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SEDIMENTATION IN A SMALL CHANNEL-TYPE RESERVOIR [1]

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ABSTRACT

Knowledge concerning the sedimentation in conservation-type structures built in hilly country and forming a reservoir similar to a river channel is practically nonexistent. Reservoir sites in such areas are becoming more valuable and are being used extensively. Information is needed on anticipated sediment accumulation and on the physical properties of the deposited sediment to facilitate the design of more efficient and longer-lasting structures.

Ashland Lake in central Missouri is a channel-type reservoir that was built in 1937 with a capacity of about 346,000 cubic meters. Its drainage area is 979 hectares. A study of its sedimentation was undertaken to provide essential design information. Detailed reservoir sedimentation surveys were made in 1949, 1951, 1955 and 1962.

The distribution of sediment in the vertical and in the horizontal planes remained fairly constant between surveys. The particle-size distribution of the deposited sediment was found to vary, depending on the distance from the dam. The volume-weight of the sediment increased with depth in the deposit and decreased with percent clay.

Physical and chemical measurements of the lake water show that Ashland Lake is stratified thermally May through October, confining circulation to the upper one-third of the lake. Water turbidity may reach 200 ppm (platinum wire). Concentrations of cations are less than amounts considered effective in flocculation of clay particles.

RÉSUMÉ

Des résultats concernant la sédimentation dans des réservoirs et en conservation-type de structures analogues, servant à la conservation du sol et de l'eau, construits en terrain accidenté et formant des réservoirs similaires à un chenal de rivière sont pratiquement non existants.

Des sites de réservoirs dans ces régions deviennent de plus grande valeur et sont plus intensément utilisés.

Il est nécessaire d'avoir des indications sur l'accumulation antérieure des sédiments et sur les propriétés physiques des dépôts afin de faciliter le projet de structures plus efficaces et plus durables.

Ashland Lake dans le Missouri Central est un réservoir du type canal qui fut construit en 1937 avec une capacité d'environ 346.000 mètres cubes. Son bassin de drainage est de 979 hectares. Une étude sur sa sédimentation fut entreprise pour fournir les informations essentielles pour le projet. Des mesures de détail de la sédimentation furent faites en 1949, 1951, 1955 et 1962.

La distribution des sédiments dans les plans verticaux et horizontaux resta presque constante entre les levés. La distribution de la dimension des sédiments déposés variait avec distance du barrage. Le poids spécifique des sédiments augmentait avec la profondeur du dépôt et décroissait avec le pourcentage en argile.

Des mesures physiques et chimiques de l'eau du lac montrent que Ashland Lake est thermalement stratifié du mois de mai jusqu'en octobre, la circulation restant confinée au tiers supérieur du lac. La turbidité de l'eau peut atteindre 200 ppm (file de platine). Les concentrations de cations sont inférieures aux montants considérés effectifs dans la flocculation des particules d'argile.

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Soil and water conservation agencies urgently need information and guidelines on the sedimentation in small reservoirs. Their planners and designers need to know how to estimate the sediment deposition—the total volume, its volume-weight, and distribution of sediment within a proposed reservoir—in order to design a structure and reservoir for a given site that will operate efficiently and will not fill with sediment faster than anticipated. Volume-weight, as defined here, is the dry weight of a unit volume of reservoir sediment in place, usually expressed as grams per cubic centimeter.

Such knowledge is needed for all types, sizes, shapes, and locations of reservoirs and other conservation structures that help resist the loss of upland soil and water. In some places, the topographic characteristics of the site are such that most of the storage is within the confines of the river channel; these are called channel-type reservoirs. USDA Miscellaneous Publication 964 (7) [3] summarizes sedimentation surveys made through 1960 on reservoirs in the United States. Detailed data on the sedimentation of small channel-type reservoirs like the one presented in this paper are not readily available, and they are a worthwhile addition to that store of information.

Ashland Reservoir in central Missouri was built in the rolling hills country, and most of the water storage is contained in a relatively deep and narrow channel. It was studied to obtain design criteria for similar types of reservoirs.

This report analyzes and compares the volume of deposited sediment and its volume-weight at four survey dates. The distribution of sediment is given graphically for the same dates. In addition, physical and chemical features of the lake water are enumerated, which help to explain some of the sedimentation activity in Ashland Lake.

Ashland lake and watershed

Ashland Lake is located on Brushy Creek in Boone County, near central Missouri at latitude 38° 46′ North, longitude 92° 12′ West.

Dam and Reservoir

The dam, which forms the lower extent of the lake, was constructed in April 1937 by the former Resettlement Administration, an agency of the Federal government. The dam is an earthfill structure with a concrete core wall, and is about 12 meters high. The spillway is a concrete drop chute.

Storage of water began in June 1937, and the reservoir was filled by February 20, 1938. The original capacity of Ashland Lake was about 346,000 cubic meters, and the surface area at the spillway elevation was 7.22 hectares.

The reservoir (fig. 1) is long and narrow; the main body is about 1.1 kilometers long, and has an average width of about 56 meters. The channel side slopes are relatively steep and are covered with trees and brush above the water line. Excessive turbidity of the water is a dominating characteristic, and it affects biological and physical features.

Watershed

The drainage area for Ashland Lake is 979 hectares; it is about 8 kilometers long and has an average width of 1.2 kilometers. The total relief is 27 meters.

Soils in the drainage area are dominantly of a silt loam texture and are highly erosive. Sheet and gully erosion have been quite severe.

The lake and watershed are in the 970-mm average annual rainfall zone. The nearest weather station (22 kilometers), Fulton, Missouri, was used for information on the long-term annual precipitation and the average for the periods between survey dates.

[3] Superior numbers in parentheses refer to Literature Cited, p. 11.

Investigations

Sedimentation Surveys

Ashland Lake was surveyed in detail four times before 1966. The dates of the surveys were November 15, 1949; April 11, 1951; July 26, 1955; and June 15, 1962. They were made cooperatively by the Agricultural Research Service and Soil Conservation Service of the USDA, the University of Missouri, and the Missouri Department of Conservation. Following is a description of the details of the surveys, a summary of the data, and analyses of the findings.

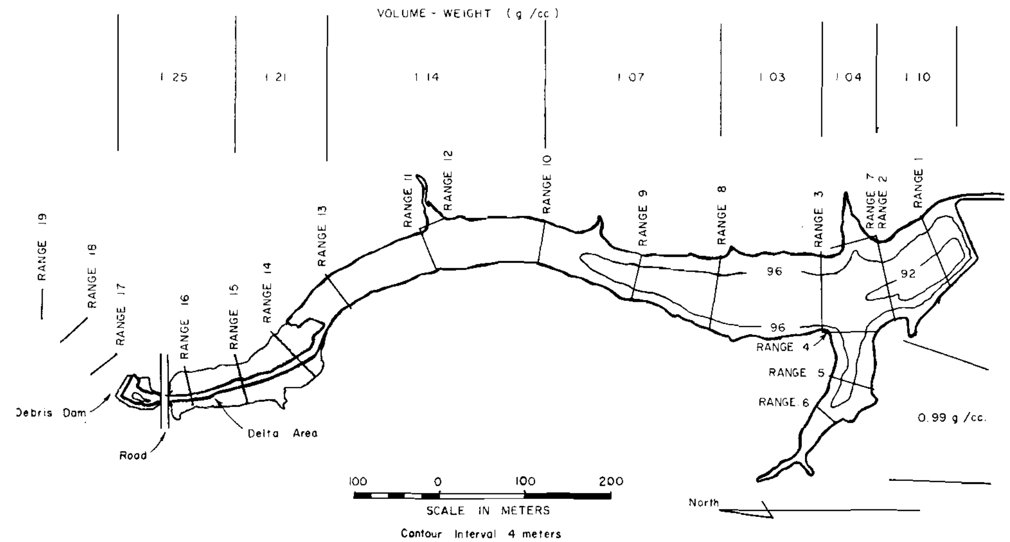

Fig. 1 — Ashland Lake, 1962 Survey.

The reservoir was surveyed according to the general techniques outlined by Heinemann and Dvorak (5). The spillway contour, 16 established ranges traversing the main body of water and tributaries, and three additional ranges located on the main stream above the headwaters were surveyed. We sounded along the water ranges shown in figure 1 to get the remaining depth in the reservoir. Plane table and alidade and level were used to survey the range lines and the delta areas above the water surface.

During the 1949, 1951, and 1955 sedimentation surveys, split-tube and special tubular volumetric samplers were used to obtain volume-weight information. During the 1962 survey, we used the gamma probe (6,3) and a volumetric piston-type sampler to get volume-weight data. We made density probe readings at short intervals of depth in the deposited sediment at 17 locations on the established ranges.

The volumetric piston-type sampler has interchangeable barrels that are 1 and 2.7 meters long and 7.30 cm in diameter. The length of core depends on the depth the sampler can be driven into the sediment by its hammering device. A 10.2-cm sample was taken approximately every 30 cm of core length. We selected 57 such samples from 13 locations on the ranges. The samples were then dried and weighed in the laboratory to get the volume-weight (volumetric). These samples were also used for our laboratory studies.

Laboratory Analyses of Samples

The laboratory determinations included particle-size distribution, specific gravity, and spectographic analyses. We used the hydrometer method to get the particle-size distribution and pycnometer bottles to measure the specific gravity or particle density. Organic matter was not removed prior to the density measurement. Six samples were also analyzed by spectographic methods to determine the amounts of those elements which affect the absorption of gamma rays and, in turn, affect the operation of the gamma probe.

Studies of Water

Studies of the physical and chemical qualities of Ashland Lake water covered a 12-month period in 1952 and 1953, and again in 1962 and 1963. Observations were made at two-week intervals in 1952 and 1953, and at monthly intervals in 1962 and 1963. One sampling station was located over the deepest water at range 1 and one at range 11. The vertical series of temperature readings were at 0.3-meter intervals, and the chemical series at 1.5-meter intervals.

Standard methods described by the American Public Health Association (1) and Welch (9) were employed in these studies. Turbidity was measured with a U S Geological Survey turbidity rod; the depth at which the rod was visible was expressed in parts per million of suspended matter. Dissolved solids were analyzed in the Spectographic Laboratory of the University of Missouri.

Results

Sediment

The volume of deposited sediment was the difference in reservoir capacities between the original and later surveys. Reservoir capacities were computed by the stage-area method (5).

The Sedimentation Information Curves (fig. 2) give considerable data on the sedimentation activities in this lake. For example, in the lower 40 percent of the original depth, there was 10 percent of the original capacity. By 1962, 24 percent of the total sediment (1937-1962) was distributed below this depth, and 84 percent of the capacity below this depth was replaced by sediment. In addition, the intersection of the "capacity replaced by sediment" curves with the 100-percent original depth shows that 34 percent of the original capacity was lost to sediment by the 1962 survey. The intersection of these same curves with the 100-percent line on the abscissa shows that the capacity in the lower 25 percent of the original depth of the reservoir was lost by 1962.

The gradient of the sediment (fig. 3) shows that the lower half of the reservoir remained approximately the same as the original channel. The elevation of the low point on the cross sections of range 14 and above reached a maximum by the 1949 survey. As the delta continued to build up on the sides, the bottom of the channel through the delta remained constant through 1955, but by 1962 the channel had become narrower and deeper.

Physical Properties of Sediment

The particle-size distribution of the sediment varied with the distance from the dam. Sand and silt were maximum near the headwaters of the reservoir and decreased in percentage as the dam was approached. The percentage of clay ($<4\mu$) was the lowest at the headwaters and increased toward the dam.

Volume-weight increased proportionally to the logarithm of the depth below the surface of sediment (fig. 4). Sediment located above the low water elevation (fig. 4, range 13) was more dense than that constantly submerged.

Volume-weight decreased with an increase in percent clay ($<4\mu$). The degree of correlation between percent clay and volume-weight was not as significant as that found by Heinemann for Sabetha Lake, Kansas (4).

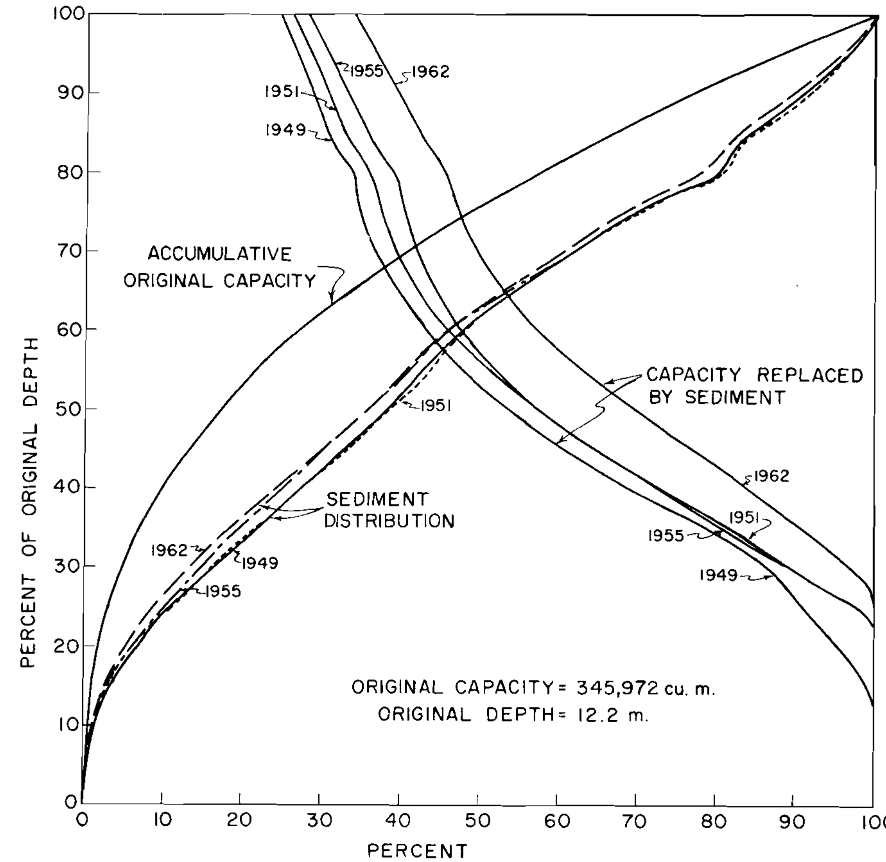

Fig. 2 — Sedimentation Information Curves.

The variation in the average volume-weight for different segments of the reservoir (portion between ranges) is shown in figure 1. The average volume-weight for the segment was determined from the weighted average of gamma probe volume-weight readings in that segment. The average volume-weight was maximum in the delta area where the sediment is exposed at low water levels (approximately 1.2 meters below spillway elevation), and where the percentage of clay is minimum.

The volume-weight determined by using the volumetric sampler was generally lighter than comparable determinations from using the gamma probe. The difference between the two methods seems to remain constant regardless of the magnitude of the

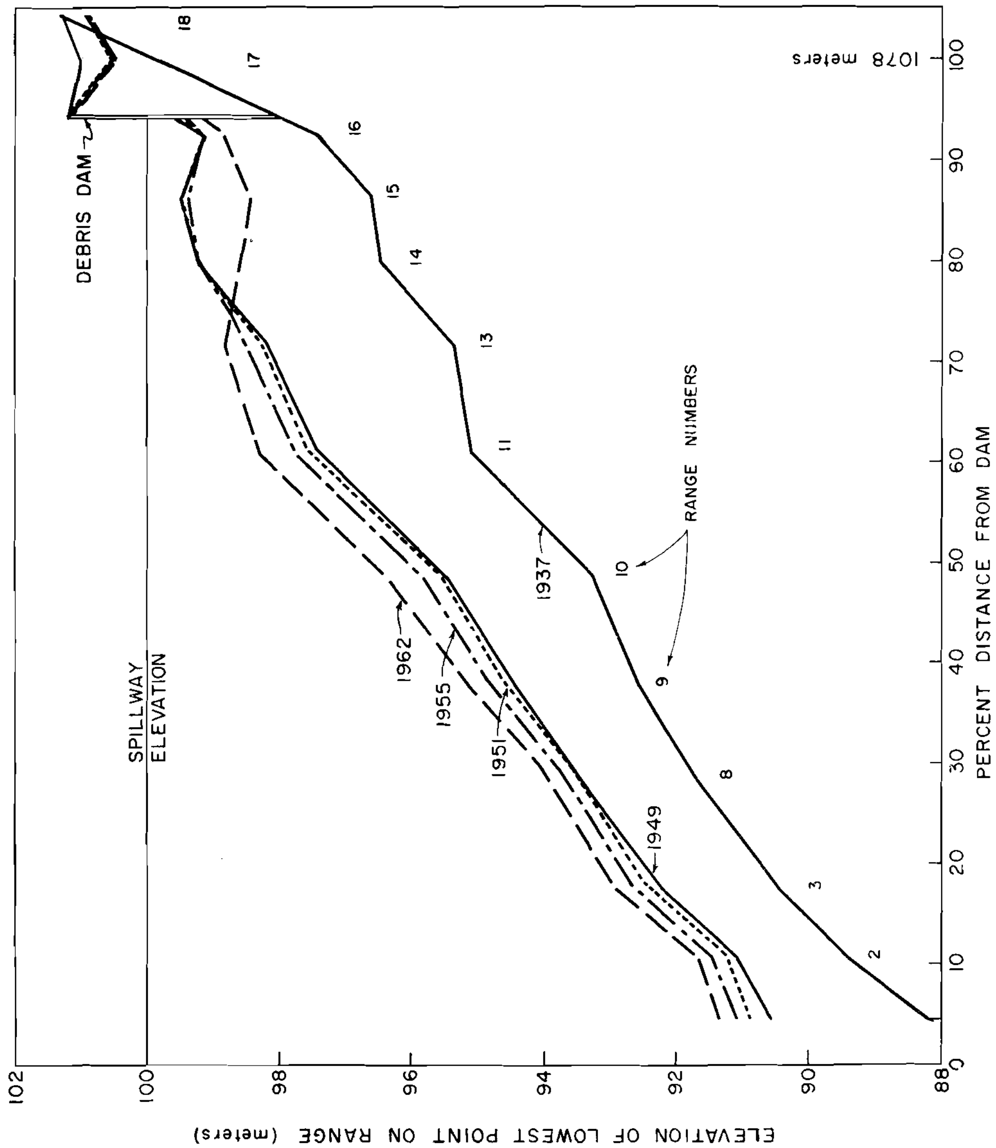

Fig. 3 — Gradient of Reservoir Bottom.

volume-weight, and is similar to the comparison made on Sabetha Lake (4). The gamma density probe is believed to be the more accurate of the two methods and its results are reproducible.

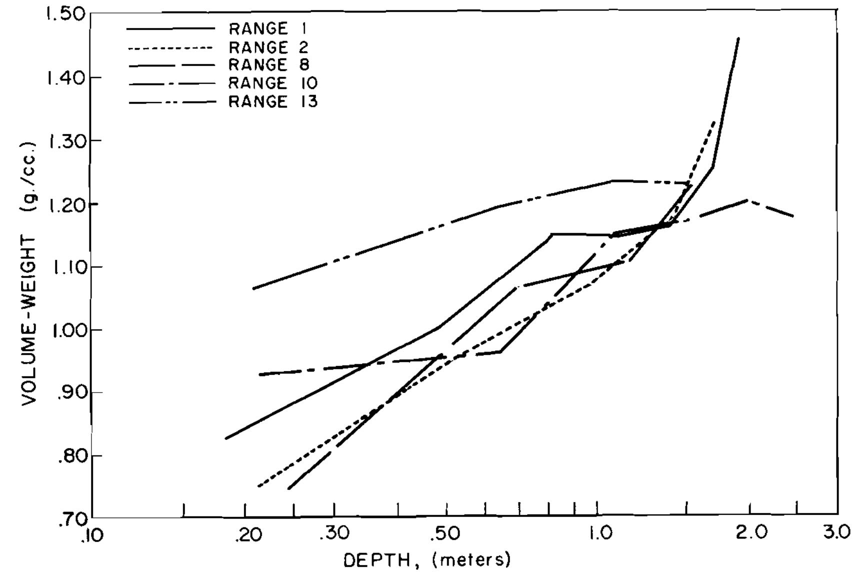

Fig. 4 — Volume-weight Versus Depth in Sediment.

Sediment Accumulation

The weight of accumulated sediment was computed from the weighted average volume-weight for the sediment within each re ervoir segment and the volume of sediment in that segment. The sum of the weight of sediment in all segments gave the total weight of sediment in the reservoir. The accumulation at the time of each survey is shown in table 1.

TABLE 1

Sediment Accumulation, Ashland Lake

Date of Survey	Period Years	Sediment Accum. Metric Tons per hectare-year for period	Average Volume-Weight g/cc	Average Precip. for period mm	Number of Years with Precip. > Long-Term Average
April 1937	(constructed)				
Nov. 1949	12.6	7.63	1.11	1044	7
April 1951	1.4	2.83	1.09	1071	1
July 1955	4.3	1.90	1.09*	825	1
June 1962	6.9	3.64	1.11	873	2
1892-1961				971	

* Estimated.

Physical and Chemical Characteristics of Lake Water

Temperature. — There are two periods of thermal stratification, one during ice cover and one during summer, seperated by spring and fall overturns when lake waters are in circulation.

The period of winter stratification is quite variable in Ashland Lake, since it is dependent on the frequency and persistence of ice cover. Ice was present less than 4 weeks of 1952 and 1953, but lasted more than 10 weeks in 1962 and 1963. During this period of stratification, a thin layer of colder water is superimposed on warmer water (fig. 5, January 1953). Frequently, this is the time when the surface waters attain their greatest clarity.

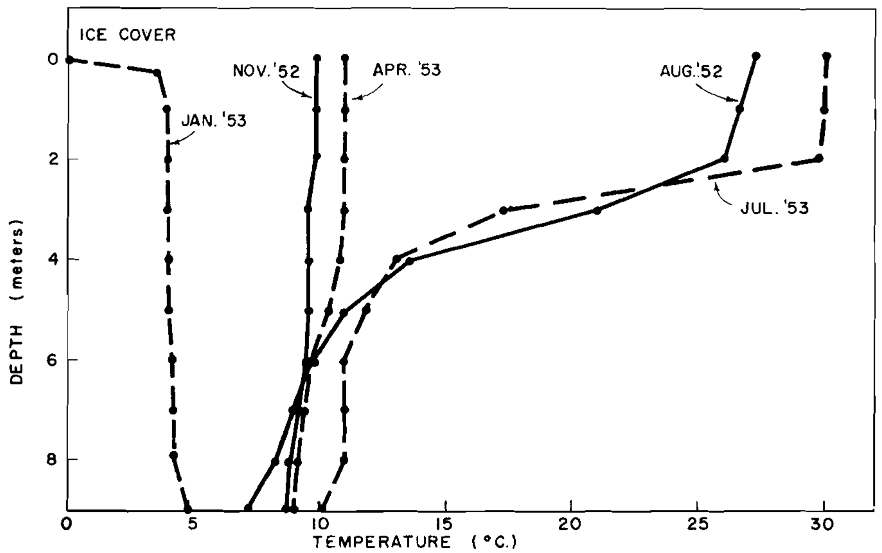

Fig. 5 — Representative Seasonal Temperature Curves-Range 1.

During summer stratification, insolation results in a surface layer of warm water 2 to 3 meters deep. This is separated from the deeper mass of cold water by a narrow stratum within which there is a sharp drop in temperature. This stratification is well established by July and continues through October (fig. 5, July 1953 and August 1952) The thickness of the upper warm layer is a measure of the depth to which winds are able to accomplish mixing.

Fall circulation, with temperatures approaching uniformity at all depths. is usually well established by November (fig. 5) and persists until the development of ice cover. Since suspended materials such as plankton organisms are well distributed at most depths at this time, we would expect suspended clay particles to be uniformly dispersed throughout the lake water. The spring circulation period follows the melting of the ice cover and usually extends into April.

Turbidity. — Turbidity readings varied between 5 and 40 parts per million (ppm) from June through February. The water is most transparent, averaging 10 ppm, under ice cover and during summer stagnation. However, during spring overturn, a period which coincided with spring rains, turbidity was much increased—with a maximum reading of 200 ppm.

Flocculating Agents. — Mineral content was measured at 0- and 8-meter depths seven times during the latter study period. Concentrations of calcium and magnesium cations ranged from 9 to 58 ppm and from 3.8 to 15.5 ppm, respectively. Amounts of both sodium and potassium ions were less than 7 ppm; soluble iron varied from 0.3 to 14.4 ppm.

Discussion

Sediment

The constant vertical distribution of sediment accumulation shown in figure 2 indicates that, on an average, the same proportion of sediment is deposited in the same location or elevation from year to year. This is further exemplified by the relatively parallel "capacity replaced by sediment" curves. The slope of different segments of the "sediment distribution" curve points out that the 60- to 80-percent depth zone has the most sediment—about one-third of the total accumulation. The horizontal distribution did not change appreciably between surveys.

The change in the gradient (fig. 3) at the upper end of the reservoir shows how deposition was affected by the velocity of the inflowing suspended sediment. Through the delta area where most of the inflow was confined to the channel, there has been no deposition of sediment in the channel since 1949. During periods of overbank flow, sediment was deposited on each side of the channel, building up the delta and, by 1962, the channel had become narrower and deeper. Along range 13, the channel was no longer well-defined, the inflowing suspension spread over a larger cross section, and the velocity and turbulence decreased. This allowed for the rapid deposition of sand and the larger fraction of suspension, making the bottom elevation higher than immediately upstream in the channel.

As the remaining suspension moves toward the dam, the silt fraction and some clay are deposited. The percent clay ($<4\mu$) is maximum near the dam, since the sand and silt settled prior to reaching that area. This is in accordance with Stokes Law.

The volume-weight of the sediment increased with depth in the sediment. It is therefore logical to assume that consolidation takes place throughout the sediment profile. Taylor ([8]) and others have shown that the void ratio for the initial compression of clay material is given by the following expression:

$$e = e_0 - C_i \log \frac{P}{P_0} \tag{1}$$

where e is the void ratio at equilibrium with intergranular pressure, P, e_0 is the void ratio at a fixed pressure, P_0, and C_i is the compression index. The void ratio can be computed from the volume-weight, and the logarithm of P/P_0 is proportional to the logarithm of D/D_0. This allows us to write equation 1 in terms ot volume-weight and depth in sediment:

$$\frac{1}{w/v} = \frac{1}{w/v_0} - \frac{C_i S}{\gamma G} \log \frac{D}{D_0} \tag{2}$$

where w/v is the dry volume-weight (g/cc), w/v_0 is the volume-weight at a fixed depth D_0, S is the slope of the P vs. D relationship on logarithmic paper, γ is the unit weight of water, and G is the specific gravity of the sediment.

Because of the varying composition of the sediment throughout the reservoir, an additional term, C, percent clay ($<4\mu$), was added to the above equation. For sediment in delta areas or areas not always submerged, the intergranular pressure is greater than in the rest of the reservoir; therefore, this sediment has a greater volume-weight.

To incorporate this difference into equation 2, the depth measurements in this area were adjusted to a new depth which gave a submerged pressure equal to the original nonsubmerged pressure. Multiple regression analysis was used to determine the following equation for predicting the volume-weight:

$$\frac{1}{w/v} = 0.824 - 0.32 \log D + 0.0019\, C \qquad (3)$$

The coefficient of determination for this equation was 0.823. The coefficient of partial correlation between w/v and log D is -0.899 and, with C, it is 0.527 (2).

Variation in the rate of sediment accumulation may be attributed to differences in the rate and total precipitation, land use, surface condition at the time of precipitation, and trap efficiency of the reservoir. Table 1 lists the sediment accumulation and precipitation for the periods between surveys and also data on precipitation. The number of years with precipitation greater than the long-term average explains some of this variation, but data are not available on the other parameters affecting the sediment accumulation.

The "true" rate of sediment accumulation must be based on the weight of sediment. The volume of sediment is inadequate because of the variation and constant consolidation of the sediment. This is verified by the increase in sediment volume-weight with depth. The weight of sediment accumulation is only as accurate as the volume-weight and volume measurements. In the first three surveys of Ashland Lake, the volume-weight was determined using small-diameter core samplers which penetrated only the upper portion of the sediment. For this reason, the weight of sediment at each survey date has not been compared critically.

Water Studies

Temperature conditions in Ashland Lake are similar to those in other reservoirs in the north temperate region. Spring and fall overturns continue for several months. This is the time of highest turbidity, and when physical and chemical conditions are rather uniform at all depths throughout the lake. The summer is marked by pronounced thermal stratification. During this period, the effects of wind circulation are confined to the upper 3 meters, leaving a cold, stagnant water mass below. This condition reduced the overall ability of the reservoir to trap sediment during periods of small outflow.

Periods of high turbidity also correlate with periods of heavy runoff. Comparisons of turbidity measurements in Ashland Lake with measurements in other reservoirs in the Midwest make it clear that Ashland Reservoir is to be classed with the more turbid reservoirs.

The concentrations of calcium, magnesium, sodium, and potassium ions are all too low to be effective in the flocculation of clay particles.

Summary

Sedimentation surveys were made of Ashland Lake (a channel-type reservoir) in 1949, 1951, 1955, and 1962. The distribution of sediment in horizontal and vertical planes remained relatively constant between all four surveys. The gradient of the reservoir bottom remained the same for the lower portion of the reservoir, while the upper end was affected by the build-up of the delta area. The particle-size distribution of the sediment was found to change with distance from the dam.

The 1962 survey data showed volume weight to increase with depth. The theory of consolidation was applied to give the basis for statistical analysis of the data. The logarithm of intergranular pressure was proportional to the logarithm of depth. Percent of clay was used as a measurement of the sediment composition. The best equation determined by regression analysis showed that the reciprocal of the volume-weight was inversely proportional to the logarithm of the depth in sediment and proportional to the percent clay. Eighty-two percent of the variation of volume-weight can be accounted for by these two factors.

Ashland Lake is strongly stratified May through October and, during this stagnation period, circulation is restricted to the upper 3 meters. Spring and fall overturns are a time of rather high turbidity compared with the winter and summer periods of quiescence. The lake is also highly turbid following rainfall, but clears slowly during the stagnation periods.

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