and refinement of methods for adjusting short-term sedimentation records in terms of the longer runoff and preceipitation records for a particular watershed or locale. Studies made to date indicate that sedimentation rates, in general, will be accelerated in the next 40 or 50 years.

Presentation of Results of Analyses

When an analysis of a mass of complex reservoir sedimentation data is completed the results should be presented in some simple usable form for practical application. This may be in the form of curves, nomographs, charts, or formulas. Because of the lack of refinement of data and the numerous variable factors involved in sedimentation, it is difficult to develop single curves or formulas to adequately express sedimentation on a watershed or regional basis. Often envelope curves are drawn for this purpose. These show certain well-defined minimum and maximum expected rates for various watershed areas. From these the mean and design curves may be interpolated.

Attempts have been made from time to time to develop empirical formulas for expressing rates of silting of reservoirs on a watershed or regional basis. Reasoning indicates that the compound discount formula might be used to explain rates of sediment accumulation in reservoirs. Not enough work has yet been done, however, to evaluate the relative effects of such factors as density currents, capacity-watershed ratio, specific weight of sediment, and watershed characteristics in order to fit them into this type of formula.

Some progress has been made in analyzing sedimentation data by multiple-linear and curvilinear regressions. The use of multiple regression to estimate rates of sedimentation in a number of Government-owned stock-water ponds and reservoirs in a 327-square-mile area near Pierre, S. Dak., showed very good results 3/. In this study it was necessary to determine sedimentation damages to 43 Government-owned stock ponds. In the time allotted for field investigation, detailed sedimentation surveys could be made on only 18 ponds. A multiple regression was made to determine the function of various factors related directly or indirectly to sediment accumulation. Analysis of the results provided a formula which covered 93 percent of variability in sediment accumulation as expressed by the standard deviation. This formula was used for estimating the sedimentation damages to the other ponds in the area.

Use of Reservoir Sedimentation Data

The results obtained from a sedimentation survey of a particular reservoir are used: (1) For determining the prevailing and probable future sedimentation damages to that reservoir, (2) for determining the most effective and economical control measures needed to reduce the rate of sedimentation of the reservoir, and (3) in combination with results from other reservoir sedimentation surveys and suspended-load measurements, for preparing regional indices of sediment production.

The measurement of the volume of sediment in a particular reservoir provides the basis for determining the rate of silting of that reservoir up to the date of survey. To project this rate into the future requires adjustment for changing trap efficiency and the specific weight of deposits. Progressive deposition of sediment reduces the trap efficiency of the reservoir until it approaches zero when the capacity of the reservoir is exhausted. On the other hand, progressive increase in thickness of superincumbent deposits increases the specific weight of underlying sediment, thus reducing the volume occupied by a given weight of sediment. More research on both trap efficiency and specific weight of sediment is needed to better enable us to approximate the expected rate of silting of an existing reservoir in say 10, 50, or 100 years. Heretofore it has been necessary to assume that trap efficiency and changing specific weight counter-balance each other and, consequently, the rate of silting progresses at a constant rate until the storage

3/ See "References" at close of comments.

capacity is depleted.

Maximum depletion of the storage capacity of a reservoir varies from one region to another in accordance with the relation of the original capacity to the channel volume required to carry the normal base flow of the stream through the reservoir reach. When the original capacity is reduced to this volume, no further net loss occurs and the capacity, in effect, is exhausted. Studies by the Soil Conservation Service indicate that the residual volume ranges from 1 or 2 percent to about 20 percent of the original capacity except for reservoirs of very low capacity-watershed ratio. Often a reservoir loses most or all of its usefulness long before maximum depletion of total storage occurs.

Although it is of interest to know the approximate date of maximum depletion of storage, it is more important, from the standpoint of evaluating sedimentation damages, to determine when sedimentation begins to encroach on the dependable storage capacity. The dependable storage capacity of a reservoir is that part of the usable capacity which is needed during periods of sustained low flow to offset consumption requirements and seepage and evaporation losses. Determination of the dependable storage capacity requires an analysis of runoff, evaporation, and seepage data as well as an analysis of water-consumption records. An economic study of damage by sedimentation to reservoirs in the Trinity River Basin in Texas 4/ showed that the dependable storage capacity of 23 reservoirs, built mostly for water-supply purposes, ranged from 38 to 85 percent of the total storage capacity.

Analysis of water-consumption records in many cities in the United States shows progressively increasing demands for water resulting from increase in area and population served and industrial expansion. To meet these demands a progressively increasing dependable storage capacity is required. When sedimentation reduces the capacity of a reservoir so that the dependable storage is not sufficient to supply primary services, then new sources must be developed to avert a serious water shortage. A recent analysis of water-consumption records at Decatur, Ill. 5/, for example, showed that, as of 1946, the dependable storage capacity of the water-supply reservoir for that city amounted to about 48 percent of the original storage capacity. At the 1936-1946 average rate of silting determined by a recent survey, loss of usable storage will become critical by 1956. After that date, the usable storage will become progressively less than the dependable storage required. If no sedimentation had occurred, the present lake would have been adequate to meet the needs of increased consumption until the year 2000. This type of analysis has been used to determine sedimentation damages to other water-supply reservoirs and to stock ponds and in principle can be applied to reservoirs designed for irrigation, power, and flood control storage as well.

The results of a sedimentation survey of a particular reservoir may be used for determining the control measures justified for reducing the rate of sedimentation of the reservoir. Reduction in the rate of sedimentation of certain types of reservoirs can be effected solely by conservation practices. In others, because of the rapid rate of silting and delay in installing conservation programs, by-pass channels, sluicing, dredging, etc., are required. In still others, where rates of silting are low, negligible benefits accrue, according to conventional economic thinking, from either conservation practices or other methods. The method of determining proper control measures has been discussed by C. B. Brown 6/ elsewhere. It includes an analysis of the following conditions:

1. The rate, character, and sources of sediment production from the watershed.

2. The effect of capacity-watershed ratio on rate of silting.

3. The relative value of dam sites as determined by their abundance and demand for the services which their utilization can produce.

4. The economic pressure of the discount rate in computing benefits from sedimentation control.

5. The time required for application of soil conservation practices, the costs involved, and results to be expected from watershed treatment.

By proper analysis of data and using the criteria established by Brown, determination can be made of the proper type of measures to use for reduction in the rate of sedimentation of a reservoir.

4/, 5/, 6/ See "References" at close of comments.

Regional indices of sediment-production rates useful for estimating sedimentation damages to reservoirs, canals, ditches, etc., can be developed by combining all known sedimentation data, including suspended-load measurements, from a particular watershed or region. The importance of reservoir sedimentation surveys for determining regional indices has not been fully realized. Where investigations are made specifically to determine regional indices, emphasis is placed on selecting reservoirs for survey which provide representative sampling of the principal variants within the region. Reservoir surveys have an advantage over suspended-load measurements in that sedimentation data covering longer periods of record can be obtained. The average period of record for reservoirs on which the Soil Conservation Service has made detailed sedimentation surveys is about 14 years. It is not possible to measure past rates of sediment production with current suspended-load measurements. Except on a very few of the larger streams in this country, suspended-load measurements usually cover only a few years of record.

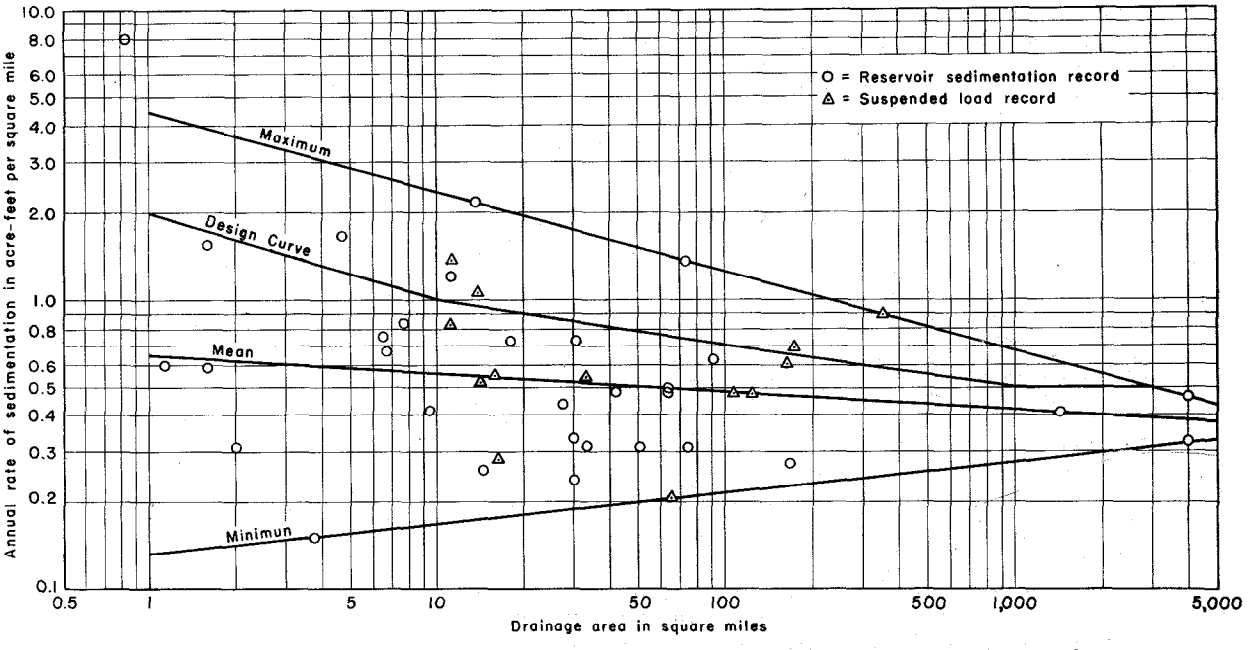

Fig. 4.--Relation of rate of sediment production to size of drainage area in the Southern Piedmont.

Indices of rates of sediment production are usually prepared in the form of envelope curves from which the minimum, maximum, and mean rates and the design curve can be determined (See Figure 4). Such curves have been widely used for estimating extent of sedimentation damage in existing and proposed reservoirs in connection with U. S. Department of Agriculture flood-control surveys. They have been supplied to other agencies and to private organizations for determining silting factors in connection with the design and maintenance of flood channels, drainage ditches, and other water-control developments.

Conclusions

There is a definite need for additional reservoir sedimentation data in many parts of the country for determining rates of sediment production under different climatic, watershed, and reservoir conditions. Particularly there is a need for additional research on such factors as trap-efficiency, specific weight of sediment, and land use. By proper analysis, interpretation, and correlation of reservoir sedimentation data with other determinable information, rates of sedimentation can be predicted for existing and proposed reservoirs, the effects of such sedimentation on dependent developments evaluated, and the best methods of control determined.

References

1. Brown, C. B. Discussion of "Sedimentation in Reservoirs" by B. J. Witzig, Trans. Am. Soc. of Civ. Engrs., Vol. 109, pp. 1080-1086, 1944.

2. Lane, E. W. and Koelzer, Victor A. "Density of Sediments Deposited in Reservoirs." Report No. 9, Cooperative Research Program, published by St. Paul U. S. Engineer Suboffice, Hydraulic Laboratory, University of Iowa, Iowa City, Iowa. 60 pp. Nov., 1943.

3. Gottschalk, L. C. "Silting of Stock Ponds in Land Utilization Project Area SD-LU-2, Pierre, S. D." U. S. Soil Conservation Service, Special Report 9, 11 pp., illus., processed, Washington, D. C., Oct., 1942.

4. Garin, A. N. and Gabbard, L. P. "Land Use in Relation to Sedimentation in Reservoirs, Trinity River Basin, Texas." Texas Agricultural Experiment Station Bulletin 597, 65 pp., 1941.

5. Brown, C. B., Stall, J. B., and DeTurk, E. E. "The Causes and Effects of Sedimentation in Lake Decatur." Illinois Department of Registration and Education, State Water Survey Division, Bulletin 37, 62 pp., illus., Urbana, Ill., 1947.

6. Brown, C. B. "Aspects of Protecting Storage Reservoirs by Soil Conservation." Journal of Soil and Water Conservation, Vol. 1, No. 1, pp. 15-20, 43-45, July 1946.

DISCUSSION

M. G. BARCLAY.* Mr. Gottschalk has presented a very interesting and informative paper on the analysis and use of reservoir sedimentation data. He has emphasized the need for additional studies, particularly of such factors as trap efficiency, specific weight of sediment, and land use. These are points upon which we can readily agree.

Today, most engineers and conservationists recognize the probable effects and damages that will result from reservoir construction on sediment laden streams. Depletion of effective reservoir capacity by sediment deposition is the outstanding example recognized by both laymen and engineers. Failure to recognize the importance of sediment depletion in the design of reservoirs has resulted in the construction of many with uneconomical life spans. This has reduced the confidence of the general public in reservoir projects as effective and desirable flood control and water conservation measures.

Recognizing the importance of sedimentation, it is paramount that adequate basic data be obtained. As has been pointed out by Mr. Gottschalk, reservoir sedimentation datum is a basic step.

The effect of soil conservation and land management measures upon the reduction of sediment burden of streams has been demonstrated to date on only small watershed areas, but has not been definitely evaluated for larger watersheds. Reliable information on this project is needed so that effects of watershed treatment can be recognized in the design of reservoirs in the future.

Next to knowing how much sediment will accumulate in a reservoir, it is important to know where it will be deposited. It is important from the standpoint of location of recreational areas, and possible relocation of railroads and highways upstream from the reservoir. Also in irrigation and water supply projects, it is important to know if deposition of sediment in a reservoir is likely to change its area-capacity relationship over a period of years of operation. Since evaporation is a function of the surface area of a reservoir, it is essential to be able to anticipate such changes so that reliable forecasts of reservoir yields can be made.

It is only through intensive study of sediment deposition, based upon accurate surveys of reservoirs and upstream areas made at appropriate intervals, that such information can be obtained. In this connection, it is highly essential that accurate maps on an appropriately large scale be made of reservoir sites and upstream areas where sediment deposition may occur prior to or at the time of reservoir construction. Such surveys should be properly referenced by both vertical and horizontal control. Range lines at strategic points should also be established. Although considerable headway has been made in this direction, many reservoirs in the past were either improperly mapped or not mapped at all at the time of construction. This no doubt led to difficulty in obtaining reservoir sedimentation data, and has often resulted in such data being none too reliable.

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* Area Planning Engineer, Bureau of Reclamation, Oklahoma City, Okla.

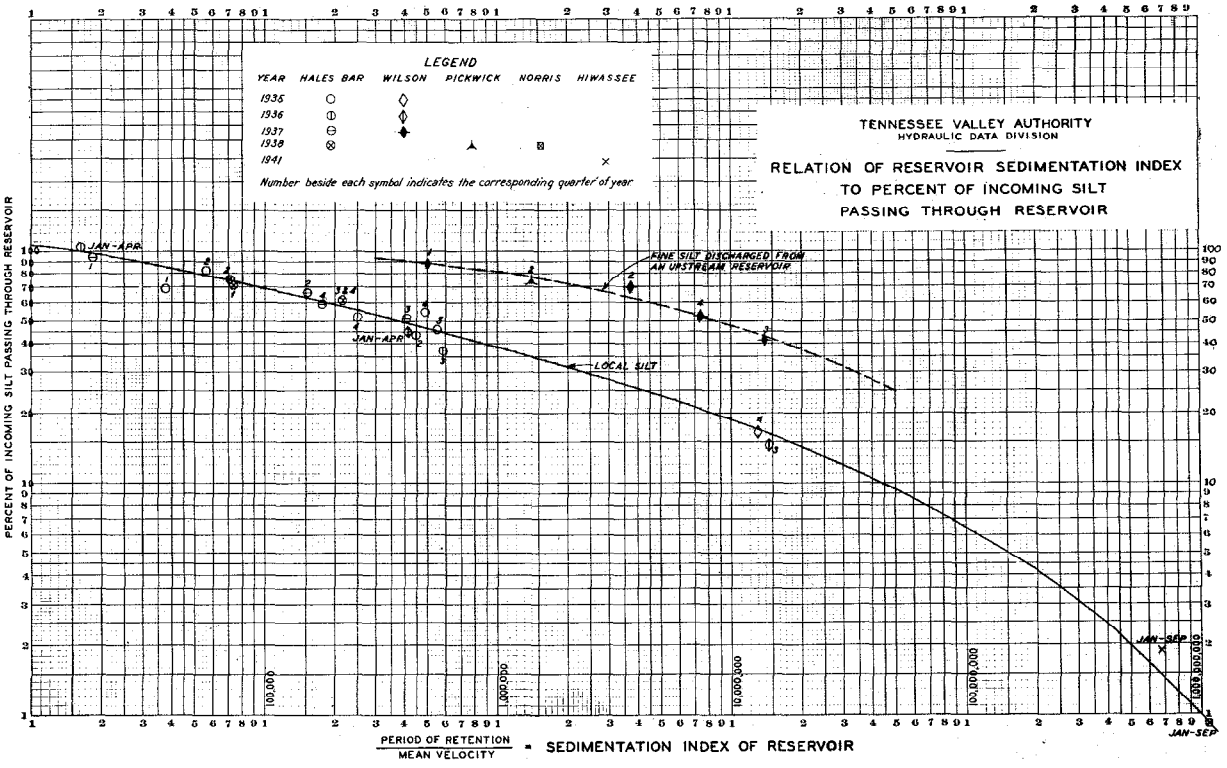
Since accurate basic data is fundamental, steps necessary for obtaining them should be recognized and carried out according to plan. This applies to reservoir sedimentation data as well as any others.

M. A. CHURCHILL.* A considerable portion of Mr. Gottschalk's excellent paper is concerned with the analysis and use of sedimentation data obtained from small reservoirs. As he has stated, stream flow data for these small reservoirs are, in many cases, not available. In such cases, Mr. Gottschalk has used the capacity-watershed ratio of a pool as an index to its trap efficiency in as much as the lack of flow data prevents the use of the capacity-inflow ratio for this purpose.

A somewhat different method of analyzing reservoir sedimentation data has been used by the Tennessee Valley Authority in arriving at a basis for estimating probable future rates of reservoir silting. The majority of Authority reservoirs are relatively large and stream-flow data are rather complete in each case. In an attempt to add to the value of Mr. Gottschalk's paper, the approach used by the Authority will be outlined briefly.

Two sizable reservoirs, Hales Bar and Wilson, were in existence on the Tennessee River for a number of years prior to the creation of the Authority in 1933. The trap efficiencies of these two pools under varying stream-flow conditions have been used as the principal basis for estimating trap efficiences of the other reservoirs in the Tennessee Valley. A certain amount of data on percentage depositions in several other relatively new reservoirs has also been included with the Hales Bar and Wilson information as supporting evidence.

It is apparent that the greater the period of retention in a given pool, and the lower the transit velocity and turbulence, the higher will be the percentage deposition of incoming sediment. The ratio of these two reservoir characteristics, period of retention to transit velocity, has been used by the Authority as a measure of the sedimentation efficiency of a reservoir. This ratio is termed the Sedimentation Index.



* Tennessee Valley Authority, Knoxville, Tenn.

It should be recognized that the Sedimentation Index of a pool is not the same as the capacity-inflow ratio but is this ratio divided by the mean velocity. The capacity-inflow ratio is nothing more or less than the period of retention. Regardless of the period of retention in a basin, if the velocity and resulting turbulence are too high, no sedimentation will take place.

Computed values of the Sedimentation Index for successive periods of time were limited against the measured percentage of incoming silt that passed through Hales Bar and Wilson reservoirs for a number of years, as shown by the lower of the two lines on the accompanying diagram. The upper line on the diagram applies to that portion of the total incoming silt load which is discharged from a main-river reservoir into the one next downstream. Any silt that passes one main-river dam is obviously finer grained that local silt from the same general area but which has not passed through a desilting basin. The TVA system of main-river reservoirs is unique in the respect that the nine pools, one immediately below another, form a chain of lakes some 650 miles in total length. In this system the desilting action of the upstream pools must be taken into account in estimating silting rates for the downstream reservoirs.

As a pool becomes filled with sediment, its Sedimentation Index value is reduced and a greater percent of the incoming load is passed on through. Thus a reservoir is filled with sediment at a continually decreasing rate, assuming that incoming silt loads and stream flows remain unchanged.

In view of the fact that inflows to the reservoir are included in the Sedimentation Index, there is no necessity for flows to be normal during the period when the suspended loads above and below the pools under study for the establishment of the relationship shown on the diagram are being determined.

The method of analysis outlined above has been used to estimate future silting rates for all TVA reservoirs.

The relationship shown between the Sedimentation Index and the percentage of incoming silt that will pass through a reservoir has been established for the relatively fine-grained sediment found in the Tennessee Valley. While the method of analysis is of course applicable to any reservoir, coarser or finer silt will result in a different relationship between the Sedimentation Index and the percentage of silt carried through a reservoir.

GAIL A. HATHAWAY.* Mr. Chairman, Mr. Churchill touched on a question that I feel is somewhat confusing when he mentioned that Mr. Gottschalk's very excellent paper concerned primarily small stock ponds. I would like to raise the question, when does a reservoir cease to be a reservoir and become a stock pond? I personally feel that perhaps the laws of sediment deposition in stock ponds and reservoirs may be somewhat different, and I think that question is something that the Inter-agency Sub-committee should establish a definition for, i.e., define a reservoir and define a stock pond and try to draw a line between the two. Do you care to comment on that, Mr. Gottschalk?

MR. GOTTSCHALK. I am sorry if I implied that all of our data are on stock ponds. Actually of the 600 reservoirs on which we have data not over 5 percent are stock ponds. We have made surveys on some very large reservoirs such as Elephant Butte, San Carlos, and a number of others. A stock pond is considered to be a special type of reservoir just as a water supply reservoir is a special type designed for a particular purpose. The laws of sediment deposition are the same for all types of reservoirs, including stock ponds, but the rates vary in accordance with method of operation and the relative effects of reservoir, watershed and climatic conditions as pointed out in my paper.

VICTOR H. JONES.** I would like to add a brief comment on this question of Mr. Hathaway's about the relationship between stock ponds and reservoirs. I think we can look at this problem as an extension of the curve, or the relationship of variability in sedimentation rates as shown on one of the diagrams that Mr. Gottschalk showed on the screen; namely, the one in which a greater

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** Soil Conservation Service, Ft. Worth, Tex.

variability of sedimentation range is shown for the smaller reservoirs. If we discount the important factor of capacity drainage-area relationship, assuming that may run uniformly in the smaller reservoirs, we should expect to find much greater variability on the same scale as we find greater quantities of sediment production from smaller unit drainages. We are moving up towards the head of the smaller drainage areas and should include more sediment which has moved a relatively short distance. In the larger reservoirs, where the capacity-drainage-area relationship is favorable, we generally find that the range of the sediment contribution annually per square mile of drainage runs from a fraction of unity up to possibly one or two acre-feet per square mile annually, which would be a fairly high rate. In the small reservoirs with a drainage area from a few acres up to a few hundred or thousand acres, we might expect to find, in some cases, four or five acre-feet of sediment contribution per square mile, or conversely, if the drainage area was under good control we would find a low rate. The main point I want to stress is that the smaller the reservoir and unit drainage area the greater variability we may expect. We may find under bad conditions very high rates, and under good conditions very low rates.

EFFECTS OF SEDIMENT ON DESIGN AND OPERATION OF DAMS AND RESERVOIRS

by Albert E. Coldwell *

Introduction

This discussion of effects of sediment on design and operation of dams and reservoirs is based primarily on experience in the Tulsa District of the Corps of Engineers which comprises portions of the drainage areas of the Arkansas and Red Rivers (Exhibit 1). This district includes all the area draining into the Arkansas River between the mouth of Walnut Creek near Great Bend, Kans., and the mouth of the Poteau River at Fort Smith, Ark., except that it extends up the Canadian River only as far as the State boundary between Texas and New Mexico. It includes all the area draining into the Red River above Fulton, Ark. Virtually the entire State of Oklahoma, and portions of the States of Missouri, Arkansas, Texas, Kansas, New Mexico and Colorado are within its boundaries. Important existing projects are Pensacola Dam, constructed by the Grand River Dam Authority, an agency of the State of Oklahoma; Lugert-Altus Dam, under the supervision of the Bureau of Reclamation; and Denison, Great Salt Plains and Fort Supply Dams, operated by the Corps of Engineers. The construction of Canton Dam by the Corps of Engineers has progressed to the point where closure of the river is planned for this summer.

Reports prepared by the Corps of Engineers during the period 1932 to 1936, popularly known as the "308 reports," for the Arkansas and Red Rivers both make note of the sediment problem for these streams.

The Arkansas River report 1/ said: "The construction of channel reservoirs in the principle sand-bearing tributaries, the Canadian, Cimarron and Salt Fork Rivers should be approached with considerable caution. The sand and silt content lessens as one goes downstream, but at their mouths the solid load will probably average 2 percent of the total flows during flood periods." Incidentally, though no special study has been made of conditions during flood periods for which the 2 percent estimate was made, the year-round average sediment content of these streams is now computed as being: Canadian, 0.9 percent; Cimarron, 0.6 percent; and Salt Fork, 0.8 percent.

As another example from these reports, it was predicted 2/ that Denison Reservoir would be half filled with sediment in 150 years. This agrees with present-day estimates indicating a life of almost 300 years for the reservoir actually constructed. It should be noted, however, that the ability of the reservoir to control the peak discharge of large floods will be impaired before the reservoir is entirely full of sediment.

Samples of suspended sediment were collected 3/ from the Arkansas and Red Rivers downstream from the present Tulsa District as early as 1879. The first intensive program within the present district boundaries was carried on in water year 1931 in conjunction with the "308" reports. The collection of suspended sediment samples was resumed on an extensive scale when an expanded stream gaging program was started about 1938. Data obtained from these samples, as well as information about sedimentation in reservoirs on other watersheds, were used in the design of authorized reservoirs.

When preparation of the comprehensive survey report on the Arkansas River was underway in 1942 the question of the effect of Canadian River sediment on navigation was considered important. Use of a dam at the Eufaula site was proposed as a solution, and as the investigations proceeded the advantages of this site for a multiple-purpose flood-control, power and sediment control reservoir became apparent. As a logical extension of these investigations, the proportionate sediment contribution from each tributary above the proposed Arkansas River navigation system was determined (Exhibit 2). This resulted in the consideration of sediment retention dams for the main stem of the Arkansas River, and they are included in the multiple-purpose plan authorized by Congress.

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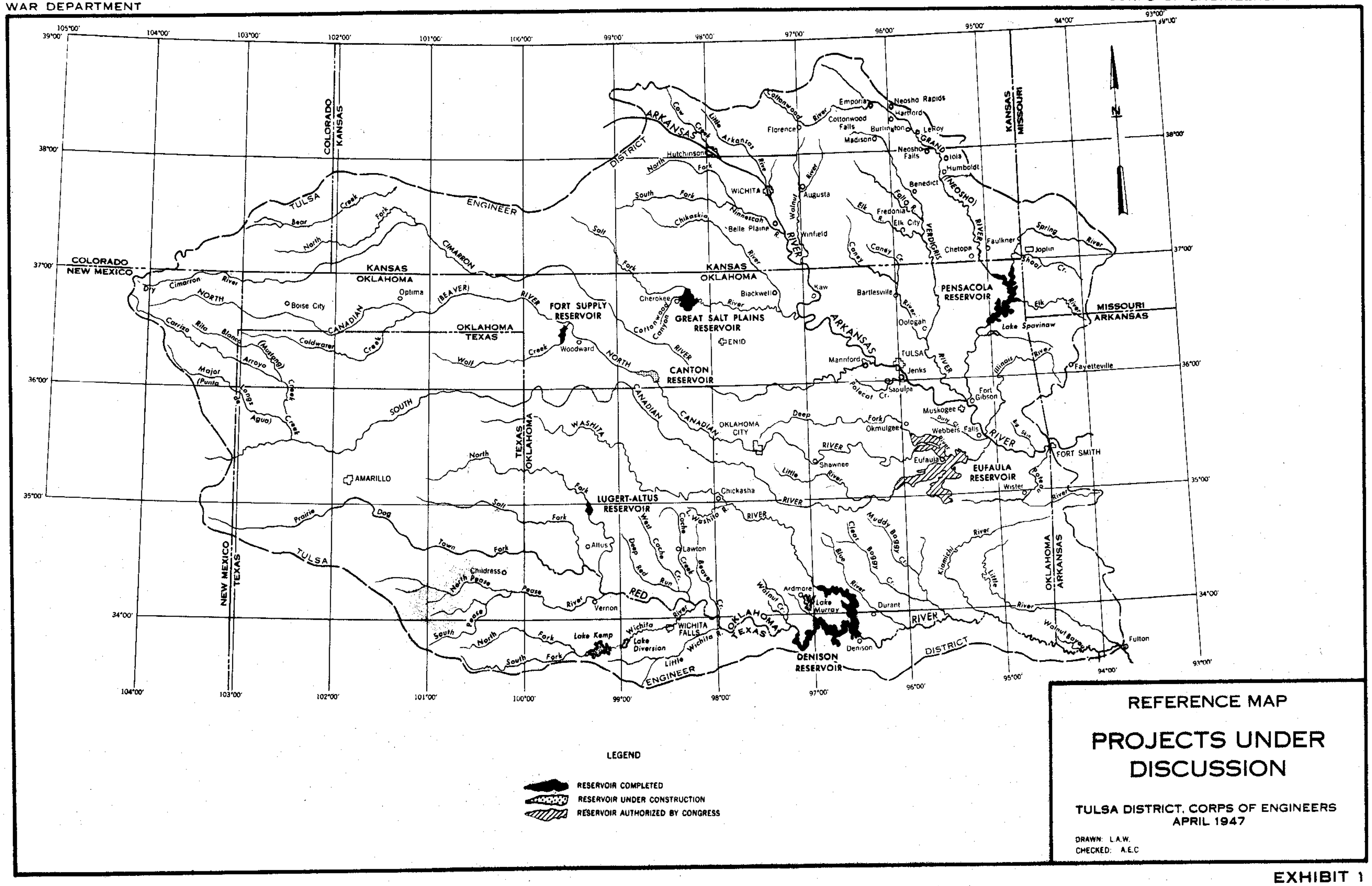
* Tulsa District, Corps of Engineers, Department of the Army, Tulsa, Okla.

1/, 2/ and 3/ See "References" at close of comments.

WAR DEPARTMENT

CORPS OF ENGINEERS. U S ARMY



REFERENCE MAP

PROJECTS UNDER DISCUSSION

TULSA DISTRICT, CORPS OF ENGINEERS
APRIL 1947

DRAWN: L.A.W.
CHECKED: A.E.C

EXHIBIT 1

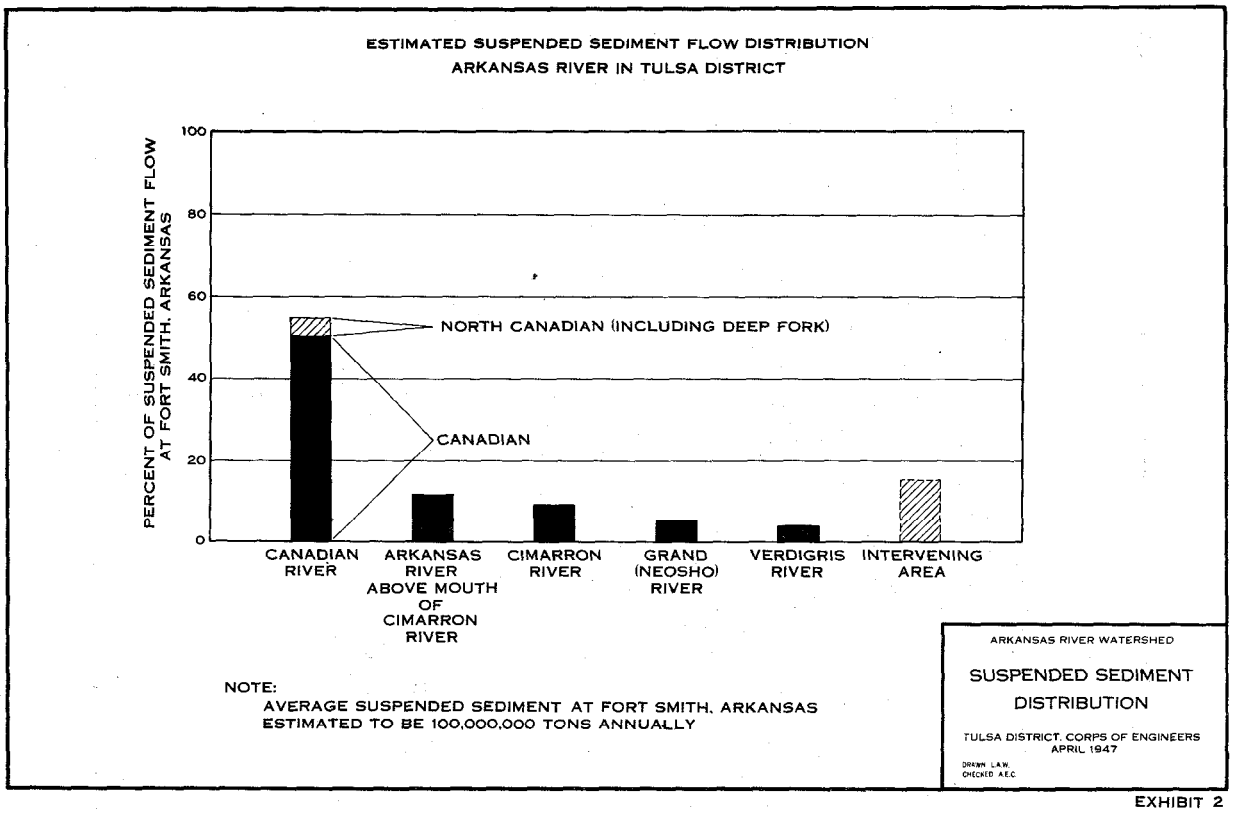


EXHIBIT 2

Mr. E. W. Lane was retained as a consultant on this problem, and he prepared as an exhibit for the Arkansas River Survey Report a thorough treatise on the subject. Acknowledgement is extended to Mr. Lane for his assistance to the Tulsa District, especially to the extent that points discussed herein had their original beginnings with him. One of Mr. Lane's recommendations was that certain future studies should be made to determine more accurately the sediment difficulties of the Arkansas River project. Acting upon this recommendation, the Division Engineer, Southwestern Division of the Corps of Engineers, obtained the services of a consulting board to assist in the formulation of a coordinated program of sediment studies in the Division. Members of this board of consultants were Mr. Lane, the late Mr. O. N. Floyd and the late Mr. G. C. Dobson.

In line with the suggestions of the board of sedimentation consultants and the Division Office, the Tulsa District established a program of sediment investigations which largely forms the basis for the present paper. This program covers the following eight points:

1. Sediment deposits within and above reservoirs.
2. Sediment variation within flow section.
3. Bed material samples.
4. Subsurface samples.
5. Routine extensive suspended sediment sampling.
6. Intensive suspended sediment sampling for daily flows.
7. Degradation of river channels below dams.
8. Bed-load movement.

Some progress has been made on all these subjects except one, namely bed-load movement. However, the Little Rock District of the Southwestern Division has carried on some experiments with bed load.

In April of 1945, by merger of the Denison and Tulsa Districts, the coordination of theory and practice in the same district became feasible. Operation of the Denison Dam, completed in 1944, and its reservoir, Lake Texoma, the fourth largest reservoir in the United States in terms of controllable capacity, could be observed in relation to their behavior in controlling one of the notable sediment carrying streams of the country--as witness its name, Red River.

In the presentation of this paper it will be noticed that there is no distinct line of demarcation between the effects of sediment upon design and upon operation. This is because information gained gradually from operation is being used for design purposes and, similarly, the design of structures already in existence has its effect upon their operation.

Reservoir Capacity. - In designing a reservoir the capacity allocation reserved for sediment depends upon the amount of sediment inflow, the suspended portion of which is usually measured at or upstream from the dam site. For the portion of the total sediment inflow not measured in suspended samples, valley surveys or other methods of determining abnormal bed deposits may be used. In computing the average suspended sediment load over a period of years the first step is preparation of a rating curve of sediment concentration versus discharge (Exhibit 3). The resulting rating on logarithmic paper usually takes the form of a smooth curve rather than one or more straight lines. In general, a sediment rating curve has the following tendencies as the discharge increases: the concentration remains almost constant during base flow, increases rapidly during small to moderate rises, levels off before bankfull capacity is reached and then decreases at flows above bankfull (in this case about 8,000 c.f.s.). It is to be noted that this refers to concentration rather than load. The sediment load usually appears to continue increasing even after bankfull capacity is exceeded, though this is not always the case.

The second step in computing average sediment load is plotting duration curves of water and sediment discharge and obtaining the area under the sediment duration curve (Exhibit 4). Four-cycle logarithmic probability paper is useful for this purpose. It allows close analysis of suspended sediment behavior during the first one percent of duration time - a period of high water flows during which a large part, sometimes even the major portion, of total sediment load is carried.

Sediment reserve storages in reservoirs are usually computed as being available for 50 years. This means that the storage uses for which the reservoir is designed, such as flood-control, irrigation, water-supply, etc., will not begin to be depleted until the reservoir is 50 years old.

In the humid and sub-humid regions the volume reserved for sediment is usually small in comparison to the volume needed to control floods. In fact, the sediment reserve storage is often less than the desirable recreation pool.

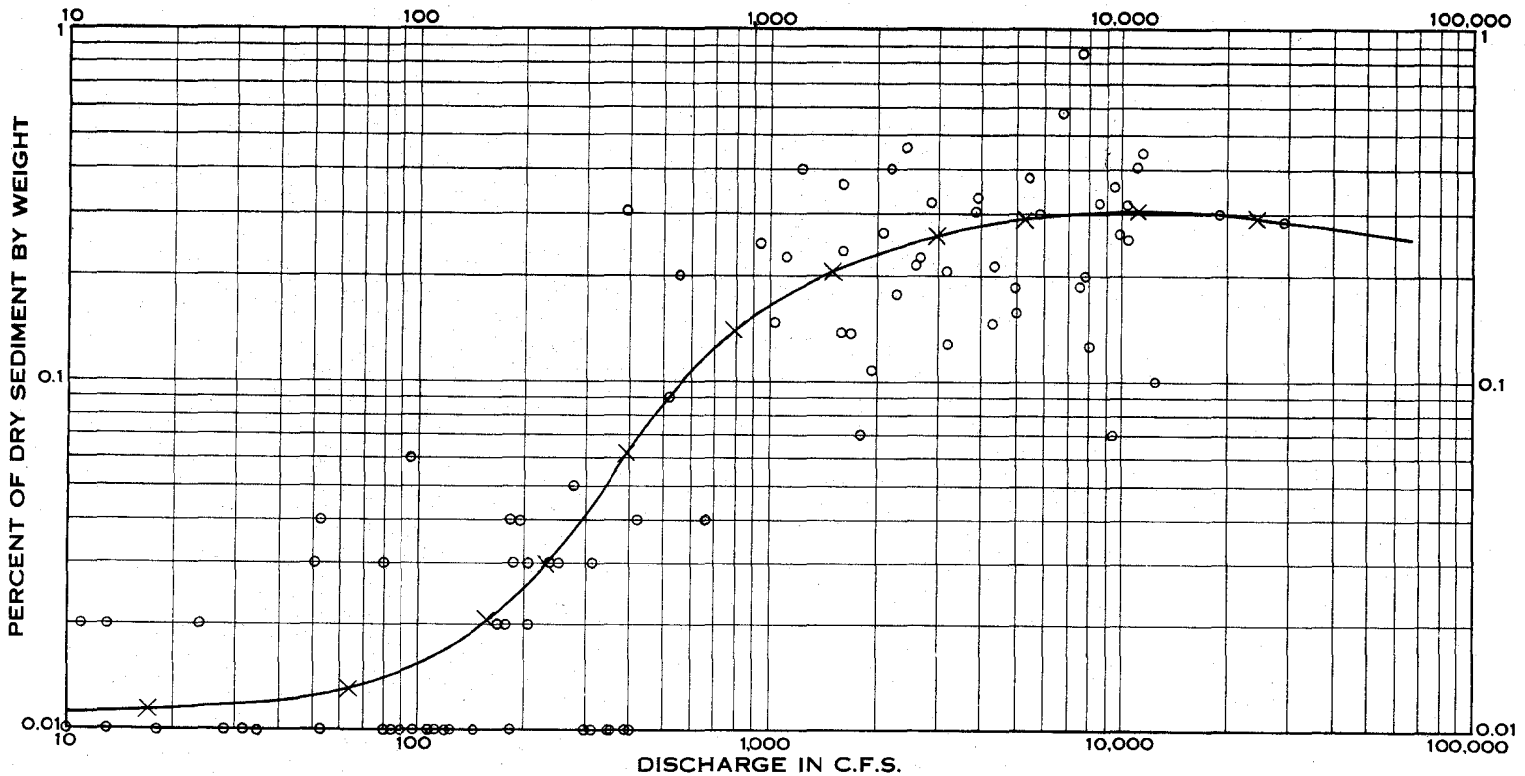
In contrast, in the arid and semi-arid regions the sediment reserve is a large proportion of the storage, in some cases as much as half. One good effect is that it often provides large recreation pools in localities where such facilities are usually few in number.

Upstream Delta Effects. - Reservoirs which still remain economically feasible after provision of adequate sediment reserve present no further difficulty if the deposits occur in the portion of pool reserved for them. Actual deposits may occur at the upper end of the reservoir, thus depleting storage which may be useful only between certain elevations. For instance, at Denison Reservoir the power drawdown storage is between elevations 590 and 617. Any trading of storage space below elevation 590 for space above that would have a detrimental effect on available power head during a drawdown period. It may be seen (Exhibits 4A,5,6,7 and 8) that some depletion of the Denison power pool is beginning to occur.

In cases where it becomes apparent during design studies that useful storage will be lost by sedimentation it is highly desirable to decide at that time which of the various allocations should absorb the loss. For instance, in the Tulsa District a step in this direction has been made at the Canton Reservoir on the North Canadian River, where, even before the construction of of the dam has been completed, irrigation storage has been authorized by Congress 4/ in the words of the following partial quotation ".....upon the condition that when siltation of the reservoir shall encroach upon the flood-control allocation the irrigation storage will be reduced progressively unless provision is made to raise the height of the dam or otherwise provide compensatory storage....."

Besides the loss of useful storage in place of waste space, the upstream deposits may complicate the problem of land acquisiton and relocations. Usually, the top of flood-control pool is so high above the permanent pool that land acquisition is automatically high enough, though not necessarily upstream far enough. Relocations well down in the pool are usually worked out by negotations. Sediment is so small in volume compared to the pool that backwater caused by sediment is negligible.

4/ See "References" at close of comments.

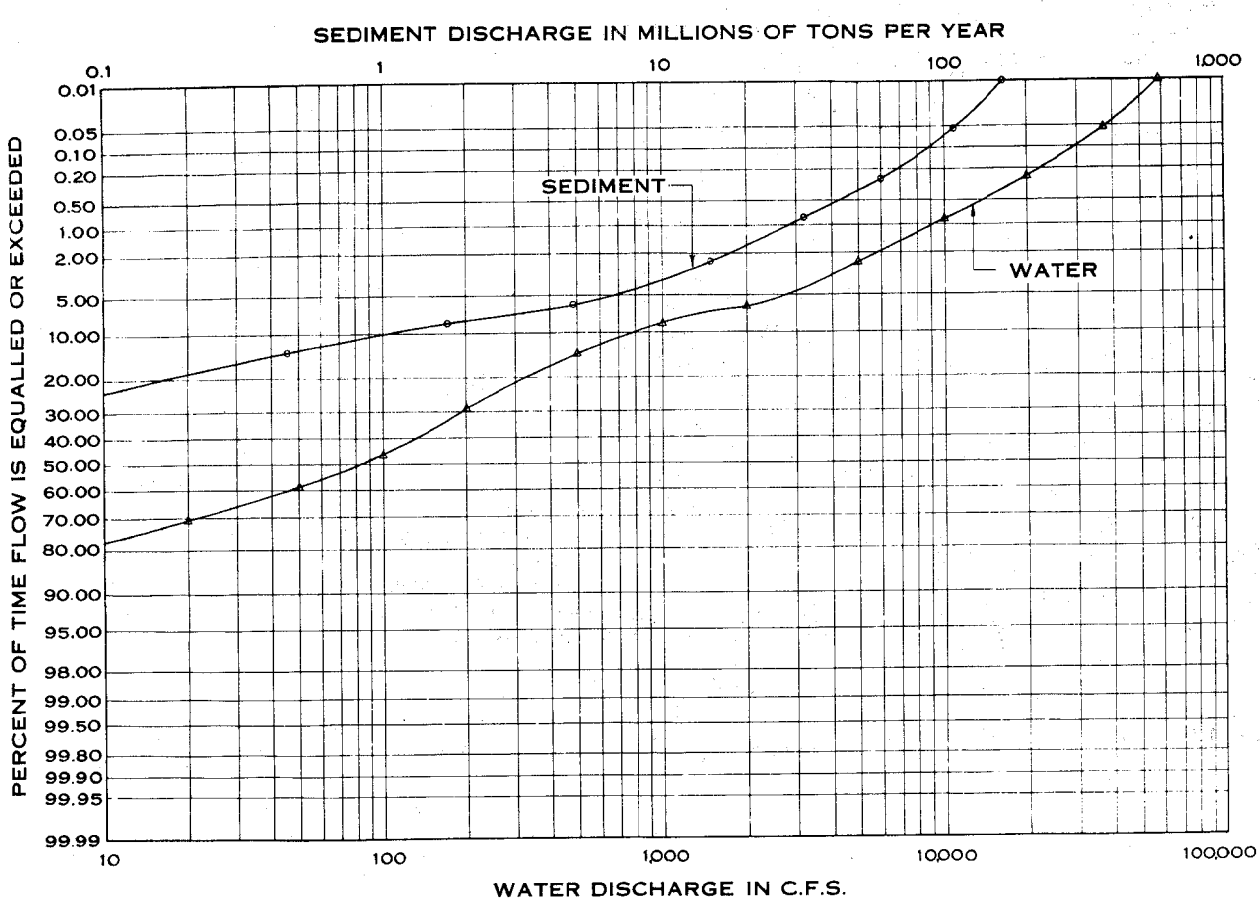


ARKANSAS RIVER WATERSHED
VERDIGRIS RIVER
KANSAS
SUSPENDED SEDIMENT
RATING CURVE
COYVILLE, KANSAS
TULSA DISTRICT, CORPS OF ENGINEERS
APRIL 1947
DRAWN L.A.W.
CHECKED A.E.C.

EXHIBIT 3

WAR DEPARTMENT

CORPS OF ENGINEERS, U. S. ARMY



ARKANSAS RIVER WATERSHED
VERDIGRIS RIVER
KANSAS

WATER AND SEDIMENT DURATION CURVES
COYVILLE, KANSAS

TULSA DISTRICT, CORPS OF ENGINEERS
APRIL 1947

DRAWN L.A.W.
CHECKED A.E.C.

EXHIBIT 4

WAR DEPARTMENT

CORPS OF ENGINEERS, U. S. ARMY

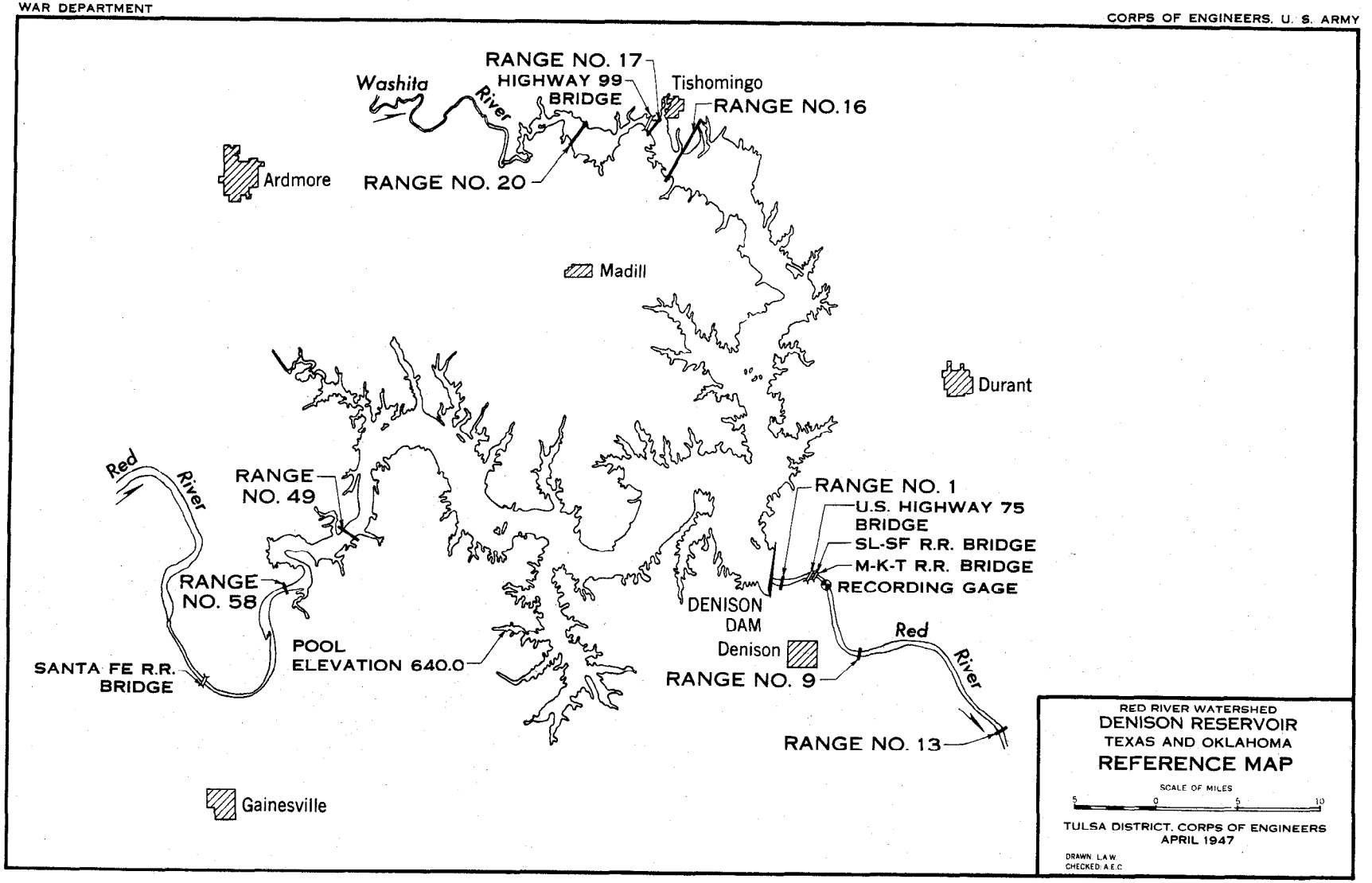
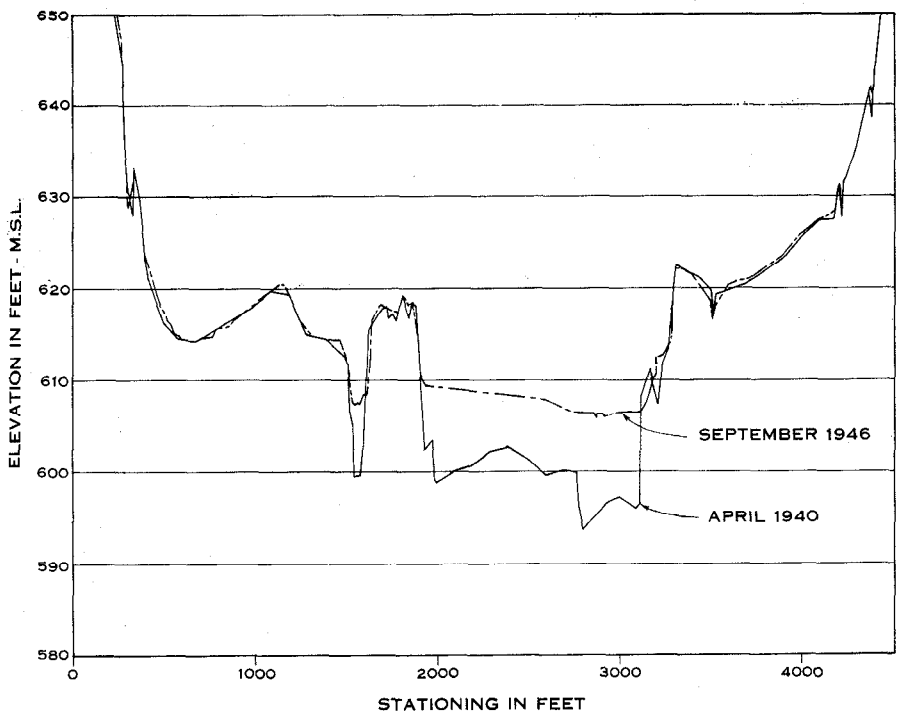


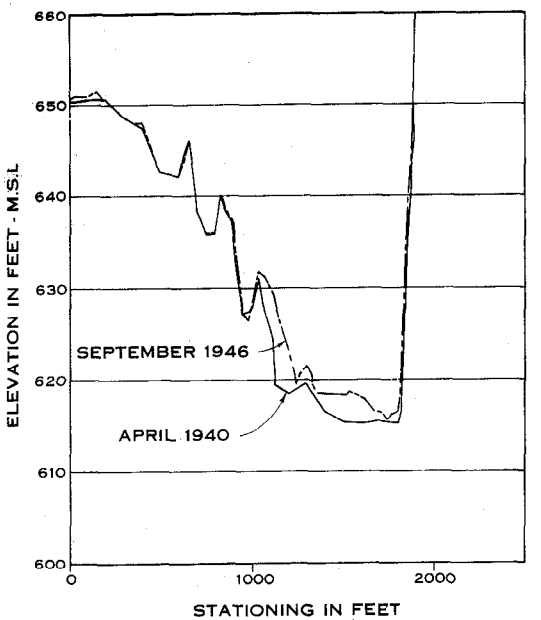
EXHIBIT 4 A

WAR DEPARTMENT

CORPS OF ENGINEERS, U. S. ARMY



RANGE NO. 49



RANGE NO. 58

RED RIVER WATERSHED
DENISON RESERVOIR
TEXAS AND OKLAHOMA
TYPICAL SEDIMENTATION
RANGES IN
RED RIVER ARM
TULSA DISTRICT, CORPS OF ENGINEERS
APRIL 1947

DRAWN L.A.W.
CHECKED A.E.C.

EXHIBIT 5

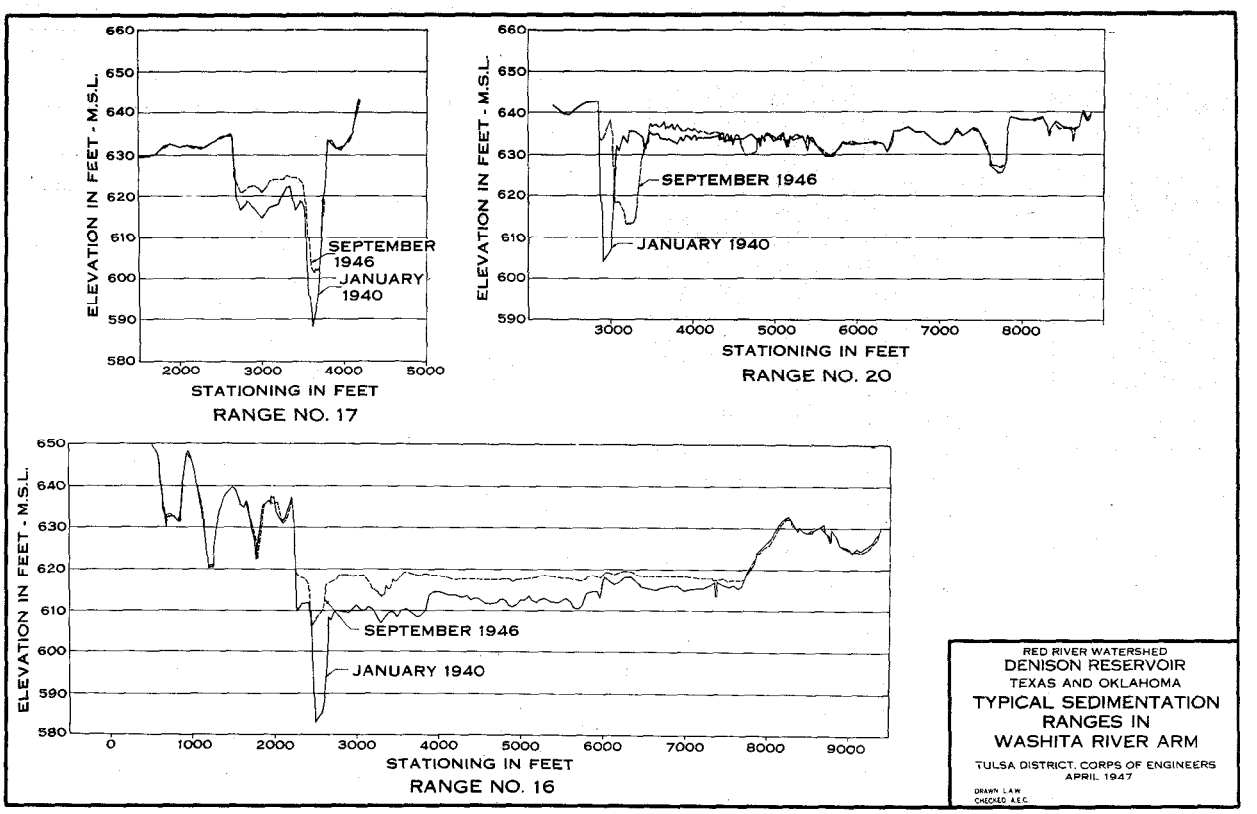
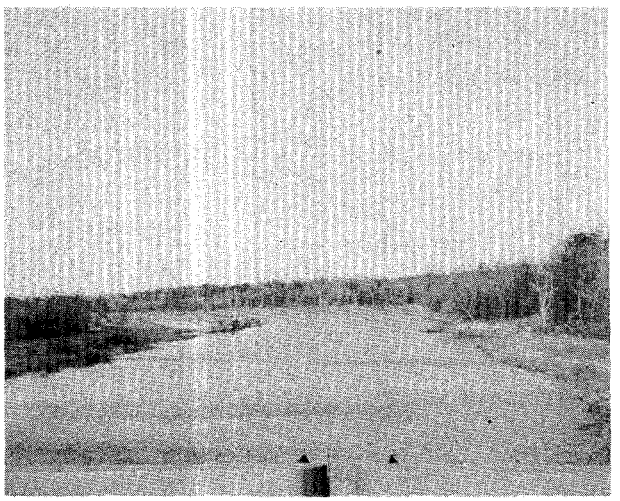
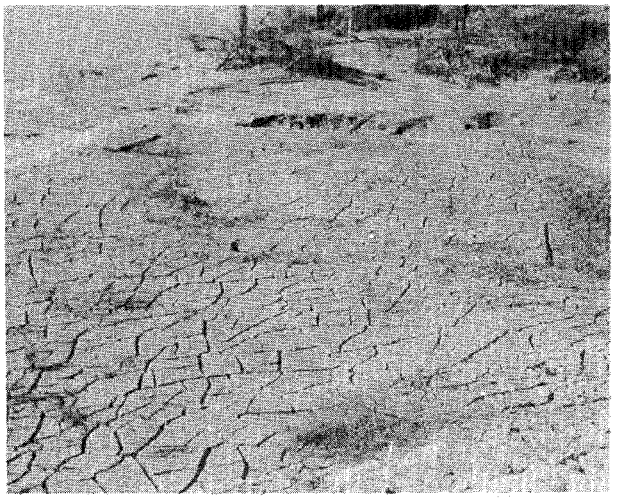


EXHIBIT 6



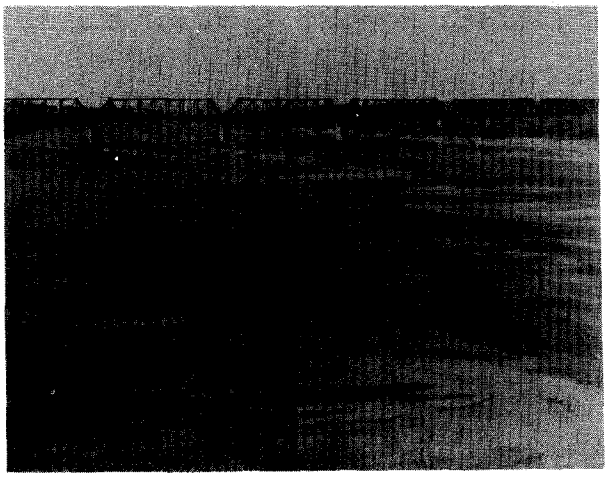
GENERAL VIEW OF WASHITA RIVER AT STATE HIGHWAY NO. 99 BRIDGE CROSSING DENISON RESERVOIR NEAR TISHOMINGO, OKLAHOMA

EXHIBIT 7



DETAIL VIEW OF SEDIMENT DEPOSITS IN WASHITA RIVER AT STATE HIGHWAY NO. 99 BRIDGE CROSSING DENISON RESERVOIR NEAR TISHOMINGO, OKLAHOMA

EXHIBIT 8

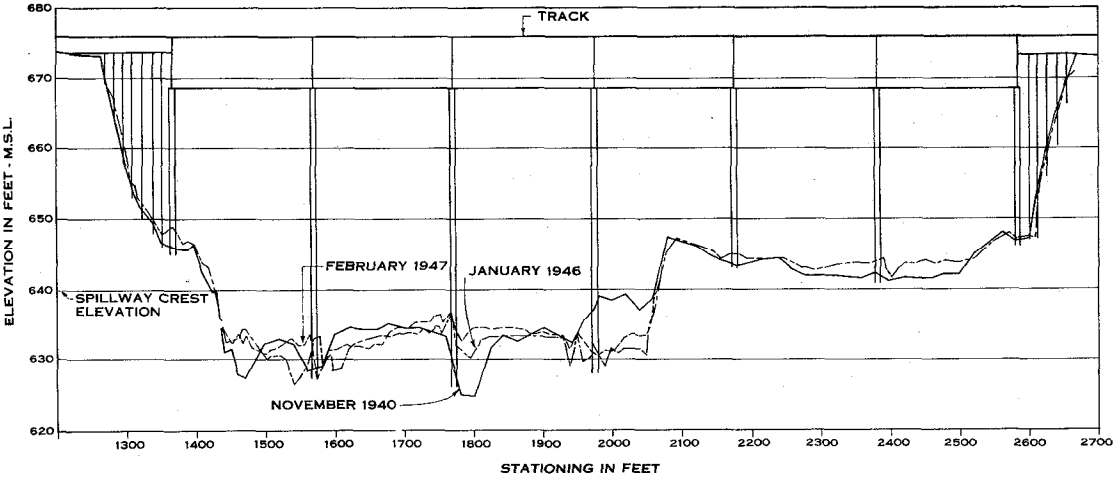


SANTA FE RAILROAD BRIDGE CROSSING RED RIVER ARM OF DENISON RESERVOIR NEAR GAINESVILLE, TEXAS

EXHIBIT 9

At the upper end of the pool, or even out of the pool, it is often questionable whether the reservoir would affect the facility. Without sediment the question is rather easily answered by backwater computations. With sediment, such factors as eventual stream bed elevation, new roughness factor, scour conditions during pool drawdown, vegetation, etc., must be considered.

An example of a case where the effect of sediment is questionable is the Santa Fe Railroad bridge crossing of the Red River near Gainesville, Tex. (Exhibit 9). This is on the main line between Oklahoma City and Fort Worth, and the railroad officials have claimed that the presence of Denison Dam will adversely affect the safety of the bridge. There is no present indication of a hazardous condition at the bridge, and periodic surveys will reveal sedimentation, if it occurs, in sufficient time to allow precautionary measures to be taken. An original and two repeat surveys of this kind show that there has been only slight change in cross-section at the bridge up to the present time. (Exhibit 10).



RED RIVER WATERSHED
DENISON RESERVOIR
TEXAS AND OKLAHOMA

PROFILES OF RANGE AT SANTA FE RAILROAD BRIDGE

TULSA DISTRICT, CORPS OF ENGINEERS
APRIL 1947

DRAWN L.A.W.
CHECKED A.E.C.

EXHIBIT 10

Sediment Movement Through Reservoirs. - In order to maintain useful reservoir capacity as long as possible, it is desirable for sediment to be deposited in the pool reserved for it at the bottom of the reservoir. In some cases, such as a reservoir which is not used as a sediment detention reservoir and which does not have a hydroelectric power plant, it is even desirable to pass as much as possible of the inflowing sediment entirely through the reservoir and into the river below the dam.

Since it is not practicable to drain most reservoirs to keep them empty, the movement of inflowing sediment to the lowest pool or entirely through the dam must depend upon the flow of sediment-laden currents. Several rather thorough tests have been made to determine the nature of such currents in Denison Reservoir. Up to the present time these have been found to be apparently simple displacement currents, the muddy water pushing the clear water ahead of it through the reservoir. The concentration of suspended sediment in water during rises has decreased rather rapidly upon reaching the main lake (Exhibits 11 and 12). Although there has been no flow of

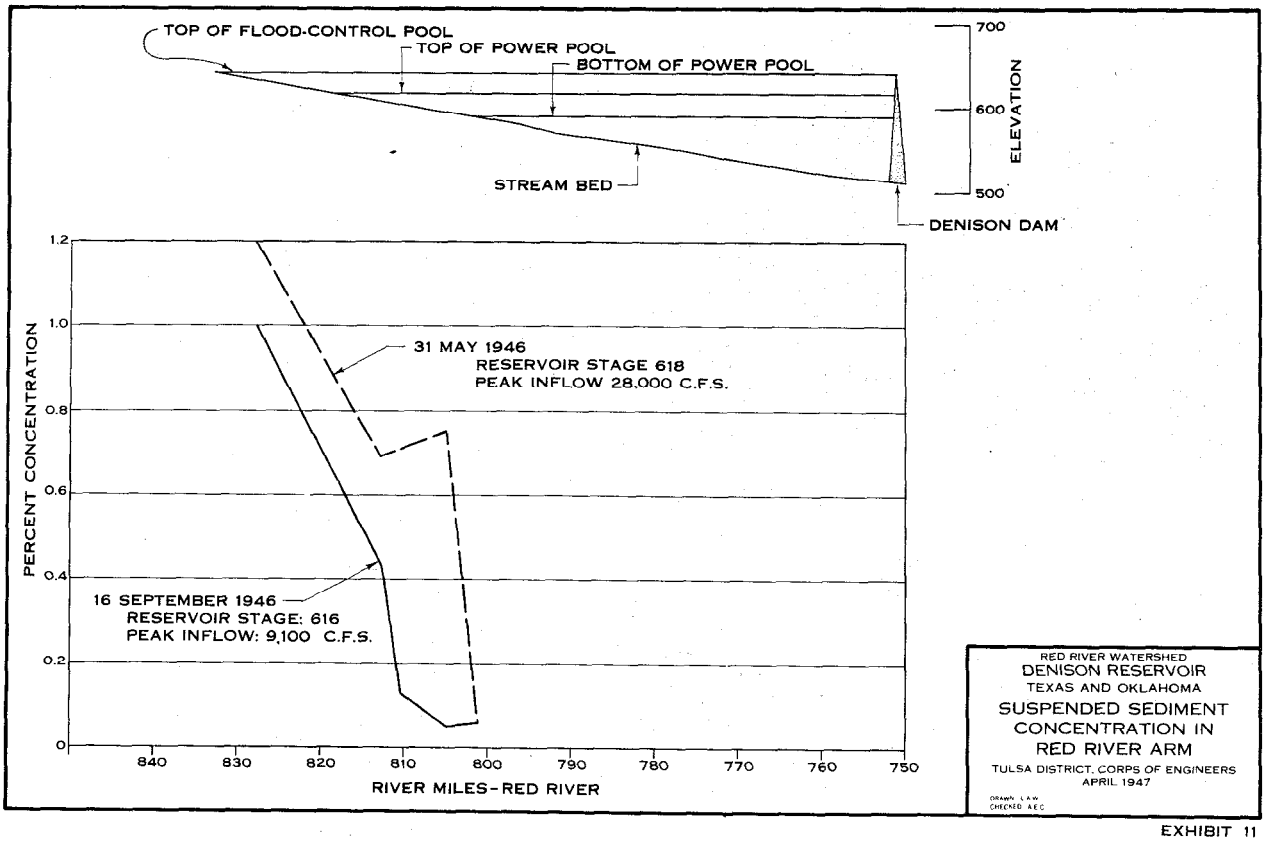


EXHIBIT 11

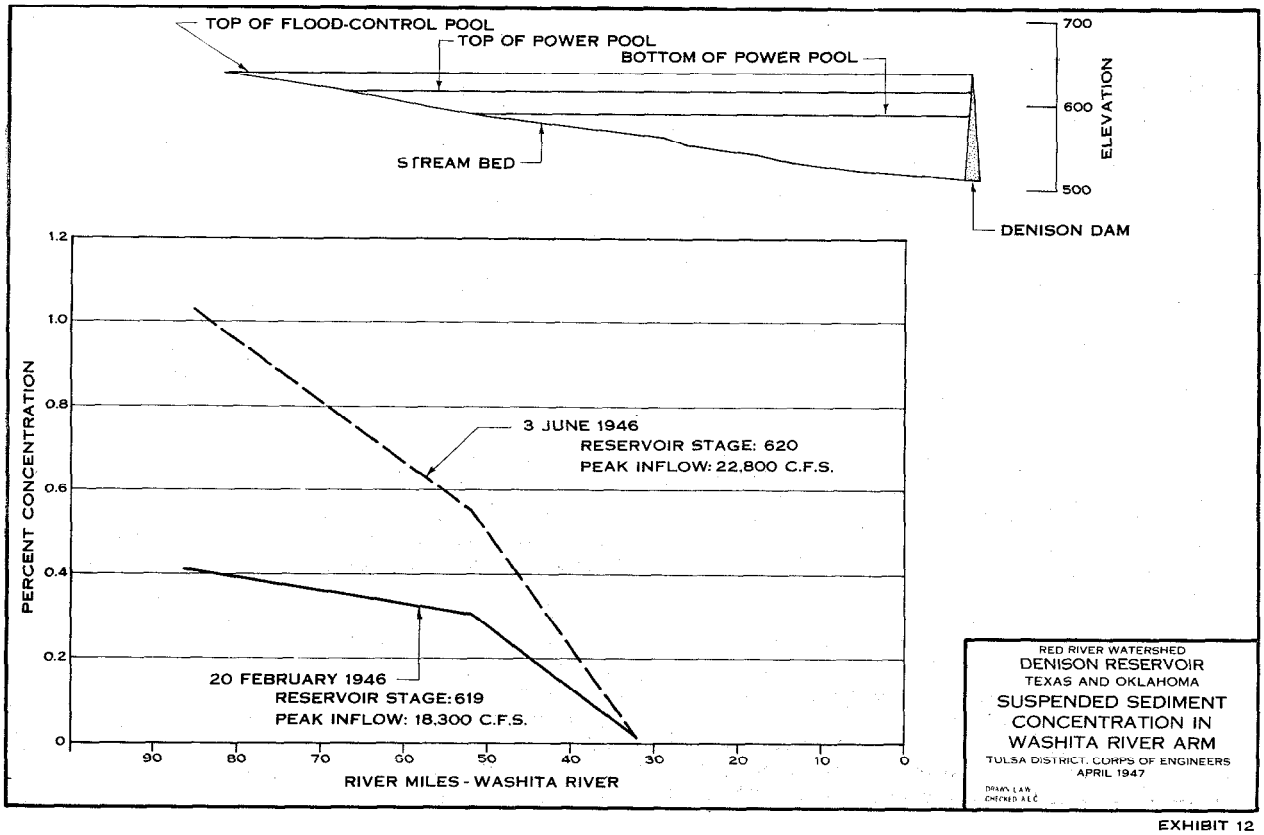


EXHIBIT 12

definitely muddy water through Denison Dam, at Great Salt Plains Reservoir water containing as much as 0.14 percent sediment has passed through the outlet works. Its red color was visible on the surface of the lake during its passage through the reservoir.

Density currents, as such, have not had any effect up to the present time on design or operation of existing and proposed reservoirs. Such low-level outlets as are in existing projects are at sufficiently low elevation for any flushing which will ever be necessary, but their presence is largely incidental as part of the most desirable design from standpoints other than sedimentation.

Inclusion of low-level or variable-level sluices in dams appears to be gaining increased support from the fish and wildlife agencies of the nation, and the definite identification of density currents, especially if they are found to carry worth-while loads of sediment, might strengthen the necessity for investigation of such design.

Stream slopes may be too small, or the ratio of reservoir volume to inflowing sediment volumes may be too large, to be conducive to density currents in the Tulsa District. It appears that both these factors are present at Denison. However, the subject of density currents has received a considerable amount of research elsewhere, and tests will be continued to determine whether important density currents occur in the Tulsa District.

Tailwater Conditions below Dams. - For each dam reaching the design stage, minimum tailwater curves are computed and these serve as the basis for design of spillways, outlet works or power plants, as the case may be.

Stream-bed profiles below Fort Supply and Great Salt Plains Dams have changed since the projects were constructed (Exhibit 13 and Exhibit 14). Notice the precarious conditions of the water-level gages at the stream gaging stations. In order to avoid negative readings the zero of the Fort Supply gage has been lowered 3 feet since construction of the dam. No change has been made in the zero of the Great Salt Plains gage, but it has been noted that this gage has recently been within one-half foot of its zero datum. In establishing water-level gages below dam sites on sediment-laden streams it thus seems advisable to set the original zero of the gage low enough that the possible confusion resulting from future changes may be avoided.

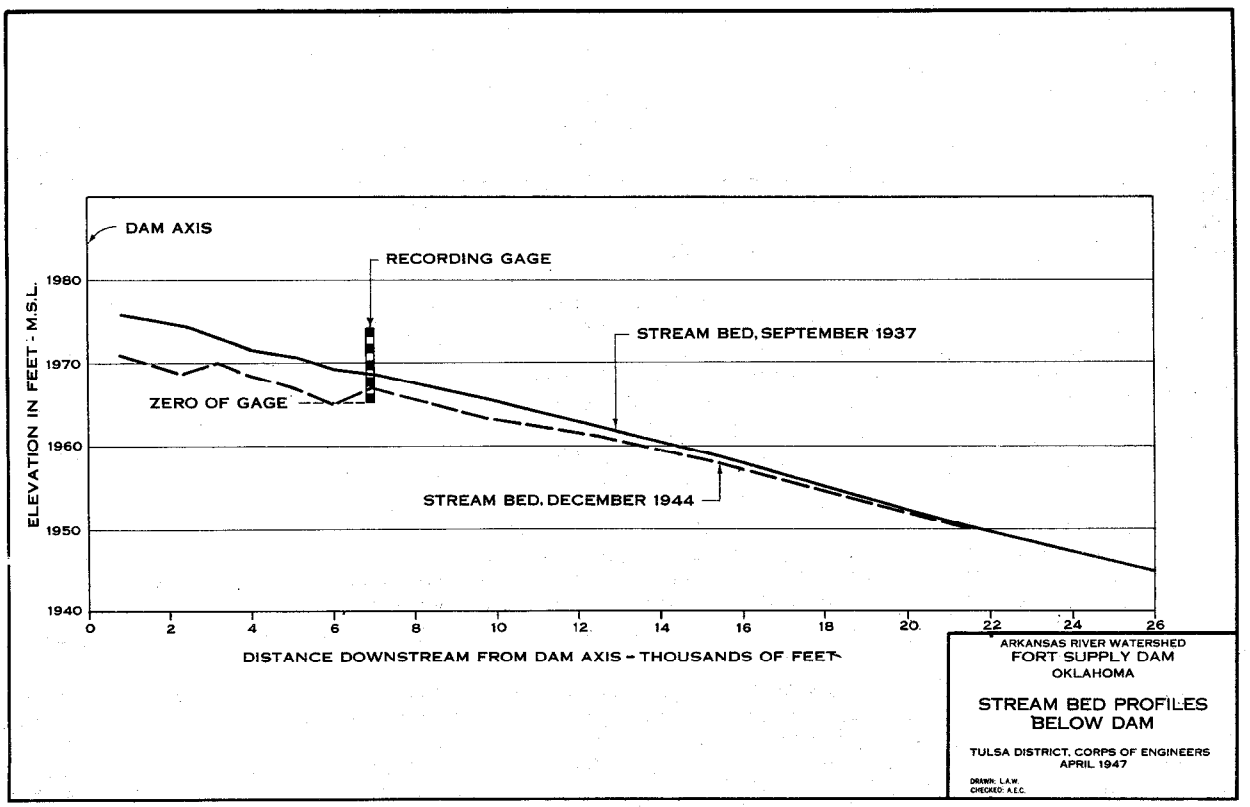


EXHIBIT 13

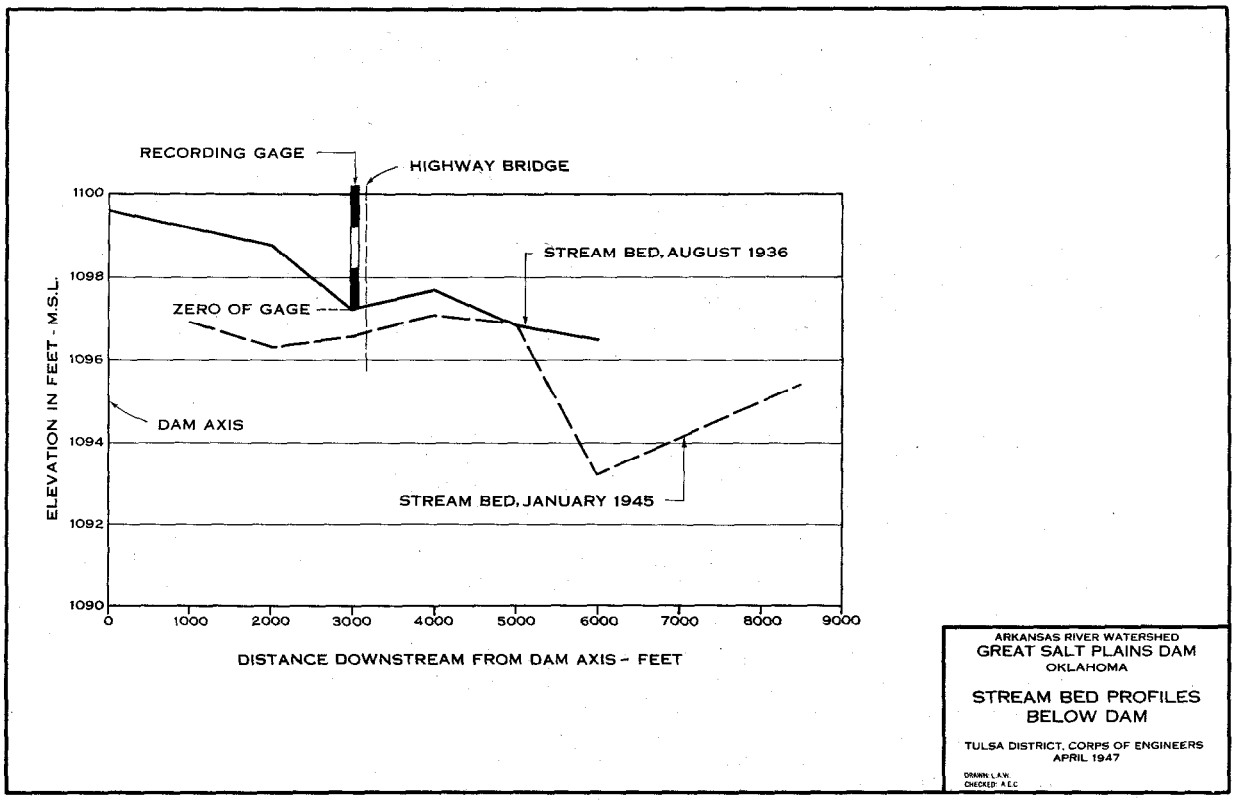


EXHIBIT 14

The stream bed profile below Denison Dam (Exhibit 15) shows that in some places the surface of low water flow is now at a lower elevation than the lowest point in the original stream. It' will be noted that the river bed at the first bridge below the dam (highway bridge) has retained its original elevation. Minimum tailwater for the design of the Denison outlet works and powerhouse was computed on the basis of the rock line at this bridge and this control appears to be holding up well. At the second bridge below the dam (railroad bridge) there has been slightly more erosion, and a picture (Exhibit 16) shows evidences of rock outcropping. It is said that the wreckage which shows in the water in the left of the picture is the remains of a box car which had been placed on the bridge in a vain attempt to anchor it during the flood of 1915, and that the box car has now reappeared for the first time since then. The third bridge below the dam is the one where the present gage is located. Because of the fairly stable control for a short distance downstream, low water is still about five feet above the zero of the gage.

Three typical degradation ranges below Dension Dam show (Exhibit 17) the bank erosion and deepening caused close to the outlet works; the deepening caused in a narrow portion of the river; and the shifting of the channel from one side of the river to the other and the severe bank caving, instead of deepening, caused by the channel shift. At this range one of the original surveying monuments was lost by falling into the river.

In the 17 river miles below Denison Dam it is estimated that about 2,900 acre-feet, or about 150 cubic yards per yard of river length, were removed in slightly more than 3 years.

An important practical aspect of the degradation problem is the increased head available for power production at Denison. Tailwater (Exhibit 18) for the range of flows used in making power, about 5,000 c.f.s. for the presently installed one unit, has lowered about 5 feet since construction of the dam started. This represents almost a 5 percent increase in available head and consequently in power revenue. Under present conditions the extra 5 feet of head is worth roughly $40,000 annually to the Denison project.

Summary. - Water-borne sediment has an important effect upon the total capacity required in multiple-purpose reservoirs. By provision of adequate sediment storage the problems which remain are simplified. Such problems include flooding caused at or upstream from the debris-filled upper ends of reservoirs; methods of transporting inflowing sediment entirely through reservoirs; and the changes caused in river channels below dams on sediment-laden streams. Depending upon the

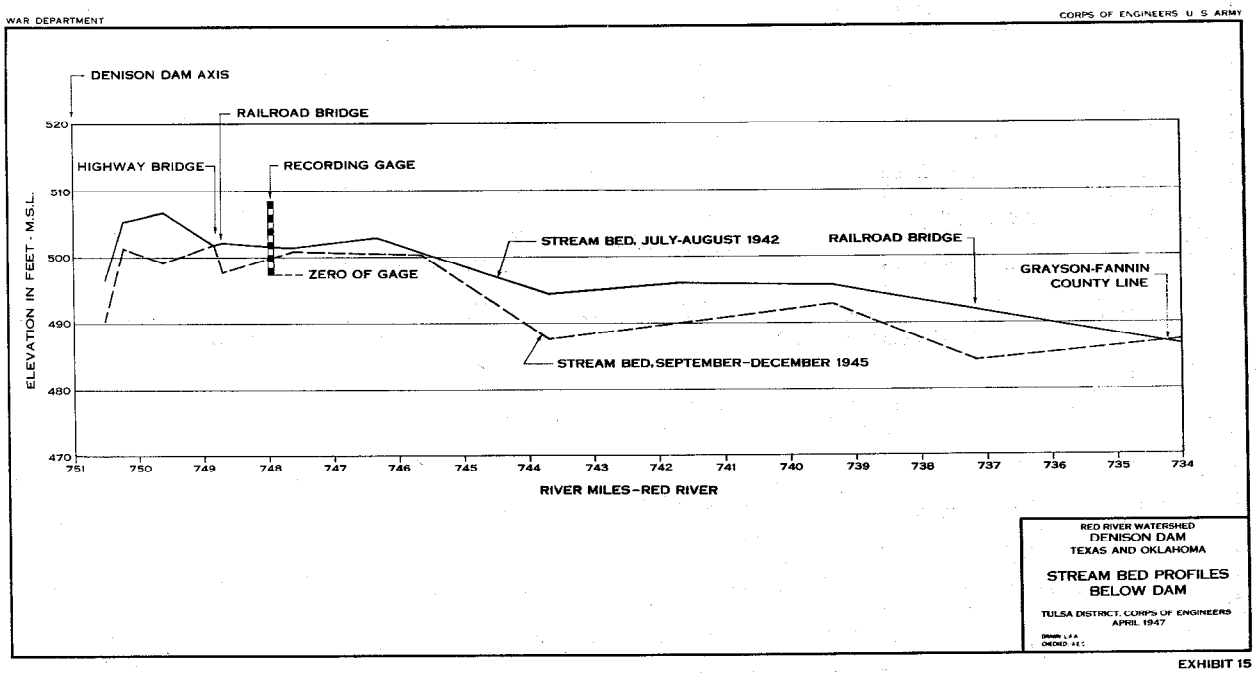
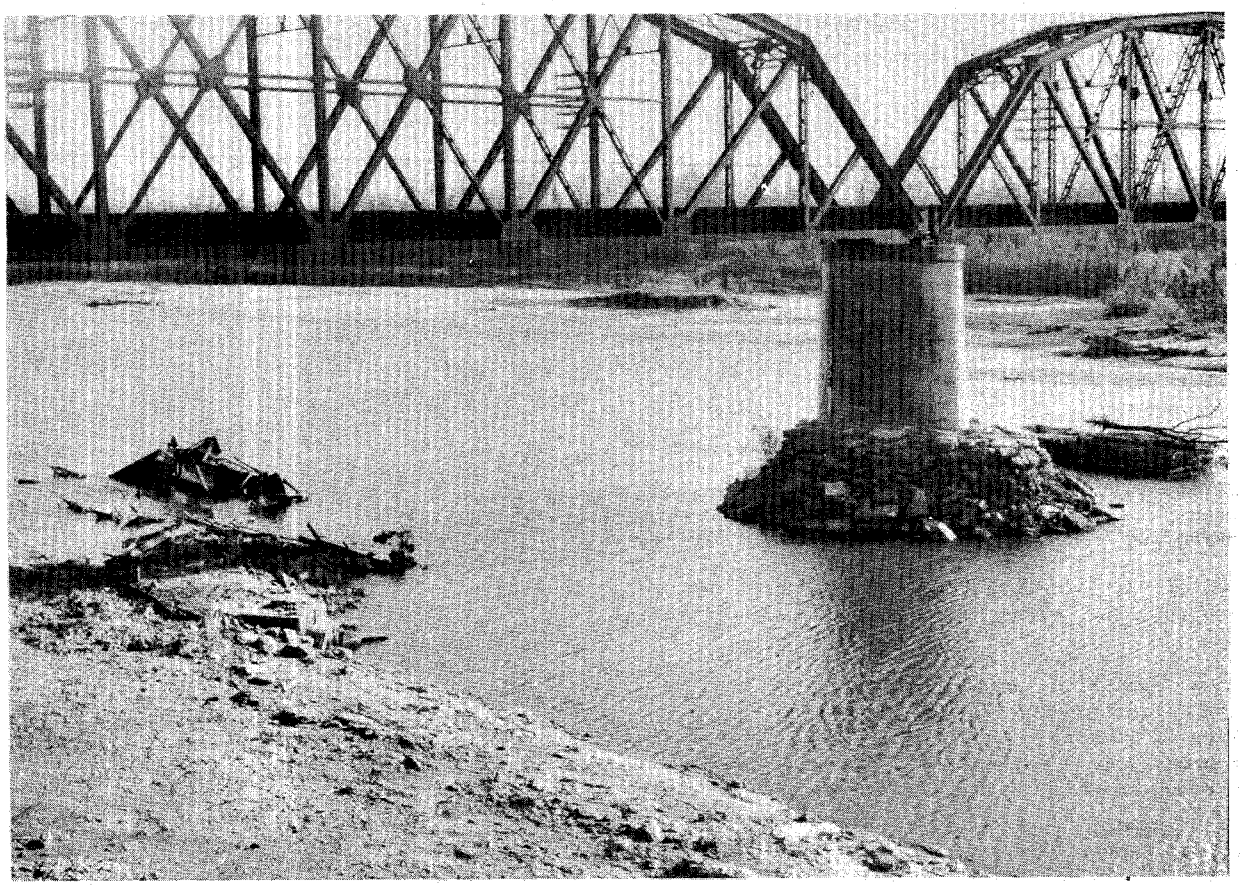
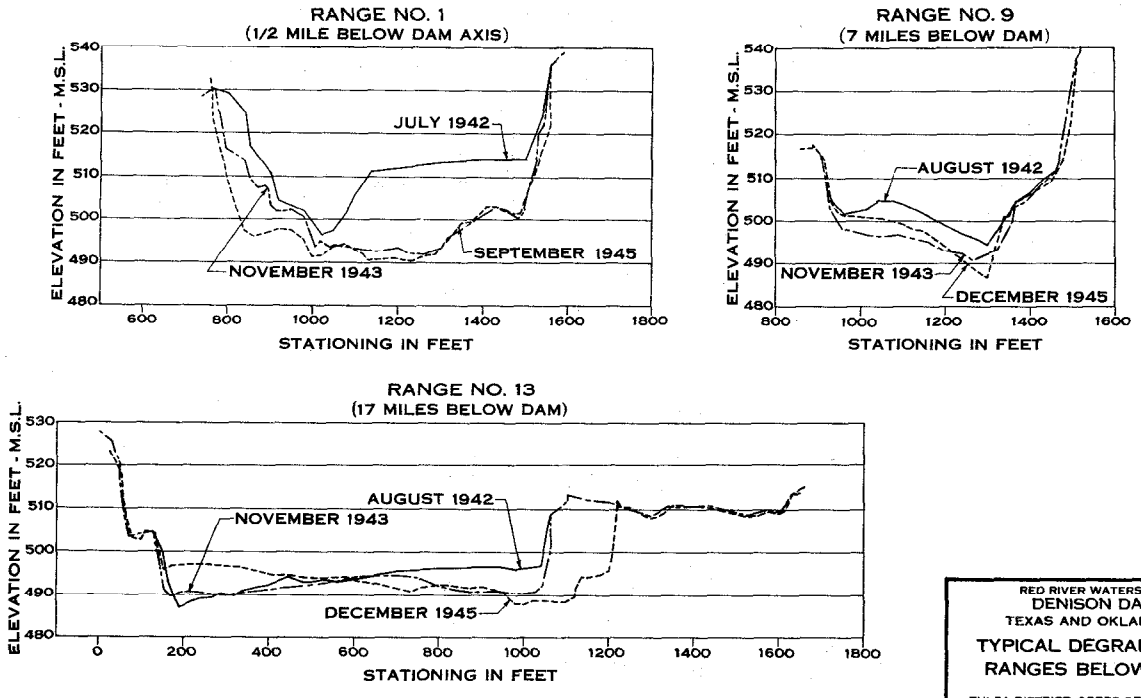


EXHIBIT 15



M.K. & T. RAILROAD BRIDGE ABOUT TWO MILES BELOW DENISON DAM

EXHIBIT 16



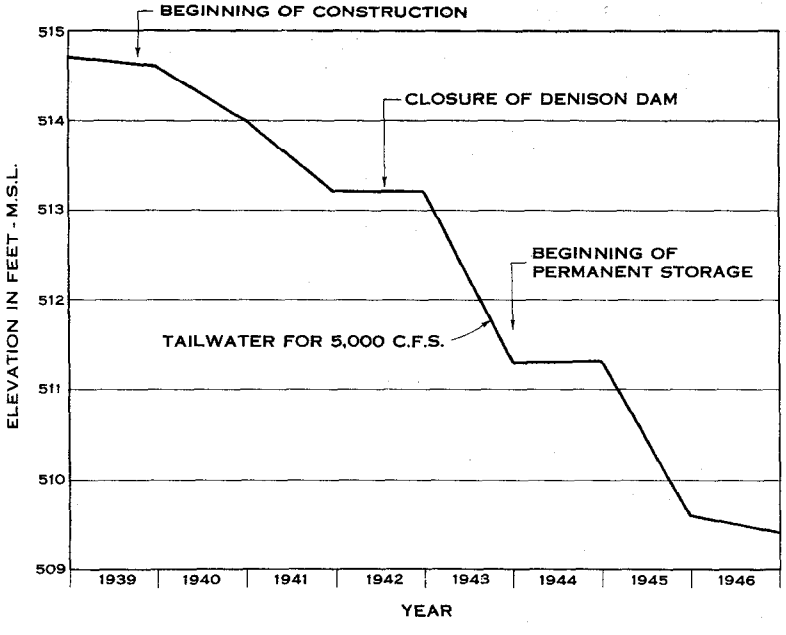
RED RIVER WATERSHED
DENISON DAM
TEXAS AND OKLAHOMA

TYPICAL DEGRADATION RANGES BELOW DAM

TULSA DISTRICT, CORPS OF ENGINEERS
APRIL 1947

DRAWN L.A.W.
CHECKED A.E.C.

EXHIBIT 17



RED RIVER WATERSHED
DENISON DAM
TEXAS AND OKLAHOMA

YEARLY CHANGES IN TAILWATER

TULSA DISTRICT, CORPS OF ENGINEERS
APRIL 1947

DRAWN L.A.W.
CHECKED A.E.C.

EXHIBIT 18

extent to which increasing experience shows them to be significant, all these factors are given consideration in the design and operation of Corps of Engineers projects.

References

1. Anonymous. "Arkansas River and Tributaries." House Document No. 308, 74th Congress, 1st Session, Vol. 1, page 569.

2. Anonymous. "Red River, Louisiana, Arkansas, Oklahoma and Texas." House Document No. 378, 74th Congress, 2nd Session, page 214.

3. Anonymous. "Sediment Investigations on the Mississippi River and its Tributaries, Prior to 1930." Paper H, U. S. Waterways Experiment Station, Vicksburg, Miss.

4. Anonymous. "Flood Control Act," approved July 24, 1946, 79th Congress, 2nd Session.

DISCUSSION

LESTER C. WALKER.* Mr. Coldwell's informative paper discusses two items which appear important from the standpoint of power development. They are: (1) Depletion of the storage capacity of the power pool by deposition of sediment in that pool instead of in the dead storage pool, and (2) degradation of the river channel below the dam with its consequent reduction in elevation of the tailwater and increase in power head.

Mr. Coldwell's statement that the storage uses "such as flood control, irrigation, water supply, etc., will not begin to be depleted until the reservoir is 50 years," provided the sediment reserve storage is computed as being available for 50 years, seems to require explanation in light of the record at Denison as illustrated by Exhibits 5 and 6. These Exhibits, which show the sediment accumulation during the two years of reservoir operation at sediment ranges Nos. 16, 17, 20, 49, and 58, indicate a pronounced accumulation of sediment within the power pool. As he points out, power pool storage space occupied by sediment may not be traded for a like quantity of unoccupied space in a lower portion of the reservoir without serious loss in power head.

The power pool at Denison, like that in many multiple-purpose reservoirs, occupies a central position vertically in the reservoir. The water surface is usually at some elevation within the power pool at the beginning of a flood, and hence the first sediment laden water deposits a large portion of its load within that pool. Thus it appears that the power pool may be expected to suffer from sediment accumulation earlier and to a greater extent than other portions of the reservoir. Therefore, it becomes important, as Mr. Coldwell observes, to determine during the design stage how the depletion of storage by sediment accumulation will affect the various storage allocations and to make proper allowances therefor. It has not come to our attention that original design plans have provided reserve capacity for sediment in any except the lower portion of the reservoir. With the present knowledge of the behavior of sediment it should be possible to improve upon design by allocating capacity between specified elevations in the upper portion of the reservoir in addition to the reserve at the lowest elevations.

Accumulation of sediment within the power pool has a continuing and increasing detrimental effect upon the power values of a project similar to Denison, an effect, too, which is permanent. As an offset to such loss of power values, which may or may not have been accounted for in the original studies, there may be degradation below the dam with its consequent lowering of tailwater and increasing of net power head. Exhibit 18 indicates, as Mr. Coldwell states, that the Denison tailwater elevation has been lowered about 5 feet by degradation. This is between 5 and 6 percent of the average power head and, inasmuch as the design and construction make possible full utilization of this increase in head, it improves the power output in kilowatt-hours more than 5 percent and the capability of the generating units at minimum head by about 11 percent. Mr. Coldwell has estimated that this extra head is worth about $40,000 annually to the Denison project. However, his estimate is based upon the present installation which consists of only one generating unit. There is provision in the Denison design for additional generating units and this extra head will be worth at least $75,000 annually when a second unit is installed and over $100,000 if a third unit is placed in operation. It should be noted that losses in power storage capacity and increase in head by degradation are time series variables.

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* Engineer, Regional Office, Federal Power Commission, Chicago, Ill.

It is important that the rate and total extent of degradation below the power plant be accurately estimated. If degradation is less than estimated there may have been an unnecessary expenditure in placing the turbine at too low an elevation and if degradation is greater than estimated it may be impossible to take full advantage of the extra head created and it may be necessary to construct an expensive barrier to prevent lowering of the tailwater with the consequent breaking of the draft tube seal. Unless the rate at which degradation will take place is known, it is difficult to forecast the power which will be available and to schedule installations to meet future loads. It is to be hoped that further studies and additional experience will permit more reliable estimates of degradation.

OLIVER JOHNSON, CLARENCE PEDERSEN, AND H. O. WESTBY.* In keeping with the views of specialists throughout the nation who realize that proper planning and design with relation to the problem of how to provide for sediment is an urgent necessity, representatives of the Portland and Seattle Districts and the North Pacific Division, Corps of Engineers, recognize that a definite problem exists and that well planned action to provide the best possible answer must be taken.

Quantitative data on the amount of sediment carried in the streams of the area are quite limited, compared to data available on streams elsewhere in the United States, and this lack of data handicaps design personnel to some extent. A sampling and survey program has been planned to furnish the required data, and this program is expected to begin very soon. Almost all of the sedimentation problems are concerned with the space in storage reservoirs that will be occupied by silt at some future date; machinery wear due to silt in flowing water has been assumed to be negligible and no provision for extra wear from this source is being provided.

The Pacific Northwest consists of several geographical areas with varying characteristics, and sedimentation problems differ in each area. Basins with streams having somewhat similar problems are (1) Upper Columbia east of the Cascade Mountains, exclusive of the Snake River; (2) Snake River; and (3) Lower Columbia, west of the Snake River Basin with Pacific Slope drainage.

A description of the characteristics of each basin, and sedimentation measurements and estimates pertaining to the area, are contained in the following paragraphs:

Upper Columbia east of the Cascade Mountains, exclusive of the Snake River. The Upper Columbia drainage area generally has moderate to low annual precipitation and is not subject to the extensive and frequent convective storms of the southern States; most of the run-off is from snow melt from the higher mountainous areas that are well forested. These factors tend toward reduced rates of erosion and make silting of reservoirs a minor problem in this region. A number of large lakes on the Upper Columbia River and tributaries are retaining a certain amount of silt, as it has been noted that during flood stages the streams enter quite turbid but have a clear discharge. Many of these lakes are very deep and much of the silt is, no doubt, being deposited in the deep portions, as visible changes are not generally noticeable in the absence of accurate surveys.

Probably because silting has not caused serious trouble on many existing projects, there has been little effort made to study this factor and as a result the available data in the form of actual measurements are very meager. Data available consist of suspended load measurements on the Columbia River at Pasco and Northport, Wash., the Yakima River at CleElum and Prosser, Wash., the Naches River at Naches, Wash., the Wenatchee River at Cashmere, Wash., the Okanogan River at Okanogan, Wash., the Spokane River near Spokane, Wash., the North Fork, Coeur d'Alene at Enaville, Idaho, and on the South Fork, Coeur d'Alene at Enaville. Most of these observations covered a period of about one year and indicate that the annual sediment carried in suspension varied from 0.009 to 0.035 acre-feet per square mile of drainage area, except for the South Fork, Coeur d'Alene, which was somewhat higher, probably due to mine tailings. Reconnaissance surveys of several reservoirs, made by personnel of the Soil Conservation Service, indicated that the reservoir having the highest sediment accumulation per unit of drainage (0.46 acre-feet per square mile) was the Tieton in the Yakima River Basin; due to the large ratio of storage to drainage area the annual rate of storage loss was only 0.04 percent, which is very low.

Based on the data available, it is estimated that sedimentation will not reduce the gross storage of any one proposed storage project on the Clark Fork and tributaries more than two percent in 50 years. With the addition of other projects and increased storage per square mile, this

* North Pacific Division, Portland District, and Seattle District, respectively, Corps of Engineers, Department of the Army.

percentage will be even smaller, and it is apparent that the sedimentation factor is of minor significance in the economics of these developments.

Although no comparative measurements are available, it is believed that the sedimentation factor of the Kootenai River will be considerably greater. This belief is based on the fact that the Kootenai has at some time in the past deposited large quantities of silt on the Kootenai Flats, and at times of flood stage it is very turbid in the vicinity of Bonners Ferry. Since much of this turbidity is probably due to bank erosion, conclusive evidence as to the rate of silting of upstream reservoirs is not present, but it is believed that it will not be excessive.

Information relative to the sediment being carried by the Walla Walla, John Day and Umatilla Rivers indicates that moderate amounts are being transported. Furnish Reservoir was built by private interests on the Umatilla River, below Pendleton, Oreg., in 1911; it had a total capacity of 5,000 acre-feet, or a capacity watershed ratio of about four acre-feet per square mile of drainage. By 1934, when the reservoir was abandoned, it had silted up so that only an estimated 1,000 acre-feet of its original capacity remained; the operators of the dam stated that most of this silt came from a small tributary, White Horse Creek, with only a small amount from Umatilla River. This rate of silting corresponds to about .15 acre-foot per square mile per year. The consultants on the project estimated that silt would not become a problem for 50 years, but this and other examples show that when a low capacity watershed area ratio is used in design, trouble and loss almost invariably follow.

In the pools behind proposed dams in the Columbia River below Grand Coulee, the storage-drainage area ratio will be small, but with existing and proposed upstream storage reservoirs, most of the sediment will be intercepted. Furthermore, these run-of-the-river plants will have relatively short detention periods during flood stages and much of the material in suspension will be carried on downstream. It is believed safe to assume that less than one percent of the storage for pondage will be lost in 50 years.

Snake River Basin. The Snake River drainage has moderate to excessive precipitation over the headwaters, most of which occurs as snow, and flows through a semi-arid region on its way to join the Columbia near Pasco, Wash. Part of the headwaters rise in the Gros Ventre, Wyoming and Salt Ranges, in areas which are chiefly folded sediments, some of which are easily eroded and subject to landslides. In the Gros Ventre and Grays River Valleys, landslides are particularly noticeable. The sides of the Gros Ventre Valley are composed of deeply folded layers of limestone, sandstone, cretaceous shales, and lava flows. When the shales are thoroughly saturated with water, landslides often occur. Evidence of some 30 or 40 of these slides has been found by geologists. The largest slide of record occurred on June 23, 1925. It formed a dam across the Gros Ventre, 180 feet high and about 3,600 feet long, and 30 to 50 million cubic yards of material were involved. As the valley filled, the slide spread downstream for a distance of $1\frac{1}{4}$ miles. When the river was in flood on May 18, 1927, the dam washed out. The release of the water impounded by the slide caused an unprecedented flood which carried about 10 million cubic yards of debris into the lower Gros Ventre and Snake River Valleys.

Although th upper reaches of the Snake River carry a fairly large amount of sediment, flowing through braided, shifting channels, this condition does not exist in the lower part of the stream. The silt problem is considered to be somewhat more severe than in the Upper Columbia Basin.

Measurements of suspended silt in the Salmon, Malheur and Palouse Rivers, in 1905, and in the Payette River, in 1906, indicate that only small amounts of sediment were being transported by those streams. Measurements were made in 1905, 1906 and 1907 on the Boise River near Boise, Idaho, and on the Snake River near Weiser, Idaho, in 1911-1912. Samples were taken on a number of streams in the Upper Snake Basin in 1939 and 1940; the records are short and definite estimates as to the rate of silting could not be drawn.

The Geological Survey, in cooperation with the Soil Conservation Service, made sediment measurements on the South Fork of the Palouse River at several stations in the vicinity of Pullman, Wash., during the period 1934-1940. The sediment production per 100 square miles of drainage area averaged about 23 acre-feet annually (assuming a dry weight of 60 pounds per cubic foot), indicating that sediment production from this area is moderate compared to the United States as a whole, but probably higher than for most parts of the Northwest.

In a report by the Soil Conservation Service on the Sedimentation survey of the Black Canyon Reservoir on Payette River, five miles northeast of Emmet, Idaho, the amount of silt deposited in 12 years was estimated to be about 4,000 acre-feet, or .15 acre-foot per square mile of drainage

area per annum. The loss in storage in the reservoir was 0.89 percent per year, which is considered to be moderately high. This is due partly to over-grazing, and partly to the low capacity-watershed ratio of 14.83 acre-feet per square mile of drainage.

In the Upper Snake Basin no complete sedimentation survey of an existing reservoir has been made. However, estimates by several agencies placed the annual silting rate of the Arrowrock Reservoir, on the Boise River, at 240 to 625 acre-feet, or .11 to .28 acre-feet per square mile of drainage area per year. The original capacity was 291,500 acre-feet, and it had a moderately high capacity-watershed ratio of 131 acre-feet per square mile of drainage. Therefore, no trouble from sediment deposits should be experienced for some time. Arrowrock Reservoir has been sluiced several times since its construction in 1915, but no information is available concerning the amount of sediment removed from the reservoir during these sluicing periods. The amount removed is probably rather small.

Lower Columbia River west of the Snake River Basin, with Pacific Slope drainage. This area of the Pacific Northwest has moderate to heavy precipitation but the areas of heaviest precipitation are generally in mountainous terrain which is heavily forested and rocky in nature, so that sedimentation is a minor problem. The headwater streams are characteristically clear except during periods of flood when silt and bed loads are temporarily carried. The main stems flow through valleys which have been built up by sedimentary deposition. Bank erosion, bed load movement, and shifting channels present serious problems of control. On the navigable portions of the lower Willamette, Columbia, Puyallup and other coast streams, the bed load movement of sands, silts and gravels are such as to necessitate a substantial annual program of dredging to maintain adequate channel depths.

Measurement of suspended silt in the Columbia River has been made at Cascade Locks for a two-year period in 1910, 1911 and 1912, by the Corps of Engineers, in cooperation with the Geological Survey. Suspended matter averaged 40 parts per million, which indicates that only a small amount of sediment was being carried. Measurements for a period of about one year, 1911-1912, were made on a number of streams in Oregon, including the Willamette, McKenzie, Santiam, Umpqua, Siletz and Sandy. These records indicate that suspended matter in this area is generally fairly low. These measurements on the McKenzie River indicated a sediment rate of about .02 acre-feet per square mile of drainage area per annum. Samples were taken for a period of one year, April 1942 through March 1943, of the water flowing over the spillway at Bonneville Dam, as part of an investigation of the excessive erosion of the baffle piers and deck of that structure. The program indicated that the average concentration of suspended matter (76 parts per million) was not large, showing that the Columbia is not a heavy silt carrier, and that due to the presence of quartz in the suspended material, some abrasive action might be expected from the Columbia River water.

No record of measurement of suspended matter in Washington streams are available, but indications are that these streams are very similar to those in Oregon in this respect. The silting up of harbor navigation channels and tributary streams, as far upstream as the tidewater effect, is an ever present problem for western Washington rivers and harbors, the most satisfactory solution for which has been maintenance dredging.

As shown by the above discussion, the sediment problem in the Pacific Northwest is not believed to be as severe as in other parts of the United States. For this reason, only a small scale program of sediment measurement has been outlined for the North Pacific Division.

The Seattle District has prepared a plan for measurement of silt deposit in Mud Mountain Reservoir, but it will probably be some time before deposits thick enough to warrant measurement are experienced. This reservoir is to be used for flood control only, and does not have a conservation pool; the outlets will be open most of the time and low flows will tend to flush out sediment rather than bring in new deposits. No sediment sampling program on rivers in the District has been planned.

The Portland District expects to make measurements of silt deposits in Cottage Grove and Fern Ridge Reservoirs in the fall of 1947. These are multi-purpose reservoirs that have been in operation for several years, and definite indications of the extent of the silting problem should be obtained from these and succeeding measurements. In addition, a sediment sampler has been obtained and it is expected that a field party will be organized in the near future in order that data on sediment in several of the streams in the Portland District will become available for aid in the design and operation of future reservoirs.

GERARD H. MATTHES.* The object of this discussion is to cite one case where sedimentation in a reservoir was largely prevented at trifling cost. This is not offered as a solution to the problem of reservoir sedimentation in general - rather, its applicability elsewhere is restricted to mountain streams carrying chiefly bed load material.

The case is that of Barker Dam Reservoir on Boulder Creek, Colorado, owned and operated by the Public Service Company of Colorado. The dam, located at an altitude of about 8,000 feet, is of the straight gravity (Wegman) type, 177 feet in height and 720 feet in length. The reservoir serves to regulate the flow of Boulder Creek for power production at a plant 12 miles downstream, which operates under a head of 1,835 feet. Storage capacity is about 12,000 acre-feet. The dam was built in 1909 and has required no major repairs until 1946 when it was found that disintegration at the upstream face, due to severe frost action, called for an extensive refacing project. In the course of this work the reservoir was drawn down to a very low level. This revealed the extent to which sedimentation had progressed.

Deposits at the base of the structure averaged in the neighborhood of thirty feet in depth, a surprisingly small amount in view of the 36 years of continuous operation of the reservoir. The sediment consists of fine clay-like materials brought in mostly by side-hill wash. All coarse bedload material brought down by Boulder Creek, which is the main feeder of the reservoir, had been intercepted by a weir at the upper end of the reservoir. This weir was not built originally to serve as a debris basin, but was designed by the writer in 1908 for the purpose of measuring the inflow from Boulder Creek, whose waters have to be accounted for, being covered by the prior rights of the irrigators of the valley lands below the power plants.

Since the weir had to be kept free from deposits upstream in order to maintain its rated capacities (the weir actually consists of three sections, a Cipoletti and two rectangular weirs placed at different elevations and controlled by a recording gage), the writer at the time of its installation had requested periodical removal of debris accumulations. During the 36 years that have elasped, the Company maintained the weir, and exercised care to remove debris after each highwater period. When visited in 1946, the accumulation of debris that had been removed was found to consist mainly of gravel. It had been piled up on ground out of the reach of high stages. As stated by the Chief Hydraulic Engineer of the Public Service Company of Colorado, the cost of removal of the gravel, year after year, has amounted to a small maintenance expense of which no separate book record has been kept. In volume, the writer's estimate would place the total at less than 10,000 cubic yards. Sedimentation in the reservoir resulting from side hill wash probably amounts to several times this amount.

From the point of view of reservoir operation, the case here described is of interest in that it proves that the life of many reservoirs built at high altitudes in the Rocky Mountains could have been similarly prolonged at small cost had such a plan been adopted. In the majority of cases that have come to the attention of the writer, no attempt has been made to provide debris basins to intercept bed load materials. The plea usually made is to the effect that no adequate place for storage of the intercepted materials is available within the proximity of the point or points of inflow.

MR. COLDWELL. I would like to comment that whereas the method described by Mr. Matthes has been effective for the reservoir mentioned, which is on a stream draining mountainous areas and with a low suspended load, the expense of keeping large multiple-purpose reservoirs free of sediment in this manner would be prohibitive unless an economic use for the dredged material could be found.

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