PREDICTING SEDIMENT DISTRIBUTION IN LARGE RESERVOIRS

By

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IN LARGE RESERVOIRS

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CHAPTER 1

INTRODUCTION

Reservoir design has been predicated on the economic principle of "supply and demand". The underlying philosophical thrust of this principle requires the optimization of storage to satisfy quantitative demands or needs. An important design consideration in determining the amounts of storage required to satisfy the needs is the amount and distribution of sediment deposition.

In the past, sediment storages were provided at the bottom of reservoirs. Since about 1950, attempts have been made to predict the distribution of sediment deposition through reservoirs. These attempts began when the fact was realized that sediment does tend to deposit through the length of reservoirs.

Sediment is defined by Blench (1, pg. 3) as, "Any material denser than water, that is transported at any stage of flow." Sediment usually consists of sand, gravel, silt or clay. The study of sedimentation examines two distinct phenomenon - degradation and deposition. Both are concerned with the effects of flow on the land surface and both occur when the flow is not in equilibrium. Deposition occurs when circumstances are such that the flow is unable to transport its sediment load. The flow, as described by Blench (2), is in equilibrium when it is neither degrading nor depositing and flows always seek equilibrium.

The source of most water-borne sediment in the southwest is sheet erosion of freshly plowed ground. In this region of the country, most rainfall occurs as thunderstorms in the spring months, and at the same time the fields are being plowed. The runoff occurs as sheets across the fields. The rainfall has a great capacity for picking up sediments. The second largest source of sediment is degradation of stream channels in the upper reaches of the streams. Here, the slopes are steep and flow velocities are high. The streams are seeking equilibrium. Once the sediment has reached a stream or river, it may be classified into the following three groups: suspended, bed load, and saltation. A discussion of the movement of sediment follows:

Brown (4, pg. 1) states:

> The movement of sediment in alluvial streams is so complex a problem, that it may never be completely subject to a rational solution. It represents, in fact, the most extreme degree of unsteady, non-uniform flow, since the streambed as well as the water surface may be continually changing in flow. With the present state of knowledge, an approximate understanding of the general transport mechanism can be obtained only by isolating particular details or by simplifying the boundary conditions that only the most significant variables need be considered.

In light of this comment, a discussion of sediment movement is limited to an explanation of the three groups of sediment transport.

1. Suspended sediment. This sediment is suspended in the stream flow and is usually the smaller grained material.

2. Bed load. This material usually is larger and more dense material which is rolled along the bottom of the stream.

3. Saltation. This material is transitional between the suspended and bed level material and is thought to be bounced along

the bottom of the stream.

Since, in any stream flow, a certain amount of turbulence exists, it is at times difficult to separate the three groups into distinct classifications.

Another type of sedimentation process is air-borne sediment. This type of process is characterized by dust or sand storms and is not infrequent in the southwest. Air-borne sediment is difficult to measure, so the discussion in this thesis will deal exclusively with water-borne sediments.

The amount of sediment being caused by rivers is proportional to the discharge of the river and the availability of sediment. The higher the discharge, the greater the volume of sediment. The greater volumes of sediment are then deposited in lakes during high or flood type flows. (This is also when the greatest rainfalls occur, and sheet erosion occurs). Sediments deposit in lakes because of a change in flow characteristics of the transporting streams. Under normal conditions, the following should occur as described by Fowler (5):

1) The heavier grains will deposit first in the upper reaches of the lake.

2) The silts and fine sands will be transported and deposited downstream of the heavier grains since these particles require lower velocities to remain in suspension.

3) The first visual evidence of sedimentation will be the forming of a delta where the river bed intersects the normal water level of the lake.

4) As the delta continues to grow and reduce the flow area

at the mouth of the river, the inflow velocities will increase and sediments will be transported further downstream. Eventually, the fine sand will be distributed in the lower reaches of the lake.

5) As the sediment deposition increases, the ability of the lake to trap the sediment will decrease, causing reduction in trap efficiency.

This distribution of sediments throughout the lake have major consequences on the ability of the lake to perform its project purposes. Obviously, if flood control is a purpose and since most of the heavier grains are deposited in the flood pool, this would reduce the total volume available for flood control operations. A major portion of the sediments are deposited just below the top of normal pool which is usually considered the conservation pool. Sediments in this pool could afford project purposes such as; water supply, irrigation, and hydro-power. Sediments which deposit in the inactive pool could effect the power intake structures.

The objective of this thesis is to present a critique of several methodologies used in predicting the distribution of sediment deposition in reservoirs. This thesis is not meant to be critical of these methods, but will compare results using these methods with an actual sediment deposition occurrence in an attempt to aprise the reader to the problems involved in predicting sediment deposition distribution. This thesis will also attempt to alert the reader to the importance of a careful analysis of the problem in designing a reservoir.

The construction of any large reservoir requires a great sum of money. Contracts will be signed to provide a certain amount of water for useful purposes such as water supply, irrigation and hydro-electric power. If that reservoir is to provide the intended functions over a long period of time, each phase of its design must be thorough and competent. The amount of water necessary to fulfill the project purposes can be determined by rather rigorous hydrologic computation. The amount of storage spaces or volume in each of the various parks is determined by the volume of water required for the purpose plus the volume of expected sediment. Many texts have been written on hydraulics, and engineering students are fairly competent in this field. No texts and few publications exist on the prediction of sediment deposition, hence, the justification for this work.

This thesis is organized in such a manner as to be useful in the prediction of sediment deposition. Two different methods are described and the same sample problem is worked with each method and compared with actual measurements of sediment deposition.

CHAPTER II

REVIEW OF LITERATURE

An understanding of sediment transport in rivers can be obtained from a study of Dr. Blench's (1) many works. Notably among Dr. Blench's books are Mobile Bed-Fluviology and Hydraulics of Sediment-Bearing Canals and Rivers, both of which give a good description of how rivers transport sediment and the results of various criteria on the ability of rivers to transport sediments.

Lloyd C. Fowler (5) in his publication Determination of Location and Rate of Growth of Delta Formations gives a good description of delta formation and growth and the effects of various types of soils on delta formations. As in most cases in literature on sedimentation, the formulas proposed use parameters which cannot be quantified with any real accuracy.

Many articles on sedimentation have appeared in the American Society of Civil Engineers Journal of the Hydraulics Division. Noteworthy among these is the paper entitled Distribution of Sediment in Large Reservoirs by Whitney M. Borland and Carl R. Miller (3) which appeared in Volume 84, published in April 1958, on which a large portion of this paper is based. Also noteworthy is the article entitled Trap Efficiency of Reservoirs, Debris Basins and Debris Dams by Charles M. Moore, Walter J. Wood, and Graham W. Renfro (6) which appeared in Volume 86, published in February 1960.

A method of measuring sediment in reservoirs is presented in the US Department of Agriculture pamphlet entitled Silting of Reservoirs by Henry M. Eakin and revised by Carl B. Brown (4). The pamphlet also includes data from resurveys of various reservoirs. Even though the methods described in this literature are still in use, they are completely out-of-date because of technology advances in survey equipment. The literature contains useful data as to the resurveyed reservoirs.

Although tremendous volumes of work have been accomplished in the field of sedimentation, little has been written on sediment deposition distribution. Most formulas pertaining to this subject are empirical and most do not treat the whole problem as is attached in this paper.

CHAPTER III

PREDICTING SEDIMENT DISTRIBUTION

In Chapter I, the general nature of sediment transport, the trends of sediment distribution and the effects of sediment deposition were discussed. In this chapter, the art of predicting sediment deposition distribution throughout the depth of a reservoir will be discussed. The procedures discussed will be somewhat empirical, however, like hydrology, predicting the distribution of sediment in a lake is an art. It is an art, in that the number of parameters effecting the solution are beyond the limits of capability to handle in an analytical fashion. The engineer must develop a sense or feel for the problem. This sense comes from experience in the field and an understanding of geology, soil mechanics and hydrology. Certain variables have a definable effect upon the amount, kind, and therefore, distribution of sediment deposits in a lake. For comparison during the discussion, Lake Texoma, a classical problem in sediment deposition and distribution, will be referred to as an example.

The physiological characteristics of the basin above a prospective dam site will have an effect upon the amount, type, and therefore, distribution of sediment deposits in the lake. The size of the basin above the dam or the total drainage area is indicative of the amount of sediment available for transport and depending upon rainfall, the amount of flow with which to transport the sediment. However, the size of the basin above can be deceiving since as with most of the other variables used in solving the problem, it is not independent. But in predicting deposition, the first step should be to determine the size of the basin.

The shape of the basin also can have an effect upon the problem. A basin whose width equals or exceeds its length, will for the most part, have a smaller ratio of net sediment contributing area to total drainage area than one whose length exceeds its width. Normally, as the width to length ration decreases, the net sediment contributing area to total drainage area will increase. In Lake Texoma, the width to length ratio is 0.26 and the net sediment contributing area to total drainage area is 0.72. The second step in solving the problem of distribution is to determine the net sediment contributing area. Areas in the basin behind upstream large dams contribute little or no sediment to the proposed impoundment and sediment which passes through these structures may generally be assumed to pass through the proposed lake. Areas within the basin which are so broad and flat that drainage direction cannot be determined, should also be considered as non-contributing. Areas above distinct alluvial fans should be considered as only partially or non-contributing. Areas such as, above Hutchison, Kansas, on the Arkansas River, where most of the flow is lost due to irrigation or in-seep into groundwater should not be considered as contributing. Computing the net sediment contributing area in many instances will rely upon the judgement of the engineer. A careful study of the physiological features from aerial photographs and U.S.G.S. quadrangle maps will aid the engineer in his decisions. Generally, a knowledge of the topographic features within the basin is essential in determining the amount and character of the transported sediments. If time allows (and perhaps time should be provided), sediment sampling stations should be located within the basin. In most large basins within the continental United States, some sampling stations with long periods of record have been established by various governmental agencies. Care must be taken in locating sampling stations. Stations should be located for easy access and should reflect the character of the basin above the station. A station located just above or below a dramatic change in stream slope will produce readings which will be misleading for predicting sediment inflows for a proposed dam downstream. Stations should not be located in areas where stream velocities will be higher or lower than normal for the reach under investigations.

This leads naturally into a discussion of the rivers and streams within the drainage basin. Rivers are again dependent variables, dependent upon such things as topography, rainfall, runoff and use. However, a knowledge of the rivers within the basin will aid the engineer in understanding the phenomenon of sediment transport. Geologists have classified rivers into three rather distinct groups according to age. A young river has such features as a "V" shaped cross section, relatively straight alignment, high velocities, steep bed slopes and during flood, light suspended sediment loads with bed loads of heavy material. A dam located on a young river will normally produce a deep narrow lake. Light sediment deposition will occur in the bottom of the lake during floods. The heavier bed load material will probably not reach the lake as it will be dropped as the peak flow passes and will not be transported a great distance. One would not expect an extensive delta to be formed on this type of lake because of the lack of growth along the stream channel and the light sediment loads. These light loads are usually due to the lack of available sediments. An example of a stream in the young age is the Arkansas River above Canyon, Colorado. A stream in mature age has a "U" shaped cross-section with some over-bank flow during flood. The river will show mild meanders with somewhat gentler slopes and slower velocities. These rivers are normally degrading during floods and will carry large suspended sediment loads and large bed loads. Bed load material will be somewhat heavier (as discussed in Chapter 1) than the suspended loads and will be transported greater distances than young rivers are capable of doing. The river will probably experience some growth of willows and/or salt cedars in the over-bank areas. A dam across a river in mature age will produce a lake which will experience some delta growth. However, the "U" shaped cross-section will prohibit extensive delta growth. Some sediment will be deposited in the higher reaches of the lake but because of the high suspended load, most deposition will occur in the lower reaches or the bottom of the lake. A river in old age will exhibit a broad flat cross-section with extensive over-bank flow during floods. Excessive meanders with frequent ox-bow lakes representing cut-off meanders will be present. The channel slopes will be flat and the river will exhibit slow velocities with large base flows. A lake on a river in old age will most likely experience heavy delta growth with most sediments being deposited at or above top of normal pool.

Stream bed slopes or gradients are indicative as to the amount of sediment transported. Streams with steep slopes (greater 0.5%) usually carry little sediment. This is not due to lack of carrying capacity, but rather to a lack of available sediment for transport as most of these streams are located in mountainous terrain. Streams with steep slopes are degrading and over time will reach an equilibrium point with respect to sediment load. This is a primary cause of meanders in streams with mild slopes (0.5% to 0.5%). Mildly sloped streams are primarily degrading and only occasionally reach or exceed equilibrium. Once equilibrium is exceeded, deposition occurs. Streams with flat slopes (less than 0.05%) usually are constantly degrading or depositing and the sediment load to carrying capacity is close to unity. Sudden changes in stream slope affects the carrying capacity of sediment. A sudden change from steep to mild slopes could cause deposition of part or all of the streams sediment. While a change from mild to steep slopes could induce a degrading effect. The engineer should examine the stream slopes within the basin under study. This examination should help in the establishment of sediment contributing drainage area, sediment available for transport and a better understanding of the nature of the stream under study.

An accurate and long time record of stream discharges with corresponding integrated sediment measures is a tremendous aid in predicting sediment yields and distribution. Streams which show a wide variance in discharges (as due most streams within the Southwest) usually will transport large quantities of sediment. Streams with a small variance in discharge will transport less sediment. This is due primarily to a stream bed which is constantly wetted and becomes armored. A stream whose discharge varies allows the overflow area to dry and become subject to wind and rain action, thus, breaking up the top soil. Plants which survive in this type of overflow area usually aid in the breaking up of the top soil and making the soil more susceptable to erosive action.

An investigation of the land cover and use within the basin is required to understand and predict sediment loads. Heavy timbered lands usually do not erode as much as grass lands. This is due mainly to the shielding effect of trees against the forces of erosion such as wind and rain. However, if timber operations are in progress, large amounts of sediment will be produced. If the shielding effect of the trees is removed, the soil becomes very susceptable to erosion. National grasslands such as those found in the Dakotas and Nebraska will produce more sediment than timbered lands. Arid lands with little or no vegetation will yield large amounts of sediment during high flows (periods of intense rainfall). In the Southwest, lands used for agricultural purposes produce most of the sediment which occurs in the stream. Even with the relatively new methods of agriculture erosion checks, little or no gain can be found in the loss of good top soil to erosion (as measured in stream gages). As stated in Chapter I, most plowing occurs just before heavy spring rains, and most harvesting takes place just before the heavy fall rains. These actions loosen the top soil and aid the erosive action of the rainfall. Until recent Environment Protection Agency regulations become effective, this process will also contribute to pollution of the river with pesticides and other harmful farm additives.

Large stable urban areas produce little sediment, but do add greatly to stream pollution. Urban areas which are expanding, produce large amounts of sediment. In recent years, the advent of massive housing development has added large amounts of sediment to streams. If large stable urban areas exist in the drainage areas, consideration should be given to subtracting that area or at least a portion of that area from the total sediment contributing areas. If the urban area is growing and new housing developments are in process or a predicted population growth is forecast, then that area should be included in the contributing area.

Upstream reservoirs have an effect upon sediment transport in streams. Large dams effectively trap most of the suspended sediment and all of the bed load. The sediment which passes through these dams can be assumed to pass through any downstream structure. The area above large dams should not be considered as sediment contributing. Small Soil Conservation Service dams trap most sediments during normal flows. However, during high flows, a large portion of the suspended sediment will be discharged. The life of these smaller dams is short and probably will not exceed 50 years before their basin will be full of sediment. Therefore, consideration should be given to count some percentage of small dams drainage area as sediment contributing. Over a long period of time, upstream large dams will effectively reduce the amount of sediment deposition in a downstream lake. Initially, though, these structures could increase sediment in the river due to the scouring effect of their discharges. Since the water being discharged is relatively free of sediment, it has a large capacity for picking up sediment, hence, the scouring effect immediately downstream of the structure. This effect is not all bad, since in hydro-power projects, predicted scour can be used to increase the hydraulic head to the turbines.

The topography of the basin to be inundated will somewhat determine how sediment will be deposited. Before predicting sediment distribution, the engineer should derive an elevation-area curve and an elevation-capacity curve. The elevation-area curve is derived from planimetering the contours within the basin. The elevation-capacity curve is then computed from the elevation-area curve. The conic volume formula has been found to be the most accurate representation of most basins. This formula is:

$$dV = \frac{Ai + (Ai + 1)}{3} (dh) \qquad (3\text{-}1)$$

where: dV = Volume between elevations whose areas are Ai and Ai + 1, and dh = Height between elevations whose areas are Ai and Ai + 1. Progressive summations of dV will yield the capacity at any elevation whose areas are Ai + 1. From the formula, it can be seen, flat basins with broad flat areas at lower elevations will produce large volumes at those elevations with little change in elevation. While basins which are "V" shaped require a large change in elevation to produce a large volume. An example of elevation-capacity curves and elevation-area curve for Lake Texoma is shown on Figure 1. It is normally expected, that after sedimentation occurs, a somewhat smaller volume and area would be expected at each elevation but the shape of the curve would not be altered drastically.

The character or type of sediment being transported is another factor in how the sediment will be deposited. As discussed in Chapter 1, sands are vey susceptable to a change in river regimes. That is, any change in the flow characteristics of a river transporting sand will effect the amount of sand transported. When that river flows into a lake, the velocity of flow will be altered and the heavier sands will be deposited. Since most transport occurs during flood time, it is expected initially, that most sands will be deposited at or above top of conservation (normal) pool and will form a delta. As the delta grows, the flow area of the river is reduced, so that, velocities can be retained further downstream and increase the growth of the delta into the lake basin. Over a period of time, sands will be deposited throughout the depths of the lake. Rivers transporting sediments consisting mainly of clays will deposit their loads more uniformly in the lake basin. Over time, some delta growth would be expected from clay bedded streams due to a reduced basin capacity at the higher elevation in the basin and vegetation growth in the unwetted areas during normal flow periods.

A study of the climatology of the basin is important to understand the transport media or river flow characteristics. The amount of rainfall is a factor in determining the volume of water or discharge of the river. The intensity and distribution (as to

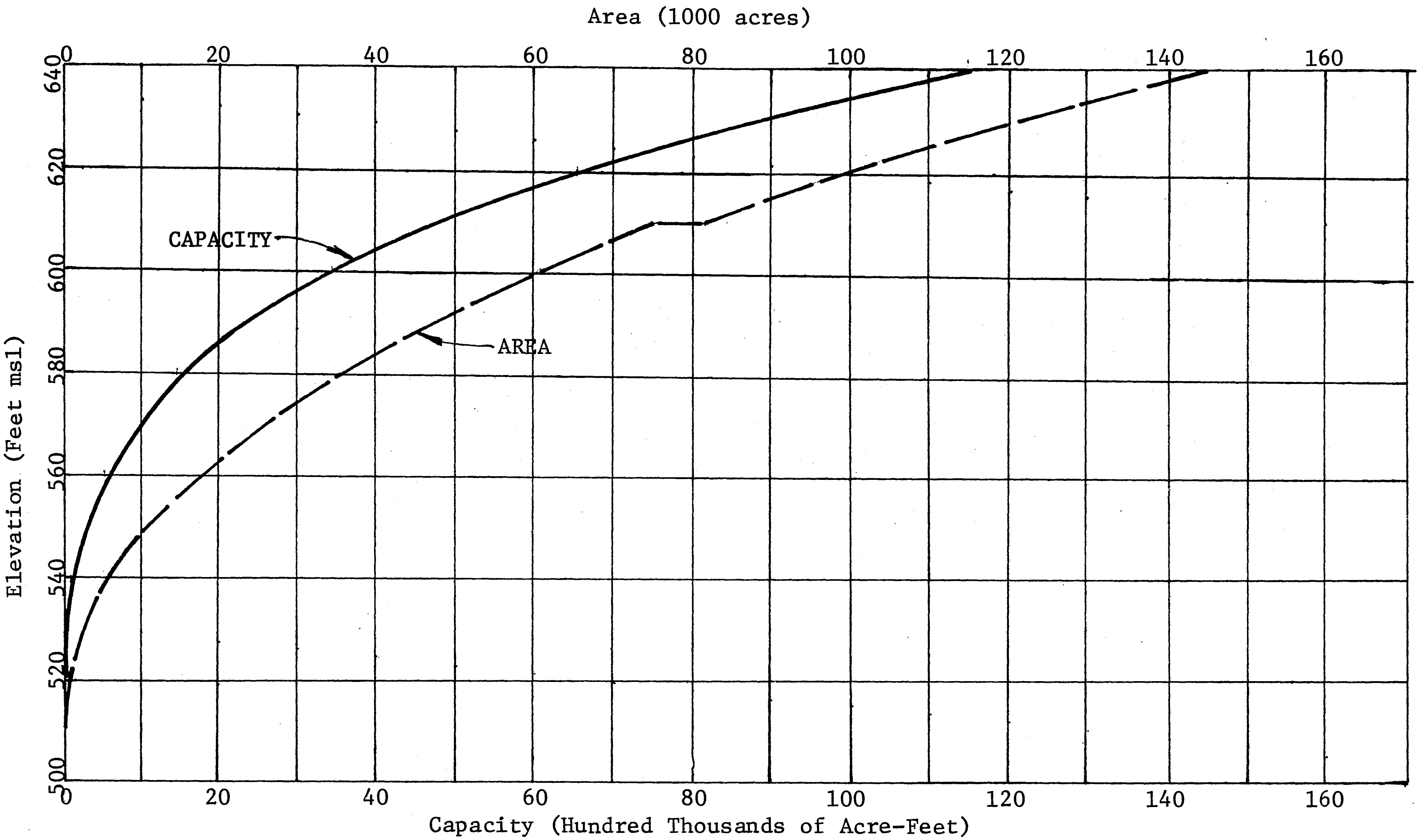

Figure 1. Elevation-Area-Capacity Curves

time of year) very often determines the amount of sediment in the rivers. In the southwest, rainfall usually occurs as thunderstorms of high intensity over a short period of time. They occur normally during the spring and fall of the year and most often just after fields have been plowed or the crops have been harvested. This phenomenon produces the high sediment yields experienced in this region of the country. The force with which the rainfall hits the earth determines the amount of soil dislodged. If the soil has been disturbed by plowing, etc., more soil will be dislodged and transported by the runoff. The picking up and transporting of the soil most often occurs as sheet erosion. This occurs during and directly after high intensity rainfall as a sheet of water flowing over a broad area. The deeper the water, the more erosion occurs as the tractive force between the water and the soil is directly proportional to the depth of water. Since sheet erosion is the primary source of sediment in the stream, much research by State and Federal agencies has been done in attempting to stop this phenomenon. However, methods such as contour plowing, sediment checks, ditch checks, etc., have yielded little results in prohibiting sheet erosion. It appears that the hedge rows of France and the stone fences of England are still the best methods of breaking up sheet erosion. But these methods are too expensive when applied to the broad expanses of most American farms.

The design of the dam is another primary factor in the way sediment is deposited in the lake basin. Following is a discussion of three types of dam designs and their effects upon sediment distribution.

1. Valley gated. A valley gated dam consists of an earthen embankment with a gated spillway. Normally, this type of dam has a flood pool not over 40 feet deep or about the height of the tainter gates. Flood protection is usually for something less than the 50-year flood. The top of water is expected to be in the flood pool often. Little or no surcharge above top of flood pool is provided (Keystone Dam has only three feet of surcharge) since operation of the gates is fast and the top of water may be controlled easily. During large floods, when most sediment is deposited in the lake, the top of flood pool is reached quickly and a higher percentage of sediment may then be assumed to deposit at the higher elevations. Trap efficiencies or the ability of the lake to trap or hold inflowing sediment is lower than can be expected in other dam designs and usually are in the range of 70 percent to 90 percent. As lakes with valley gated spillways begin to fill with sediment, trap efficiency will be markably lower.

2. Frequent service-low level spillways. This type of dam design has an earthen embankment with a chute type spillway located located at or near the top of normal pool. The spillway is frequently used and the height of flood pool rarely exceeds 20 to 30 feet. The flood pool is made up of inducted surcharge and during high flows will be used more often. The spillway is uncontrolled and is dependent on the depths of water in the flood pool to govern discharges. High percentages of sediment inflow will be deposited at or above the top of normal pool. With the range of deposition not nearly as great as experienced with gated spillways.

3. Limited Service - High level spillways. This type of dam

has an earthen embankment with a high level spillway. The flood pool is usually deeper than in the two previously discussed designs. The spillway is set at a much less frequent flood such as the Standard Project Flood. Normally during floods, sediment will be distributed over a more larger range of elevation than the valley gated spillway.

Project purposes effect sediment deposition distribution in reservoirs. Following is a discussion of various project purposes for which if a reservoir is operated will effect sedimentation.

1. Flood Control. The depth and frequency of use of flood control pools of reservoirs on sand bedded streams normally determine distribution of sediment in the lake. A small pool which is infrequently used limits the distribution of most deposits to around the top of conservation pool. While a lake with a large flood pool that is frequently used, will have a broader range of sediment deposition. A small pool which is frequently used may cause the sediment to be distributed at lower elevations because of rapid delta growth. A large flood pool that is infrequently used will cause a concentrated deposition at or just below top of conservation pool (as in the case of Lake Texoma).

2. Hydro-Power. If hydro-power is a project purpose, the top of normal pool is normally drawn down somewhat below the top of conservation pool. As flood waters enter the lake, deposition begins somewhat below the top of conservation pool. This tends to decrease the life of the conservation pool.

3. Recreation. If recreation is a project purpose, the top of conservation pool should be maintained at a fairly constant

elevation. A high percentage of sediment would then be deposited in the flood pool. Recreation areas should not be located in the upper end of pools since delta growth could limit access to favorable recreation water.

4. Water Supply. The use of the lake for water supply will cause the top of normal pool to be drawn down as in the case of hydro-power. Water supply inlets should be located close to the dam to allow a range of withdrawals which could not be achieved in areas that may have delta growth. In sizing a conservation pool for water supply, care should be taken to adequately predict sediment deposition so that contracts for water can be honored after 5-100 years of sedimentation.

Figure 2 is a cross-section of a typical large reservoir. The volume behind the dam is divided into three layers. Layer one represents the inactive storage which in the past was known as the sediment storage (7). Layer two represents the conservation storage. Layer 3 represents the flood storage. Depending upon the previously discussed project purposes, the normal water surface would be at top of conservation pool.

The foregoing discussions of the various parameters which effect sedimentation in reservoirs has been general in nature. The words; probably, most often, normally, etc., have been used liberally. As in most cases, engineers involved with predicting sediment behavior should come to expect the unusual to occur. The cause and effect of differing sediment happenings are often better explained with hindsight. But the fact is, that sediment deposition and distribution must be forecast if project purposes are to be fulfilled.

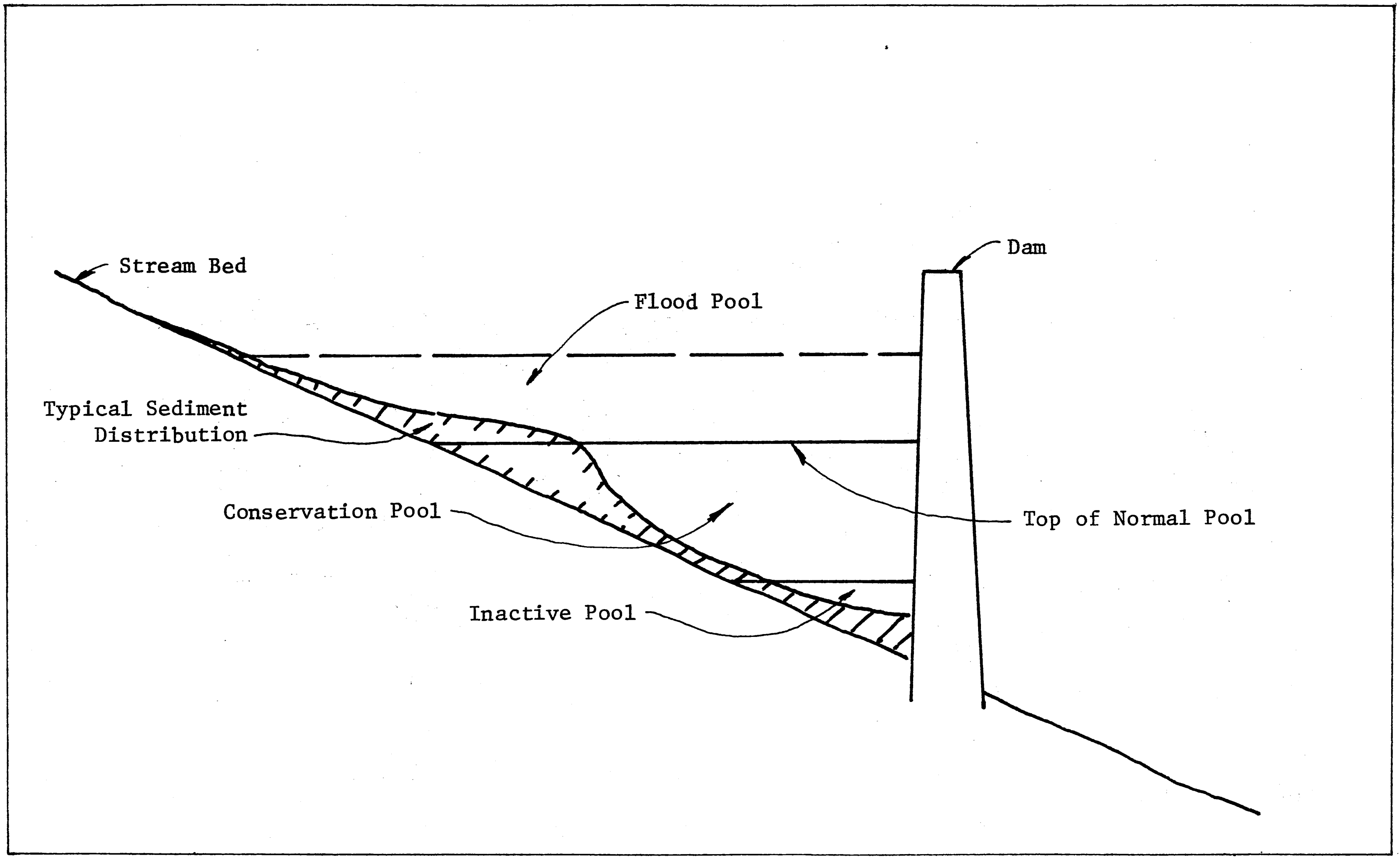

Figure 2. Profile of Typical Reservoir

Too large an estimate, would add additional costs to our already expensive structure, while a conservative answer might jeopardize the intended use of the project.

The fourth step in predicting sediment distribution is determining sediment inflows. Ideally, one will have a gaging station with a long period of record such as the Durwood, Oklahoma gage on the Washita River. The gaging station will record flows continuously with integrated sediment samples taken by hand periodically. The flows with corresponding percent concentration by dry weight of suspended sediment are recorded in ascending order according to flows. The flows are then divided into groups as shown on Table I, summed and averaged along with the corresponding percent concentrated sediment. These values are then plotted on log-log paper to produce a curve as shown in Figure 3.

The next procedure is to compute the flow-duration. This is accomplished by determining the total number of days of record then assembling the flows into representative groups and computing percentages as shown in Table II. Total time of record in Table II was 9,946 days. Using Figure 3 and Table II construct Table III. Percent concentration is read directly from Figure 3. Sediment load is computed by multiplying percent concentration times the discharge. Percent time is read from Table II. Next, plot sediment load in million tons per year. Percent time flow is equal or exceeded on special graph paper as shown in Figure 4. Sediment load is plotted on standard log scale while percent time is plotted on special scale which elongates small values for easy reading. These small values produce the largest amount of sediment yield.

TABLE 1

SAMPLE GROUPING OF FLOWS AND SEDIMENT CONCENTRATION

No Samples	Discharge CFS	Percent Concentration
	0-99	
E=52	E=2810	E=0.69
Average	54	0.0133
	100-199	
E=105	E=16.078	E=2.30
Average	153.1	0.0219
	200-399	
E=177	E=50.539	E=7.39
Average	285.5	0.0416
	400-599	
E=119	E=67.845	E=11.51
Average	483.6	0.0974
	600-799	
E=85	E=58.611	E=15.441
Average	690	0.1817
	800-999	
E=56	E=50.343	E=13.989
Average	899	0.2498
	1000-1499	
E=79	E=95.855	E=22.95
Average	1213	0.2905
	1500-2999	
E=106	E=225.426	E=50.63
Average	2.127	0.477
	3000-6999	
E=85	E=403.414	E=71.955
Average	4.746	0.8465
	7000-12,999	
E=38	E=350.655	E=44.76
Average	9325	1.1705
	13,000-24,999	
E=43	E=819.490	E=47.003
Average	19.058	1.0931
	25,000-49,999	
E=17	E=529.570	E=11.04
Average	31.151	.6494
	50,000-higher	
E=5	E=357.100	E=1.76
Average	71.420	.3520

TABLE II

FLOW - DURATION AT DURWOOD

Flow (c.f.s.)	Number of Days Equal or Exceeded	Percent of Total Time
50	9311	98.05
100	8997	94.75
200	8079	85.08
500	5017	52.84
1,000	2834	29.84
2,000	1628	17.14
5,000	678	7.14
10,000	263	2.73
20,000	72	.758
50,000	6	.063
75,000	1	.0105
Maximum Daily	85,900 cfs	
Maximum Instantaneous	91,300 cfs	

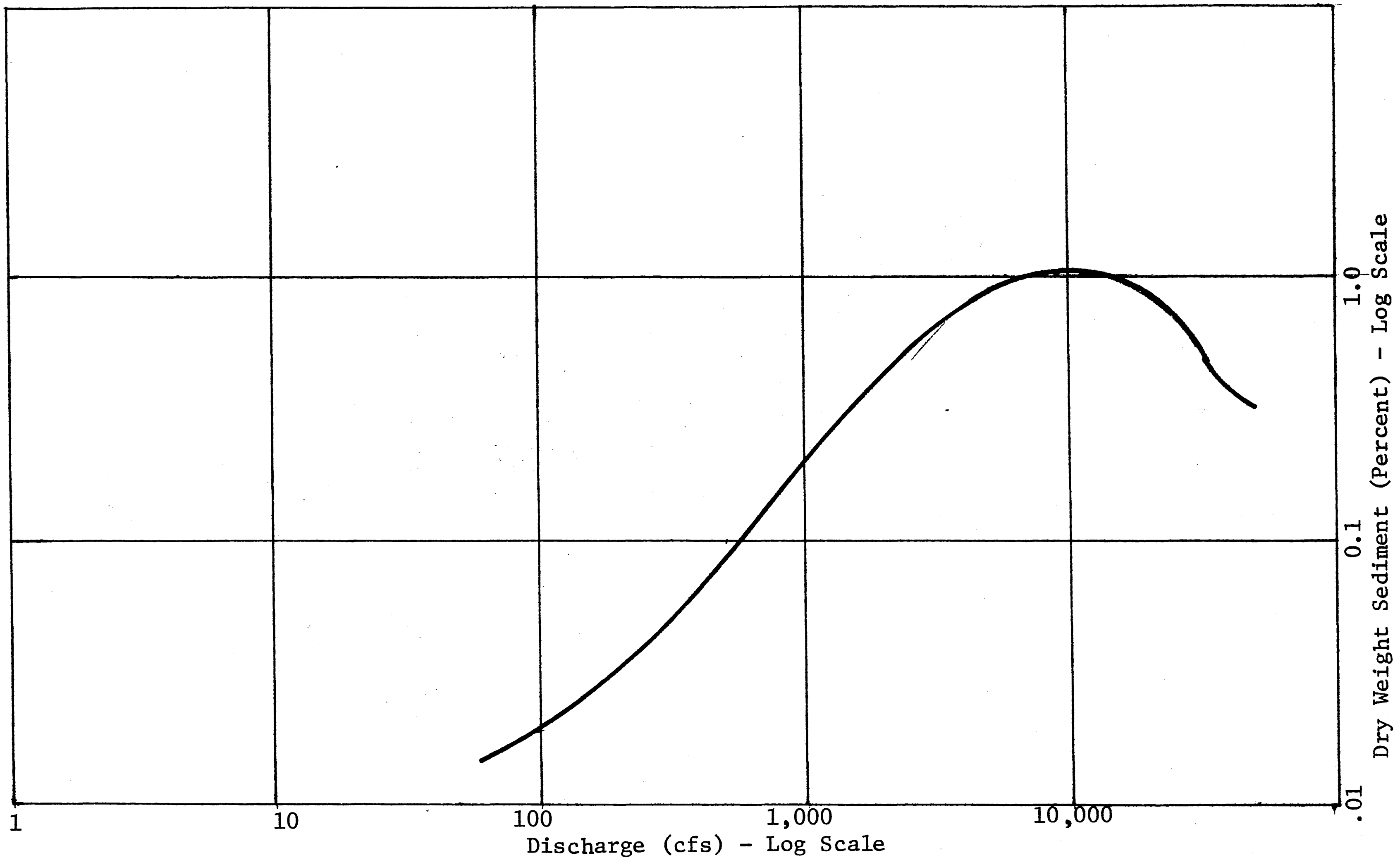

Figure 3. Suspended Sediment Concentration Curve at Durwood, Oklahoma

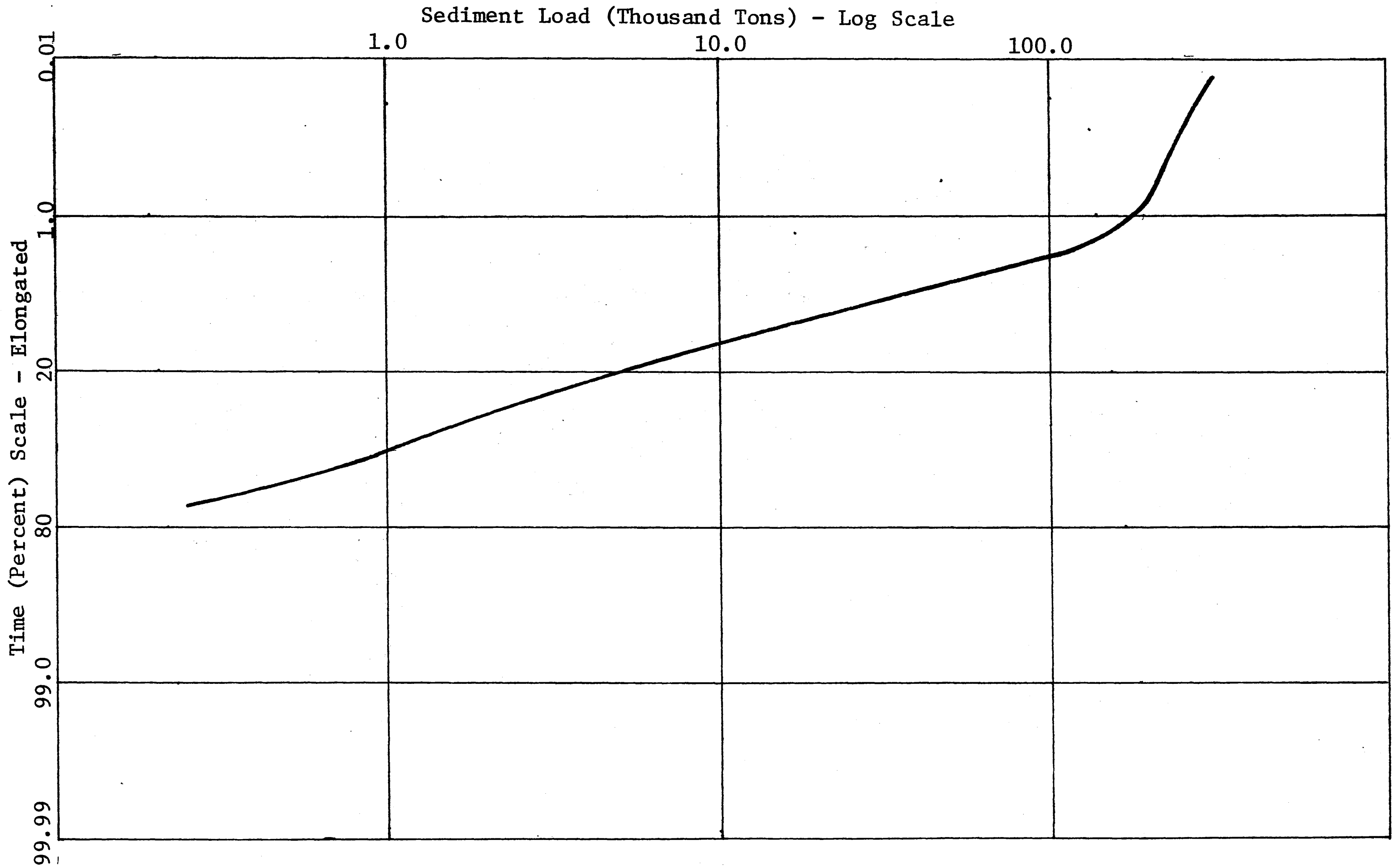

Figure 4. Sediment Load versus Percent Time Flow is Equalled or Exceeded

TABLE III

SEDIMENT LOAD versus PERCENT TIME OF FLOW AT DURWOOD

Discharge cfs	Percent Concentration	Sediment Load Millions of Tons/Year	Percent Time
91,300	.300	274	.01
85,900	.317	272	.0104
75,000	.343	257	.0105
50,000	.440	220	.063
20,000	1.040	208	.758
10,000	1.200	120	2.77
5,000	.880	44	7.14
2,000	.463	9.26	17.14
1,000	.243	2.43	29.84
500	.0965	.4825	52.84
200	.0280	.056	85.08
100	.0168	.017	94.75
50	.0127	.006	98.05

From this curve, read the average sediment load for delta increments of percent time and construct Table IV. Next, multiply the delta increment of percent time by the average sediment load to get the incremental annual sediment load. Sum the incremental annual sediment loads for the annual sediment load by the weight of an acre-foot of sediment to arrive at the annual sediment load. For Durwood, as shown at the bottom of Table IV, this value is 6,094 Ac-Ft/Yr. Divide this value by the sediment contributing drainage area which for Durwood is 7,200 square miles to arrive at the sediment yield of 0.85 Ac-Ft/Sq Mi/Yr.

TABLE IV

ANNUAL SEDIMENT LOAD

Delta Percent Time	Incremental Sediment Load	Incremental Annual Sediment Load	+	Delta Percent Time	Incremental Sediment Load	Incremental Annual Sediment Load
.00 - .01	294	2.94	+	19	5.60	5.60
.01 - .02	252	2.52	+	20	5.05	5.05
.03	238	2.38	+	22	4.25	8.50
.04	232	2.32	+	24	3.45	6.90
.05	226	2.26	+	26	2.85	5.70
.06	222	2.22	+	28	2.38	4.76
.07	218	2.18	+	30	2.01	4.02
.08	217	2.17	+	32	1.68	3.36
.09	216	2.16	+	34	1.44	2.88
.10	215	2.15	+	36	1.23	2.46
.15	213	10.65	+	38	1.06	2.12
.20	212	10.60	+	40	.902	1.84
.3	214	21.4	+	42	.785	1.57
.4	214	21.4	+	44	.680	1.36
.5	214	21.4	+	44 - 46	.593	1.18
.6	213	21.3	+	48	.520	1.07
.7	209	20.9	+	50	.458	.91
.8	202	20.2	+	52	.391	.78
.9	195	19.5	+	54	.346	.69
1.0	187	18.7	+	56	.303	.68
1.0 - 1.2	177	35.4	+	58	.264	.52
1.4	165	33.0	+	60	.234	.46
1.6	153	30.6	+	62	.204	.45
1.8	143	28.6	+	64	.179	.34
2.0	135	27.0	+	66	.157	.31
3	11.4	114.0	+	68	.138	.27
4	81.5	81.5	+	70	.122	.24
6	61.0	61.0	+	72	.107	.23
7	37.5	37.5	+	74	.093	.18
8	29.5	29.5	+	76	.081	.16
9	24.5	24.5	+	78	.061	.13
10	20.5	20.5	+	80	.060	.12
11	16.7	16.7	+	82	.051	.11
12	14.3	14.3	+	84	.043	.0
13	12.2	12.2	+	86	.043	.0
14	10.5	10.5	+	88	.030	.0
15	9.30	9.30	+	90	.024	.0
16	8.05	8.05	+	92	.019	.0
17	7.10	7.10	+	94	.014	.0
18	6.30	6.30	+	96	.9906	01
					TOTAL	929.1

or 9,291,000 tons/year ÷ 1524
or 6,094 Ac-Ft/ Year ÷ 7,200
or 0.85 Ac-Ft/Sq Mi/Year which is the sediment yield of the sediment contributing drainage area

If no gaging station exists in the basin, an estimate of the sediment yield will be required. The US Department of Agriculture (7) developed the formula:

$$Se = Sm \left(\frac{Ae}{Am}\right)^{0.8} \qquad (3\text{-}2)$$

where Se = Sediment yield to structure being designed (in tons per year), Sm = Sediment yield to a surveyed reservoir (in tons per year), Ae = drainage area of reservoir being designed, Am = drainage area of surveyed reservoir. For similar basins, Se and Sm may be expressed in Ac-Ft/Yr. Using this formula to compute the sediment yield for Lake Texoma when compared to Eufaula Lake gives a sediment yield of 23,188 Ac-Ft/Yr as compared to a measured yield of 25,700 Ac-Ft/Yr or an error of about 10 percent. This is within acceptable limits of accuracy considering the present methods of reservoir sediment surveys. Another method of estimating sediment yields is to compare similar basins directly. The sediment yield (in Ac-Ft/Sq Mi/Yr) of Eufaula is 0.931 while at Lake Texoma the yield is 0.889. In comparing the basins, one would find a higher percentage of cultivated ground in the Eufaula Basin and would reduce slightly the yield value. However, a direct comparison gives only a five percent error which is better than the preceding formula.

The fifth step in predicting sediment distribution is determining the trap efficiency of the proposed lake. Trap efficiency is the amount (in percent) of the sediment inflow that will remain in the lake basin. Researchers developed the following procedure for determining trap efficiency (6).

A. Determine total volume of sediment storage required for the proposed reservoir. For Lake Texoma;

0.889 X 28925 X 100 ≈ 2,571,000 Ac-Ft, where: 0.889 is sediment yield in Ac-Ft/Sq Mi/Yr, 28925 is the sediment contributing drainage area, and 100 is the proposed life of the lake in years.

B. Determine the amount of storage to satisfy the proposed project purposes. Inactive storage must be included since this storage provides the necessary head required for the hydro-power turbines. At Lake Texoma this storage is 3,288,000 Ac-Ft.

C. Determine the average annual runoff or water inflow. This value is 4,006,000 Ac-Ft at Texoma.

D. Compute (A + B)/C = 1.46 for Texoma.

E. Using the curves shown in Figure 4, determine the trap efficiency. In the case of Lake Texoma, use the median curve, and the trap efficiency is about 98 percent. The curves were drawn from computed trap efficiencies of some forty-one reservoirs throughout the United States.(6)

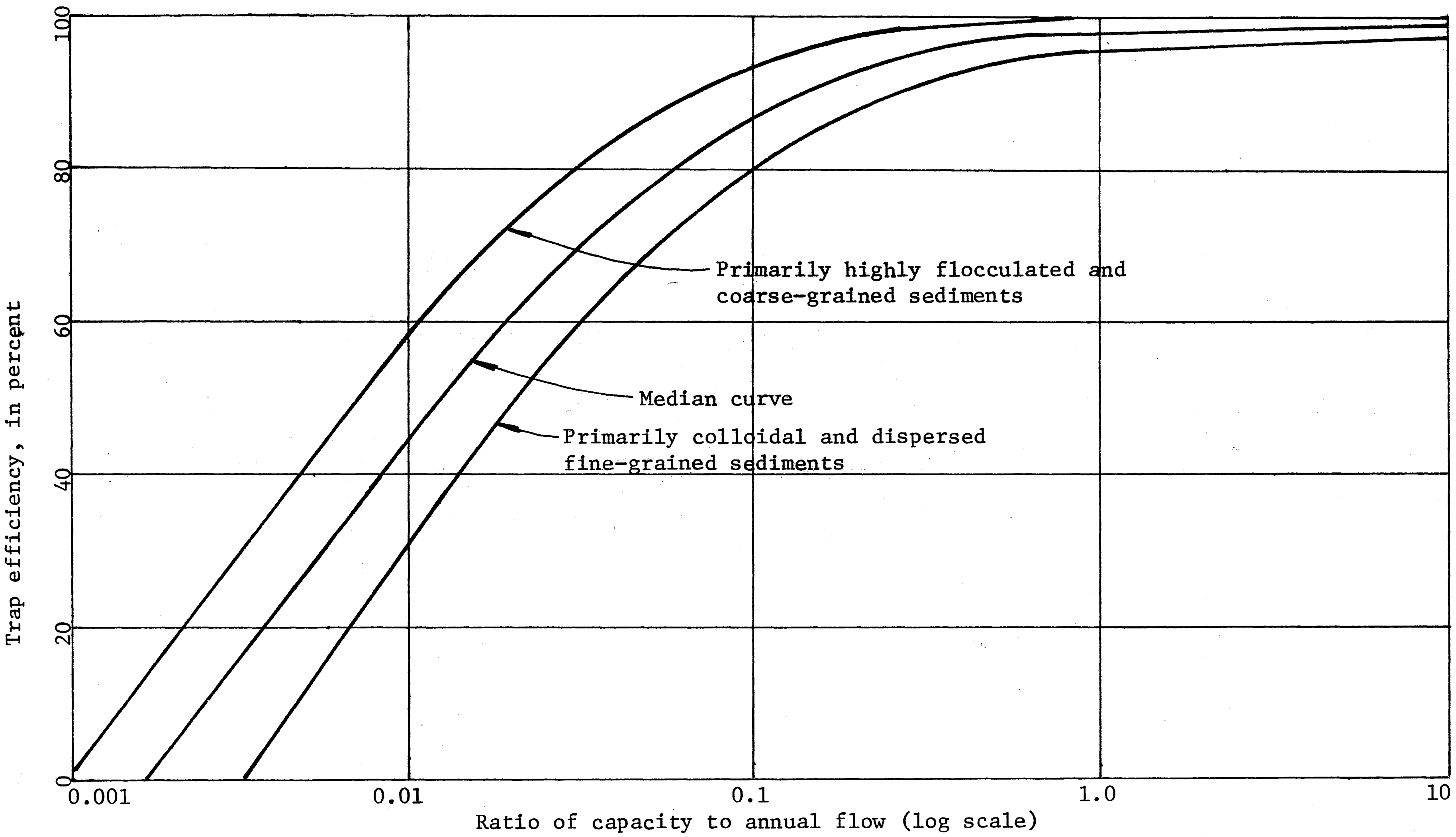

Figure 5. Trap Efficiency of Reservoirs

C. B. Brown (4) developed the following formula for determining trap efficiency.

$$C_T = 100 \left[1 - 1/(1 + 0.1\ C/W) \right]$$

where: C_T = trap efficiency and, C/W = ratio of reservoir capacity to drainage area. For Lake Texoma:

$$C_T = 100 \quad 1 - \left[1/(1 + 0.1 \left[\frac{5,859,000}{39719} \right]) \right]$$

$$C_T = 93.7\%$$

93.7 percent is somewhat low since the computed trap efficiency of Lake Texoma is 99.2 percent. The 98 percent computed by the U.S. Department of Agriculture method compares more favorably with the actual computed value. However, over the useful life of the lake, Brown's formula would probably give a more realistic trap efficiency. The problem with using this formula is that it ignores the various types of sediment possible in a river.

Several methods of sediment distribution will be discussed and compared to the measured distribution of Lake Texoma. All of the methods are empirical since a truely analytical methods which handles the multitude of parameters has yet to be developed.

The area increment method is a mathematical method developed by E. A. Cristofuno, as published in (3), while employed by the Bureau of Reclamation. This procedure is based on the assumption that the sediment in a lake can be approximated by reducing the reservoir area at each reservoir elevation by a certain amount. The method involves a series of assumptions. Using Lake Texoma as an example, the procedure follows:

Given: Original capacity at Elevation 640 = 5,859,000 Ac-Ft

Amount of sediment = 306,000 Ac-Ft.

(This is the measured amount but in a proposed reservoir would be computed by Sediment Yield (Ac-Ft/Sq Mi/Yr) times sediment contributing area (sq. mi.) by years).

Original depth at dam = 130 feet.

The basic equation is:

$$V_s = A_o\ (H - h_o) + V_o$$

where: A = area correction factor in areas which is the original reservoir area at the new zero elevation at the dam.

V_o = Sediment volume below new zero elevation.

V_s = Sediment volume to be distributed in the reservoir

H = reservoir depth at the dam

h_o = depth in feet to which reservoir is completely filled with sediment new zero elevation.

Step 1

V_s = 306,000 Ac-Ft

H = 130 feet

Assume h_o = 10 feet

then A_o = 566 feet

V_o = 2403 Ac-Ft

$$306{,}000 = 566\ (130 - 10) + 2407$$

$$\neq 70{,}327$$

Step 2

Assume h_o = 20 feet

A_o = 1545 Ac

V_o = 12,480 Ac-Ft

$$306{,}000 = 1545\ (110) + 12{,}480$$

$$\neq 182{,}430$$

Step 3

Assume h_o = 25 feet

A_o = 3500 ac

V_o = 2800 Ac-Ft

306,000 = 305 (105) + 28,000

$\neq$ 395,500

Step 4

Assume h_o = 23 feet

A_o = 2500 Ac

V_o = 21,500

306,000 = 2500 (107) + 21,500

= 289,000

Step 5

Assume h_o = 24 feet

A_o = 3000 Ac

V_o = 25,000

306,000 = 3000 (106) + 25,000

$\neq$ 343,000

use h_o = 23 feet

Area correction factor = 2500 acres

new zero elevation of dam = 533 feet

Construct Table V by computing accumulative sediment volume (Column 5) by applying the area correction factor at each depth increment (Column 4) and computing sediment volumes (Column 5) by the average end area method. Column 6 is the revised area and Column 7 is the revised capacity. Column 8 and 9 show actual measured values. Column 10 shows percent error in capacity values between estimated and measured capacity. Table VI shows that the method gives good results in the upper elevations but the errors become large in the lower elevations. This method appears acceptable for those reservoirs which have depth over 100 feet and which have deep inactive pools. One must remember that the pools of most concern are those which store water for project purposes.

The empirical area-reduction method was developed by Whitney M. Borland and Carl R. Miller (3). The two steps involved in the method are:

1. Classify the proposed reservoir using four basin curves developed from actual reservoir lakes.

2. Make trial and error computations using the average end-area or prismatical formula until the computed capacity equals the predetermined capacity.

The four basic curves were developed for resurvey data of thirty reservoirs of varying capacities and drainage basins. The general classifications are:

TABLE V

AREA INCREMENT METHOD

Elevation (Feet)	Original Area (Acres)	Original Capacity (Ac-Ft)	Ao (Acres)	Sediment Volume (Ac-Ft)	Revised		Measured		Percent Error
					Area (Acres)	Capacity (Ac-Ft)	Area (Acres)	Capacity (Ac-Ft)	
1	2	3	4	5	6	7	8	9	10
640	144,000	5,859,000	2500	289,000	141,500	5,569,000	144,100	5,553,000	0.2
630	121,000	4,534,000	2500	264,000	118,500	4,271,000	120,200	4,233,000	0.9
620	101,000	3,425,000	2500	239,000	98,500	3,185,000	98,600	3,142,000	1.4
610	73,500		2500		71,000		70,400		
	82,200	2,512,000	2500	214,000	79,700	2,299,000	76,000	2,273,000	1.1
600	61,300	1,784,000	2500	189,000	58,800	1,595,000	57,200	1,610,000	0.9
590	46,800	1,216,000	2500	164,000	44,300	1,052,000	43,900	1,106,000	4.8
580	36,500	799,500	2500	139,000	34,000	660,500	34,500	711,200	7.1
570	26,100	486,900	2500	114,000	23,600	372,900	24,500	420,400	11.3
560	18,800	264,300	2500	89,000	16,300	175,300	17,600	213,800	18.0
550	10,400	117,200	2500	64,000	7,900	53,200	9,400	80,600	34.0
540	4,400	42,300	2500	39,000	1,900	3,300	3,500	21,200	84.4
533	2,500	21,500	2500	21,500	0	0	1,500	8,000	100
530	1,500	12,480	1500	12,480	0	0	700	2,300	100
520	600	2,400	600	2,400	0	0	0		0
510	0	0	0	0	0	0	0		0

M	Reservoir type	Classification
1.0 - 1.5	Gorge	IV
1.5 - 2.5	Hill	III
2.5 - 3.5	Floodplain foothill	II
3.5 - 4.5	Lake	I

where M is the reciprocal of the slope of the line obtained by plotting depth as ordinate against capacity or abscissa on log-log paper (See Figure 5). From Figure 5, M = 3.9 and reservoir is a type I classification or Lake type reservoir.

From Figure 6, select the appropriate area design curve, in this case, select type I where $A_p = 3.4170p^{1.5}\ (1 - p)^{0.2}$. Construct Table VI. Columns 1, 2, 3, and 4 are self-explanatory. Column 5 is read from Figure 6 on the appropriate curve selected. Column 6 is obtained by selecting a new elevation whose sediment area is zero (in this case, Elevation 511.0). Divide the new zero elevations' original area by the corresponding value in Column 5. (in this case, 40/0.016) and this value becomes a constant. Multiply this constant by each value for Ap to obtain the sediment area in Column 6. Column 7 is obtained by the average end-area method:

$$dV = \frac{A1 + A2}{2} (dh)$$

Column 8 is the cumulative sums of dV. Columns 9 through 11 are again self explanatory. To make the total volume of sediment equal, the estimated sediment inflow will require a trial and error procedure for determining the new zero elevation.

Since the curves were drawn from measured reservoirs, it is permissable to alter the curves slightly in order to compensate for unusual circumstances. Other methods of distributing sediment in

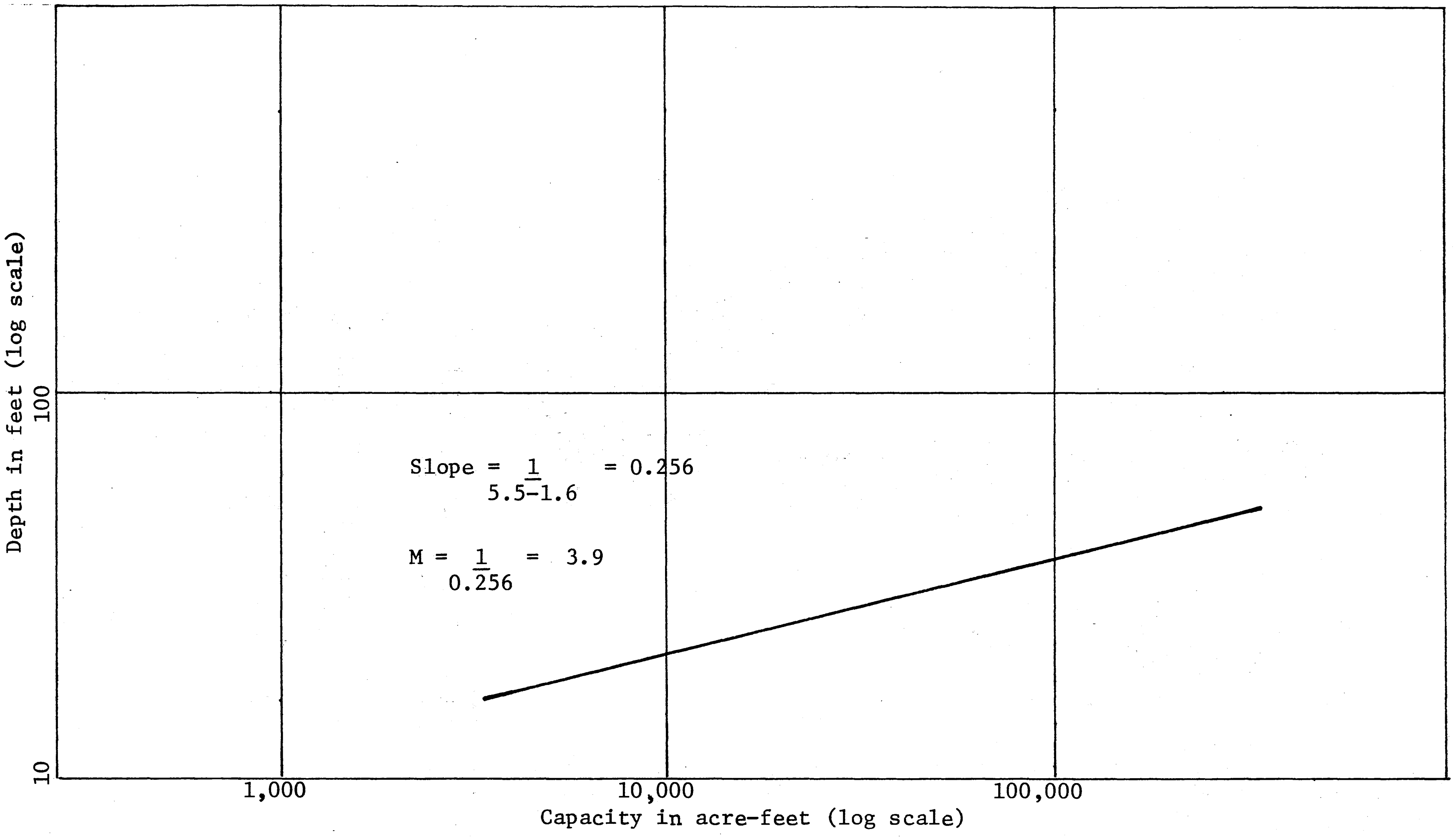

Figure 6. Classification of Reservoir

TABLE VI

EMPIRICAL AREA - REDUCTION METHOD

Elevation (Feet)	Original Area (AC)	Original Vol. (Ac-Ft)	Relative Depth	Ap (Type I)	Sed. Area (Ac)	Sed. Vol. (Ac-Ft)	Cum. Sed. Vol. (Ac-Ft)	Revised Area (Ac)	Revised Vol. (Ac-Ft)	Measured Vol. (Ac-Ft)	Error %
1	2	3	4	5	6	7	8	9	10	11	12
640	144,000	5,859,000	1.0	0	0	22,650	305,000	144,000	5,554,000	5,553,000	0.01
630	121,000	4,534,000	0.92	1.81	4530	45,400	282,350	116,000	4,557,000	4,233,000	7.6
620	101,000	3,425,000	0.85	1.82	4550	44,000	236,950	106,000	3,188,000	3,142,000	1.5
610	82,200							78,200			
	73,500	2,512,000	0.77	1.70	4250	40,750	192,950	69,500	2,319,000	2,273,000	2.0
600	61,300	1,784,000	0.69	1.56	3900	36,400	152,200	57,400	1,632,000	1,610,000	1.4
590	46,800	1,216,000	0.62	1.35	3380	31,050	115,800	43,400	1,100,000	1,106,000	0.5
580	36,500	799,500	0.54	1.13	2830	25,650	84,750	33,700	714,700	711,200	0.5
570	26,100	486,900	0.46	0.92	2300	20,900	59,100	23,800	427,800	420,400	1.8
560	18,800	264,300	0.39	0.75	1880	15,900	38,200	16,900	226,100	213,800	5.7
550	10,400	117,200	0.31	0.52	1300	10,900	22,300	9,100	94,900	80,600	17.7
540	4,400	42,300	0.23	0.35	880	6,900	11,400	3,500	30,900	21,200	45.8
530	1,500	12,500	0.15	0.20	500	2,450	4,500	1,000	8,000	2,300	247.8
520	600	2,400	0.077	0.075	190	1,040	1,060	400	1,300	0	100
511*	40	20	0.007	0.016	40	20	20	0	0	0	0
510	0	0	0	0	0	0	0	0	0	0	0

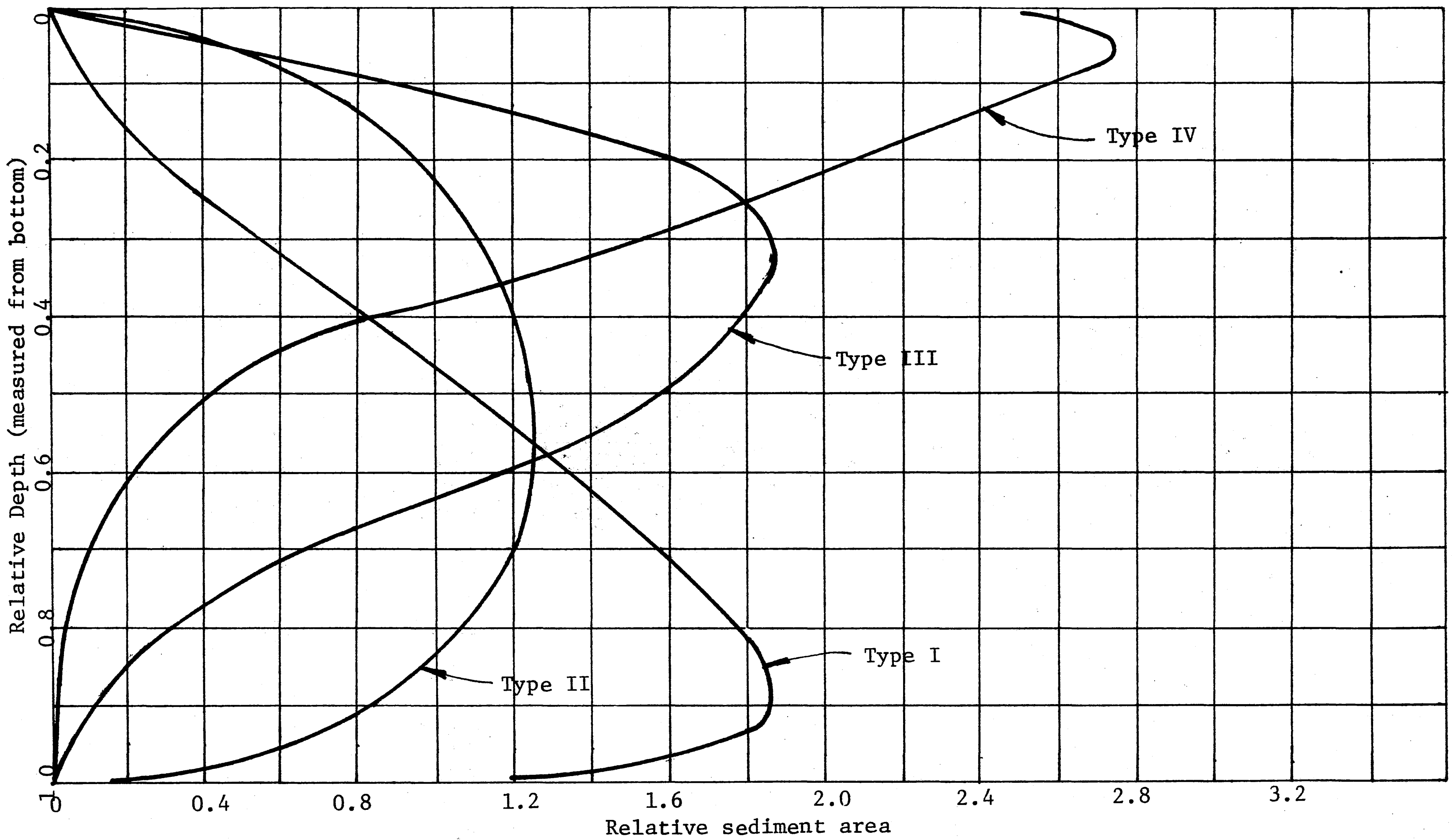

Figure 7. Sediment Distribution-Area Design Curves

reservoirs were studied; however, the two methods presented in this paper represent, in the author's opinion, the most comprehensive methods which now exist.

The other methods studied appear to rely heavily on artistic ability and a <u>feel</u> or how the sediment is distributed. For the experienced engineer, a combination of methods appears to be the best solution. Using the two empirical methods presented herein and a developed <u>feel</u> for sedimentation, the predicted distribution should be well within the measurable limits.

CHAPTER IV

CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

The following steps are necessary in predicting sediment deposition distribution:

1. Determine drainage area.
2. Determine sediment contributing area.
3. Determine sediment yield in acre-feet/square mile/year.
4. Derive an elevation-area and an elevation-capacity curve for the proposed reservoir.
5. Apply both empirical methods described in Chapter III.
6. Compare results with similar reservoirs.
7. Adjust results to account for special conditions such as may be found in the basin, due to unusual operations predicted, or project purposes.

A special note about items six and seven is required. One should not rely entirely on comparison of reservoirs of a similar character in predicting sediment distribution nor should the results obtained from the empirical methods go without question. An experienced engineer will perform items five and six, then after studying all of the factors previously discussed in the paper, perform item seven. One should also be aware that the adjusted areas and capacities at each elevation should produce a curve similar to the original elevation area and elevation capacity curves.

The importance of adequately predicting sediment distribution in a proposed reservoir cannot be understated. The writer feels that this science which is less than forty years old can be improved. Basic data in sediment yields is lacking on most rivers in the United States. The method of collection of what little data is collected is spotty and accurate. Little effort has been expended to improve data collections. The method of surveying existing lakes for sediment deposits is almost ludicrous. Sediment ranges sometimes almost a mile apart are resurveyed and the end-area method is used to determine the amount of sediment deposited. As a comparison, in highway design, cross-sections are taken at not over 100 feet apart to determine fills and cuts. This is not entirely the fault of the engineers performing the work, since the equipment necessary to adequately map the bottom of a lake is very expensive and requires highly trained technicians for which usually no funds are available. In conclusion, with the computers of today, a mathematical model could be developed to predict sediment distribution on a reservoir in any basin. The problem is, are agencies in water resource development willing to expend the necessary funds to gather accurate data in detail and quantity necessary to supply such a model?

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