Sediment Trap Efficiency of Small Reservoirs

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AS part of a rapidly expanding watershed protection plan, the U.S. Department of Agriculture began construction of numerous small multi-purpose and floodwater-retarding reservoirs in the mid-1950's. In planning and designing these reservoirs, it was necessary to allocate sediment storage space for the design life of the structures. Failure to provide adequate sediment storage could seriously impair their utility for flood control or other purposes.

The sediment trap efficiency of a reservoir, usually expressed in percent, is the proportion of the inflowing sediment that is trapped in the reservoir. While some information was available in the 1950's on sediment accumulation rates in reservoirs, little was known about the true sediment trap efficiency of small structures. Therefore, with the Agricultural Research Service and the U.S. Geological Survey as cooperators, the Soil Conservation Service initiated a study of a selected group of small floodwater-retarding reservoirs (Gottschalk 1965). The study was designed to provide basic information on trap efficiency to be used in developing and improving design criteria for small reservoirs. This report summarizes the results obtained from that study.

METHODS

The 17 reservoirs selected for the study are widely scattered throughout the U.S. (Fig. 1). They represent widely different climate, soils, topographies, and land uses. All have earthen dams and drop-inlet principal spillways at some elevation below an emergency spillway. Reservoir capacity below the principal spillway elevation is commonly referred to as the conservation or sediment pool. The conservation pool usually provides storage for the estimated volume of sediment deposited during the 50- or 100-year design life of the reservoir. Storage capacity between the principal and emergency spillways, commonly known as the detention pool, is used for flood control. Time required for a full detention pool to discharge through the principal spillway varies from a few hours to about 10 days.

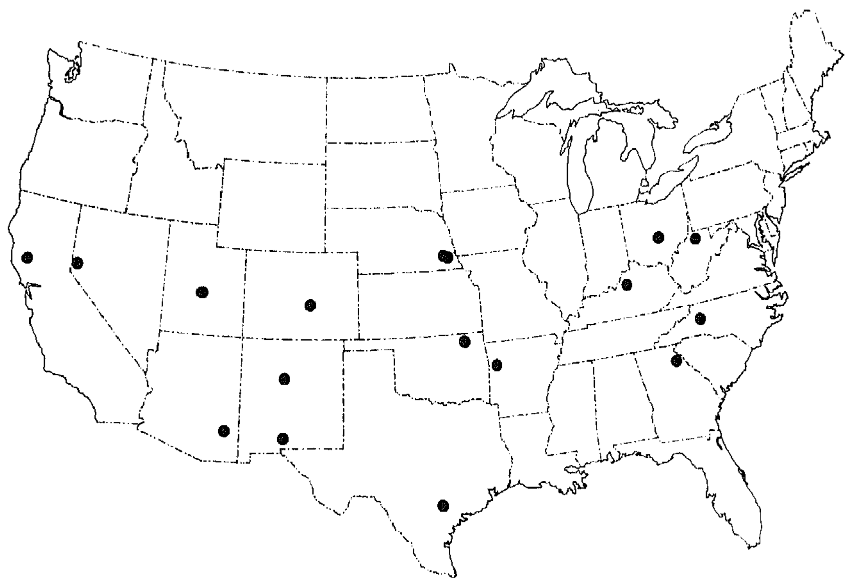

FIG. 1 Location of reservoirs studied.

Water is ponded in the conservation pool in all of the study reservoirs except those in Arizona, Colorado, New Mexico, Nevada, and Utah. The reservoirs in these arid states have dry conservation pools; i.e., water is ponded only temporarily during periods of storm runoff.

Water level recorders were used to obtain a continuous record of reservoir water stage. Water outflow volumes were computed from the stage records and discharge rating curves for the principal and emergency spillways. Water inflow volumes were not measured.

Suspended sediment samples of the outflow were collected with conventional equipment such as the US DH-48 sampler, the US U-59 single-stage sampler, and pumping-type samplers. Sediment rating curves were established and used to compute suspended sediment discharge. Since most of the samples were taken at the end of the outflow pipe or immediately downstream, and virtually all of the outflowing sediment was silt and clay size particles, the suspended sediment discharge was assumed to equal total sediment discharge. Selected outflow samples were also analyzed to determine sediment particle size, various chemical and mineralogical properties, and total dissolved solids.

Occasional measurements were made of water and sediment inflow. These data were analyzed to determine the particle size and various chemical properties of the inflowing sediments. Measurements were too in-

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frequent to compute inflow volumes.

The reservoirs were surveyed and the sediments sampled, usually at 5-year intervals, to determine the volume and weight of sediment deposits. Contour maps were prepared to show the distribution of the deposits, and the samples were analyzed to determine the volume-weight and particle size distribution of the deposits. Sediment inflow was assumed to equal sediment deposits plus sediment outflow.

RESULTS

Pertinent data for the reservoirs included in this study are given in Table 1. Additional information on some of these structures is given in USGS and Texas Water Development Board reports (Anttila 1970, Bednar and Waldrep 1973, Fancher 1971, Flint 1970, 1971, 1972, Kennon et al 1967, Mundorff 1968, Petri 1973, and Reeder 1970). These reservoirs range in size from 3.9 to 3237 acre-ft, with surface areas from 1.27 to 137.8 acres. Drainage areas range from 0.2 to 26 sq mi. The smallest, Brownell # 1-A, is a pond-type structure, located within the drainage area of Brownell # 1. The largest, Highland Creek reservoir, is a multipurpose structure, providing both recreation and flood control.

Water outflow volumes varied widely, and time of outflow ranged from continuous for Third Creek# 7-A to only a few hours or days per year for the reservoirs in the arid Western States. Both sediment inflow and outflow were essentially limited to periods of storm runoff in all reservoirs.

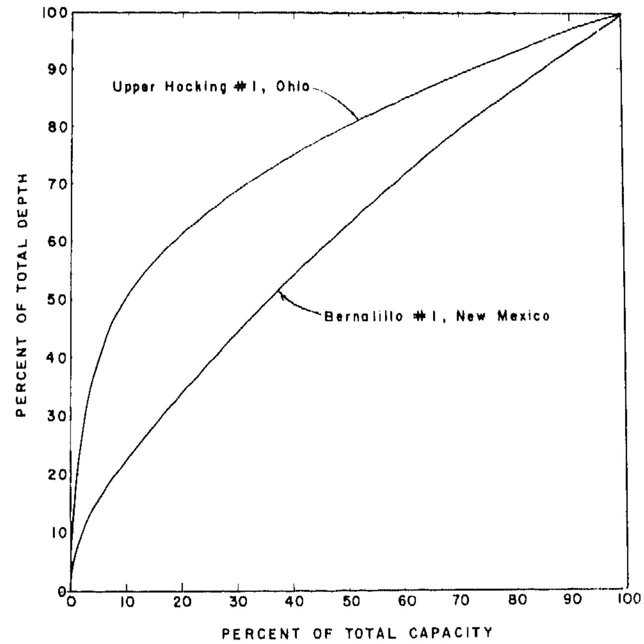

FIG. 2 Reservoir shape curves.

The reservoirs also vary widely in shape, ranging from long, relatively narrow structures in the Eastern United States to broad, relatively flat structures in the arid West. Depth--capacity curves for Upper Hocking reservoir # 1 and Bernalillo # 1, Fig. 2, give some indication of the variation in shape. Similar curves for the other reservoirs would plot between these two. Maximum depth at emergency spillway elevation ranged from 9 to 60 ft. Depth of the conservation pool ranged from 7 to 38 ft.

Sediment Inflow

Average annual sediment inflow ranged from 60 to 4400 tons per sq mi of drainage area. Most of the inflowing sediment was silt size or smaller. Average sand content of the suspended sediment inflow, as determined from periodic samples, ranged from 2 to 40 percent. Sand in the outflow did not exceed 4 percent and no sand was discharged from seven reservoirs. Most of the sediment was deposited in the upstream end of the reservoirs near the elevation of the conservation pool. Proportion of the total sediment deposited in the sediment pool ranged from 30 to 100 percent.

Trap Efficiency

The sediment trap efficiency of a reservoir depends primarily on the mean flow velocity through the pool and the particle size of the inflowing sediment (American Society of Civil

TABLE 1. RESERVOIR DATA SUMMARY

Reservoir	Location	Reservoir Type 1/	Drainage Area (mi.^{2})	Reservoir Area Total (ac.)	Reservoir Area Cons. Pool (ac.)	Reservoir Capacity Total (ac.ft.)	Reservoir Capacity Cons. Pool (ac.ft.)	Average Annual Outflow (ac.ft.)	Average Annual Outflow (in.)	Avg. Annual Sediment Accumulation Rate (ac.ft.)	Avg. Annual Sediment Accumulation Rate (tons)	Avg. Volume Weight of Deposits (lbs./ft.^{3})	Period of Record (years)	Trap Efficiency (percent)
Third Creek # 7-A	Statesville, N. C.	P	4.84	72.0	10.6	961.4	47.4	4,767.0	18.50	1.58	2,140	62.2	11.6	82.0
N. Fork Broad R. # 14	Toccoa, Ga.	P	1.20	25.6	5.9	281.1	22.7	1,473.0	23.20	.97	1,399	66.2	14.6	84.7
Salem Fork # 11-A	Salem, W. Virginia	P	.29	-	-	53.0	7.1	315.0	20.50	.16	209*	60.0*	7.8	87.9
Upper Hocking # 1	Lancaster, Ohio	P	1.04	36.9	5.4	450.0	27.5	505.0	9.11	.64	998	71.6	6.1	88.3
Plum Creek # 4	Shelbyville, Ky.	P	1.50	43.1	13.8	392.4	91.9	1,295.0	16.20	1.85	2,740	68.0	7.2	91.4
Six Mile Creek # 6	Chismville, Ark.	P	4.14	122.6	40.3	1304.0	301.6	2,898.0	13.10	3.17	5,254	76.1	16.0	94.8
Escondido # 1	Kenedy, Tex.	P	3.01	109.3	31.2	924.7	166.8	190.0	1.18	1.90	2,458	59.4	9.8	98.5
Double Creek # 5	Ramona, Okla.	P	2.39	69.7	17.0	747.4	144.9	1,007.0	7.90	1.15	1,360	54.3	14.7	93.2
Brownell # 1	Syracuse, Neb.	P	.77	16.1	4.5	124.6	28.1	265.0	6.43	.74	903	56.0	14.1	93.1
Brownell # 1-A	Syracuse, Neb.	P	.20	1.3	.6	3.9	1.8	35.4	3.41	.08	89	51.2	14.5	58.6
Highland Creek	Lakeport, Calif.	P	13.60	137.8	64.1	3237.2	949.8	20,226.0	27.90	5.68	8,659*	70.0*	6.3	84.2
Kiowa # K-79	Elbert, Colo.	D	3.20	17.7	6.2	129.6	23.3	134.0	.79	.76	1,240	74.9	9.2	81.3
Bernalillo # 1	Bernalillo, N. M.	D	4.10	21.8	15.8	310.6	162.4	7.4	.03	1.06	2,184	94.6	11.8	96.2
Tortugas Arroyo # 1	Las Cruces, N. M.	D	20.70	102.1	37.4	1324.4	284.7	106.0	.10	6.50	11,849	83.7	4.0	96.6
Mill Canyon	Glenwood, Utah	D	18.35	16.8	7.7	202.0	28.3	2.2	.002	.49	906	84.9	5.0	81.8
Frye Creek # 3	Thatcher, Ariz.	D	26.00	210.9	114.2	2187.7	762.7	379.0	.27	16.90	28,968	78.7	5.0	91.1
Upper Peavine	Reno, Nev.	D	2.71	18.7	8.8	301.7	92.6	53.3	.37	.71	1,356	87.6	4.0	88.2

1/ P - Normally ponded reservoir; D - Dry reservoir, water ponded only during periods of storm runoff.

* Estimated.

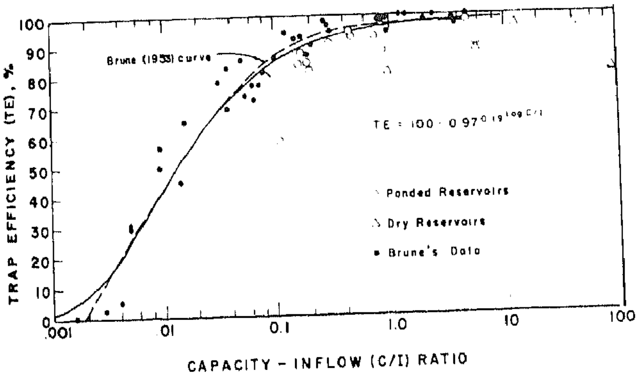

FIG. 3 Trap efficiency curve.

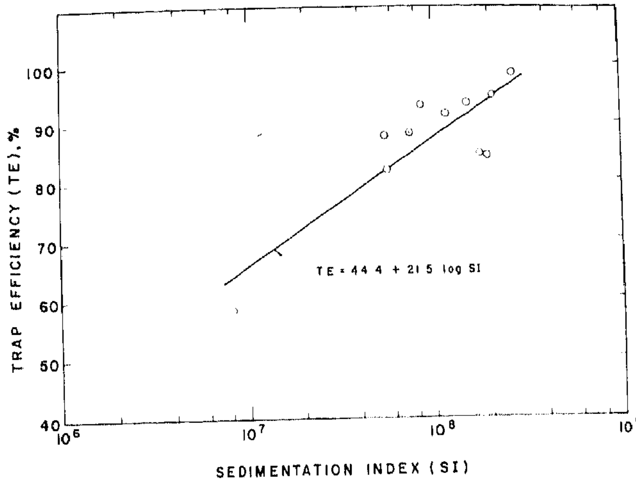

FIG. 4 Sedimentation index—trap efficiency relationship for ponded reservoirs.

Engineers 1971). Other factors such as reservoir geometry, particle shape and density, and viscosity and chemical composition of the native water may have some influence, but the overall effect of these is minor in most field situations.

The mean flow velocity through a reservoir depends on the inflow volume, available storage, and rate of outflow. Data are not usually available upon which to base reliable estimates of flow velocities through small reservoirs; thus, some related parameters must be used. Brown (1943) related trap efficiency (TE) to the reservoir capacity/watershed area (C/W) ratio and Brune (1953) developed a graphical relationship between trap efficiency and the reservoir capacity/average annual inflow (C/I) ratio.

Churchill (1948) used a computed mean flow velocity to establish a relationship between trap efficiency and reservoir sedimentation index. The sedimentation index is defined as the period of retention, a form of C/I ratio, divided by the mean velocity. Borland (1971) concluded that the Churchill relationship is superior to the Brune curve for estimating the trap efficiency of desilting and partially dry reservoirs.

In spite of widely different reservoir sizes and shapes, and water and sediment inflow volumes, trap efficiencies of the reservoirs included in this study varied relatively little. With the exception of Brownell # 1-A, a pond-type structure much smaller than the others, trap efficiencies ranged from 81 to 98 percent (Table 1). Furthermore, trap efficiencies of the dry reservoirs were essentially the same as those of the normally ponded reservoirs, and varied over about the same range. The low trap efficiency of Brownell # 1-A is probably due to its small size and short detention time. Also, sediment inflow is nearly all silts and clays.

The relatively small range in trap efficiency values and the small number of reservoirs included in the study almost preclude the development of valid statistical relationships between trap efficiency and measurable reservoir and hydrologic parameters. The mean trap efficiency for all 17 reservoirs was 87.8 percent with a standard deviation of 9.3 percent. With Brownell # 1-A excluded, the mean trap efficiency was 89.6 percent and the standard deviation only 5.6 percent. Relationships between trap efficiency and selected variables, including C/I ratio, C/W ratio, calcium-sodium ratio, reservoir capacity, and reservoir shape, were poorly defined and explained only relatively small portions of the total variation.

The effect of sediment particle size on trap efficiency was not discernible from the data available. Median particle size of inflowing sediment ranged from 0.003 to 0.017 mm. Since all structures trapped nearly all of the sand, trap efficiency primarily depended on a reservoir's ability to trap fine sediments. Median particle size of the fines ranged only from 0.003 to 0.007 mm. Thus, any relationship of particle size to trap efficiency was obscured by other variables.

The dashed curve in Fig. 3 shows the relationship between trap efficiency and C/I ratio established by Brune (1953) from records of 44 normally ponded reservoirs. The data points for reservoirs used in this study are differentiated by symbol from Brune's data. All except one plot below the Brune curve. This may be due, in part, to the method used to compute the C/I values. Since inflow data were not available, C/I ratios were computed by assuming that inflow equalled outflow. This gave somewhat higher C/I values, particularly for ponded reservoirs in areas where evaporation and seepage losses were significant.

The solid curve, Fig. 3, was established by combining the data from the ponded reservoirs and the data published by Brune (1953). It differs only slightly from the Brune curve. With the exception of Brownell # 1-A, predicted trap efficiency values are within 8 percent of measured values for the ponded reserviors.

The shape of the curve was determined by assuming that trap efficiency approaches 100 percent for high C/I ratios and zero for extremely low C/I values.

The prediction equation for the best fit curve is:

$$TE = 100 \cdot 0.97^{0.19 \mathrm{Log}\ C/I}$$

where:

TE = trap efficiency, percent
C/I = capacity-average annual inflow ratio, acre ft per acre ft

Normally, the trap efficiency of dry reservoirs would be less than that ol ponded reservoirs. Spillway openings at or near the reservoir bottom allow some of the inflowing sediment to be transported directly through the pool. Small flows, not large enough tc create ponding, may also erode anc remove previously deposited sediment Nevertheless, trap efficiencies were above 80 percent for all of the dr structures. However, the period o record was 5 years or less for most of these structures and may not be representative of long-term conditons. C/I ratios were also higher than for the normally ponded reservoirs.

Sedimentation index (SI), the ratio of the period of retention to the mean flow velocity through the reservoir, was computed for each of the eleven ponded reservoirs. Period of retention is determined by dividing reservoir capacity at mean operating pool level by the mean daily inflow rate. Mean velocity is determined by dividing mean daily inflow by the average cross-sectional area. Average cross-sectional area is determined by dividing reservoir capacity by reservoir length at mean operating pool level.

Some of the above computational procedures had to be modified to obtain plausible sedimentation index values. First, it was necessary to use outflow in the computations since inflow data were not available. Second, mean daily outflow, used to determine the period of retention, was computed only for those days when outflow volume was sufficient to provide a computed mean daily velocity greater than 0.001 ft per sec through the reservoir. This was necessary because outflow from most of these small reservoirs was ephemeral. It also eliminated the days and flow volumes that occurred at low discharge rates which normally transport only small quantities of sediment.

The relationship between trap efficiency and sedimentation index for the ponded reservoirs is given in Fig. 4. Assuming a linear semilogarithmic relationship for SI values between 8 and 300, a best fit curve was drawn through the data points. Although the prediction equation explains 74 percent of the variation in trap efficiency, the relationship is greatly influenced by one data point, Brownell reservior #1-A with a trap efficiency of 58.6 percent. With that data point removed, the slope of a best fit curve is greatly reduced and the correlation coefficient drops to 0.48.

The relationship might be further refined with more detailed flow data, i.e., flow duration curves for inflow and outflow. These types of data are rarely available for small watesheds, however, and prediction schemes based on such data would be of little value in reservoir design.

Sedimentation index values were not computed for the dry reservoirs. Inflow to these structures occurs mainly during infrequent, short-duration, summer thunderstorms. Mean flow velocities through the reservoirs could not be estimated reliably from the data available.

SUMMARY AND CONCLUSIONS

Despite widely varying reservoir size, shape, sediment inflow rates and volumes, trap efficiencies varied little among 17 small flood-water-retarding reservoirs in the Southern and Western United States. With the exception of a pond-type structure much smaller than the others, trap efficiencies ranged from 81 to 98 percent for periods of from 4 to 16 yrs.

Trap efficiencies of the dry reservoirs, although generally for shorter record periods, were essentially the same and varied over about the same range as the normally ponded reservoirs. With one exception, reservoir capacity greatly exceeded average annual inflow for all of the dry structures. Thus, the relatively short record periods may not be representative of long-term conditions. Slightly coarser sediments may have compensated, in part, for non-ponded conditions in these reservoirs.

Relationships between trap efficiency and various parameters including C/W ratio, C/I ratio, calcium-sodium ratio, reservoir shape, and sediment particle size were poorly defined and explained only small portions of the total variation. However, the data strongly suggest that, except for very small pond-type structures or other extreme conditions, floodwater-retarding structures with C/I ratios greater than 0.1 will trap 80 to 95 percent of inflowing sediments. Trap efficiency of sediment particles larger than 0.062 mm ranged from 96 to 100 percent, indicating that the overall trap efficiency for normally distributed sediments primarily depends on the reservoir's ability to trap sediments silt size and smaller.

Trap efficiency of the normally ponded reservoirs was generally less than the Brune (1953) curve predicted. The data were combined with the Brune data and a revised curve established, Fig. 3. The revised curve gives TE values slightly less than the Brune curve for C/I values between 0.07 and 2 and slightly greater for higher and lower C/I values. The correlation coefficient between computed and observed trap efficiency values is 0.96. Thus, the prediction equation should provide reasonably good estimates, within 10 to 15 percent, of trap efficiency for most small reservoirs.

Sedimentation Index explained 74 percent of the variation in trap efficiency of the normally ponded reservoirs. However, the relationship was greatly influenced by one small pond-type reservoir with a relatively low trap efficiency. Furthermore, inflow data required to compute SI values for small reservoirs are rarely available.

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The program was used to compute F values (Figs. 3 and 4) to be used in the design method. Design equations are given which can be used with known F-values to determine the lateral pressure loss and flow variation along the lateral for a given pipe size. Thus the computer solution method can be obviated when accurate F-values are available.

Experimental data are given which show the emitter flow function for three emitter types, friction loss in ½-in. polyethylene pipe, and the pressure distribution in a model lateral. The data indicate that the emitter flow function can be represented by a power-type equation with the constants determined by the empirical data (Fig. 1). The Hazen-Williams roughness coefficient was computed to be approximately 130 for ½-in. (0.622-in. I.D.) and Drip-eze DH 580 (0.580-in. I.D.) polyethylene pipe (Fig. 5). The pressure distribution in the model lateral was in close agreement with the pressure distribution predicted by the computer program for the lateral (Fig. 6). Approximately 50 percent of the lateral pressure drop occurred in the first 20 percent of the lateral distance.

As a result of this study, the following conclusions are indicated:

1 In-line emitters which are directly inserted into a cut end of the pipe can cause significant pressure loss due to the flow path restriction caused by the emitter. This pressure loss must be considered for precise engineering design of trickle irrigation laterals.

2 The Hazen-Williams roughness coefficient was determined to be approximately 130 for ½-in. polyethylene pipe.

3 F values were dependent upon the emitter friction to a large extent, and upon emitter spacing and lateral pressure to a lesser extent. When using in-line emitters, F must be determined with care, or large errors can result.

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