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Controlling Reservoir Trap Efficiency

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ABSTRACT

RESEARCH on three reservoirs in central Missouri has shown that reservoir sedimentation trap efficiency is affected by the detention time of storm runoff and by factors governing sediment particle size. Decreasing the detention time can be done by discharging storm runoff from the reservoir with the use of a bottom-withdrawal spillway. With the bottom-withdrawal spillway, the clean water remains in the reservoir and floats above the density currents caused by storm runoff moving to the deepest part of the reservoir.

INTRODUCTION

Reservoir trap efficiency (TE) is the percentage of incoming sediment trapped and deposited in a reservoir. The reservoir designer multiplies the TE value by the estimated sediment yield for the reservoir design life to determine the sediment storage requirement. This establishes the probable useful life of the reservoir. Little thought has been given in the past to reducing the trap efficiency of a reservoir to increase its life or to improve its water quality.

The sediment trapped includes both organic material and inorganic soil particles. Associated with this sediment are various nutrients that can cause eutrophication. The sediment also causes high turbidity that hampers fish production. To improve reservoir water quality, the minimum reservoir trap efficiency that will meet the downstream water quality requirements should be used.

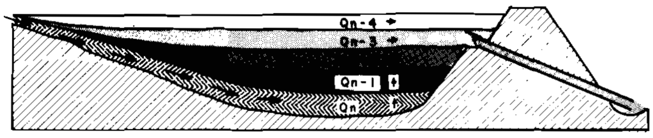

FIG. 1 Progression of inflow increments through reservoir.

This paper reviews previous research on TE and presents new findings on this important reservoir sedimentation factor. Some parameters that affect TE in three central Missouri reservoirs were evaluated and a new approach to control TE is described.

In previous TE research, Brune (1953) found that the ratio of reservoir capacity (volume) to the average annual inflow (volume/year), C/I ratio, was the most important parameter in his trap efficiency study of storage reservoirs. This factor really gives the average detention time (years) of the stored runoff.

In a preliminary report on the trap efficiency of 19 floodwater-retarding reservoirs, Gottschalk (1965) showed that most of the measured trap efficiencies agreed reasonably well with Brune's curve for estimating trap efficiency. However, the estimated value (design trap efficiency) was usually higher than the actual trap efficiency, which means that the reservoir trapped less sediment than the design amount resulting in excessive reservoir storage allocated to sediment.

Three of the 19 reservoirs surveyed by Gottschalk were also studied extensively by Heinemann and Reynolds (1962) who found that trap efficiency values for each reservoir varied considerably between sedimentation surveys. This fluctuation was attributed to changes in runoff, erosion, and storage capacity.

SMALL RESERVOIR OPERATING CHARACTERISTICS

Sediment storage requirements for most small reservoirs (capacity > 12,300,000 m^3) are based on the estimated watershed sediment yield and an estimated trap efficiency for the structure. Sometimes these estimates are very rough. These estimates, however, enter into the determinations of the capacity needed for sediment storage, total reservoir capacity, and the elevation of the principal spillway crest. Errors in any of these items may seriously affect the useful life and performance of the structure.

Most small reservoirs in temperate climates become stratified during the summer months. Clearer, less dense water accumulates near the surface (epilimniom) while denser, cooler, sediment- and nutrient-laden water accumulates near the bottom (hypolimniom). Even when reservoirs are not stratified, sediment-laden storm runoff enters the reservoir and assumes a level according to its density. When this runoff has a higher density than any of the reservoir water (usually near the beginning of the runoff event when the sediment concentration is the highest), it settles at the bottom of the reservoir (Qn, Fig. 1). Later in the runoff event, when the sediment concentration may be lower and the runoff has a lower density, the level of entry is higher in the reservoir (perhaps Qn-1, Fig. 1).

The sediment-laden runoff will start depositing its heavier particles as soon as it enters the relatively quiet reservoir. Sediment will continue to deposit, and the mixture denisty will decrease with time. If inflow continues, the less dense water will be displaced upwards to Qn-2 and Qn-3, etc., by denser sediment-laden runoff. The "clean" surface waters are then discharged through the spillway(s). Consequently, sediment- and nutrient-laden waters are retained while the less dense and cleaner surface waters are discharged

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first. This results in the highest possible trap efficiency for a given reservoir and the poorest possible quality of water is retained in the reservoir.

The use of small drainage area/reservoir surface area ratio, recommended by fishery specialists, does not solve this sedimentation and water quality problem. The recommended reservoir capacity must be sufficiently large so that it is not completely displaced during a single runoff event and the reservoir left full of muddy water. This larger capacity, however, traps more of the sediment-laden water and usually leaves only a thin layer of clean water on the surface.

REASONS TO LOWER TE

Several reasons for lowering the trap efficiency of a reservoir are:

1 To reduce nutrient and mineral content as well as sediment content for improvement of reservoir water quality for domestic and farm use.

2 To improve water quality for fishery and recreational use.

3 To increase the useful life of reservoirs which is important because good dam sites are a natural resource of limited supply.

4 To reduce downstream degradation since some streams rapidly erode when sediment-laden waters are replaced with clear water from a reservoir.

Some reasons not to lower the trap efficiency of a reservoir are:

1 Movement of sediment downstream would be greater during the life of the reservoir.

2 Water quality downstream will approach that of the original, unrestricted stream flow before construction of a dam. The larger sediment particles, however, will have been deposited.

CURRENT RESEARCH

Because of storm, season, and year-to-year variability in runoff and sediment yield, we decided to study trap efficiency on a storm basis. Three reservoirs in central Missouri were selected for this intensive study, and measurements began in 1968 and 1969. Details of this research were reported by Rausch and Heinemann (1969). The basic data collected on a continuous basis were inflow and outflow discharge and sediment concentration. From these data were computed sediment inflow and outflow rates and quantities, detention time, peak inflow, and total runoff. Particle-size data were periodically collected from major inflow and outflow storms. The physical data for the three reservoirs are given in Table 1.

The amount of sediment deposited for each storm is the difference between the amount of runoff sediment entering and leaving the reservoir. The amount deposited divided by the storm sediment yield is the trap efficiency. Trap efficiency is affected by the basic variables detention time and particle settling velocity. The reservoir capacity below the lowest spillway intake, length of reservoir, and depth through which particles must settle to be trapped may also affect TE.

The inflow and outflow of an increment of runoff are separated by the "detention time" (t_d, Fig. 2). Fig. 2 shows two examples of incremental detentin times: (a) an incremental detention time, t_{d1}, where an increment of inflow from a previous storm was not discharged until a succeeding storm; and (b) an incremental detention time, t_{d2}, where an increment of inflow entered and was discharged from the reservoir during the same storm period.

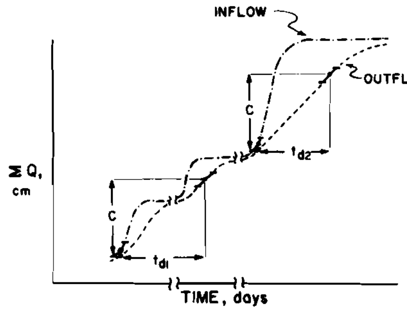

FIG. 2 Accumulated inflow and outflow hydrographs for three typical storms. Examples of detention times [t_d] between inflow and outflow increments are shown.

Two basic assumptions were used in computing detention time: (a) A unit of runoff (Qn, Fig. 1) enters and remains near the bottom of the reservoir until it is displaced upwards to the spillway by succeeding runoff volume that equals the storage capacity of the reservoir, C. (b) The storm periods considered are sufficiently long so that the reservoir level returns to near normal or outflow equals inflow. Detention time for each increment of runoff is the length of time it remains in the reservoir. This is determined by the length of time it takes succeeding runoff, equal to the capacity of the reservoir, to flow through the spillway. A runoff-volume weighted average of the detention time of each outflow increment was used as the storm detention time (T_D).

The relationship between TE and detention time is shown for the Callahan Watershed Reservoir C-1 in Fig. 3.

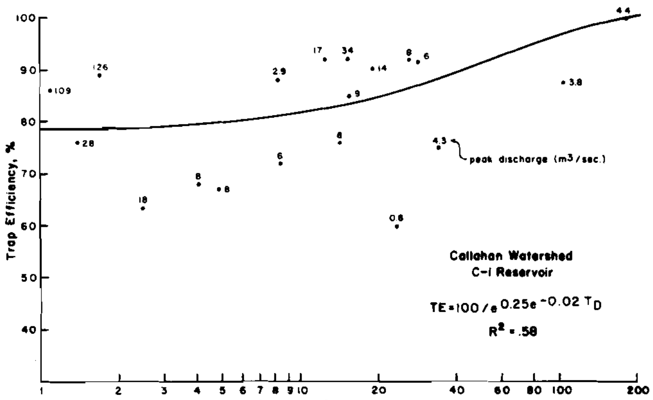

FIG. 3 Effect of detention time on trap efficiency.

TABLE 1. PHYSICAL DATA OF RESERVOIRS AND THEIR WATERSHEDS.*

Reservoir Characteristic	Ashland	Bailey	Callahan C-1
Construction date	1937	1965	1967
Surface area, ha	6.5	4(5.3)	9.3(28)
Capacity, 10^3 m^3	229	69(115)	228(1,254
Water depth, m	8	4.4(5.3)	5.7(11.5)
Shape factor†	3.74	2.01	3.71
Flood storage, runoff, cm	0	4.1	6.6
Watershed Characteristic			
Drainage area, ha	1,004	95	1,457
Average land slope, percent	0.8	1.1	1.0
Soil texture	Clay loam to silt loam	Clay loam to silt loam	Clay loam to silt loam

*Numbers in parentheses apply to the reservoir at emergency spillway elevation.

†Shape factor is the length of the reservoir divided by the diameter of a circle of equal area.

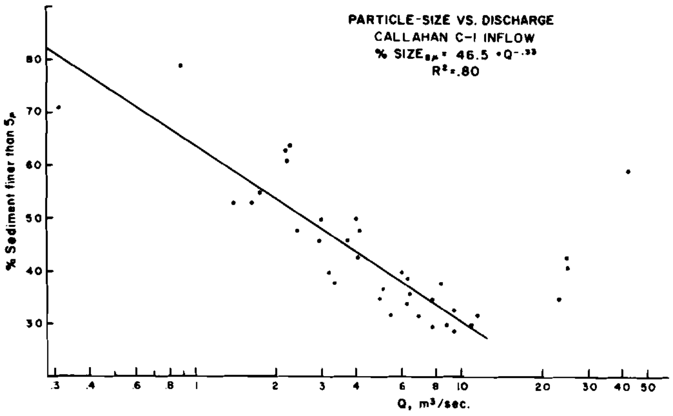

FIG. 4 Correlation of percentage of sediment less than 5μ with discharge [Q].

TABLE 2. STATISTICS OF REGRESSION ANALYSIS.

Reservoir	R^2	Variable	Coefficient	Significance
Ashland	0.61	T_D	-0.046	*
		$\ln Q_p$	-1.48	*
		$\ln Q_{tot}$	0.21	N.S.
Bailey	0.76	T_D	-0.051	*
		$\ln Q_p$	-0.76	*
		$\ln Q_{tot}$	0.42	N.S.
Callahan	0.87	T_D	-0.017	**
		$\ln Q_p$	-0.75	**
		$\ln Q_{tot}$	0.66	**
All reservoirs	0.70	T_D	-0.018	**
		$\ln Q_p$	-0.32	Δ
		$\ln Q_{tot}$	0.71	**
		ln SY	-0.39	*
		ln C	-1.61	**
		ln DA	-0.43	N.S.

Levels of significance:

**	$p < 0.01$
*	$0.01 < p < 0.05$
Δ	$0.05 < p < 0.10$
N.S.	$p > 0.10$

The following equations were tried and rejected in an attept to relate TE and T_D:

1 $TE = 100/1 + ae^{\beta T_D}$
2 $TE = 100 - a \cdot T_D{}^{\beta}$
3 $TE = a \cdot T_D{}^{\beta}$
4 $TE = ae^{\beta/T_D}$

The best correlation between TE and detention time in days (T_D) was given by the equation

$$TE = 100/e^{ae^{\beta T_D}} \quad \ldots\ldots\ldots\ldots\ldots [1]$$

where a and β are regression coefficients. The coefficient of determination (R^2) for three reservoirs was 0.54, 0.71, and 0.58, respectively, for Ashland, Bailey, and Callahan C-1 reservoirs. The fit of the equation for the Callahan C-1 reservoir is shown in Fig. 3. The number of storms used were 15, 14, and 19, respectively. Not only did this equation give the highest R^2 values, but the predicted values of TE were always between $100/e^a$ and 100 percent for the range, $0 < T_D < \infty$. Detention time was a better predictor of TE than other dependent variables like volume and rate of runoff, erosivity index (Wischmeier and Smith 1965) and kinetic energy of rainfall, sediment concentration, sediment yield, and season. A study of the scatter in TE values for various storms showed that, for similar detention times, high-intensity storms with a high sediment load had a high TE; conversely, low-intensity storms with low sediment concentrations had lower TE. The most obvious difference was particle size of the inflowing sediment. The sediment varied from a large percentage of silt, sand, and larger particles (>5μ) for the high-intensity storms to a large percentage of fine clays (<2μ) for the low-intensity storms.

Since there were not enough particle-size samples taken to characterize every storm, a substitute parameter was sought to replace or predict particle size of the sediment inflow. The discharge rate was found to correlate well ($R^2 = 0.80$) with particle size for flows of less than 17 m³/sec for Callahan C-1 reservoir (Fig. 4).

The peak inflow rate in m³/sec (Q_p) during the storm was, therefore, used in the regression equation in lieu of particle size. The equation became

$$TE = 100/e^{\alpha e^{\beta_1 T_D + \beta_2 \ln Q_p}} \quad \ldots [2]$$

Combining the variables that were significant for individual reservoirs (T_D, Q_p, and Q_{tot}) to determine one equation for all reservoirs did not prove their significance. Additional factors like the capacity of the reservoir in cm (C) and drainage area of the upstream gaging station in ha (DA) were added to the regression model to improve the "t" test for the regression coefficient of each variable to what it was before combining the three reservoirs.

The most significant equation for each reservoir and the coefficients of determination determined by nonlinear regression analysis are:

		R^2	S.E.E.	
Ashland	$TE = 100/e^{171{,}000e^{-0.046T_D - 1.48 \ln Q_p + 0.21 \ln Q_{tot}}}$	0.61	±8%	... [3]
Bailey	$TE = 100/e^{123e^{-0.051T_D - 0.76 \ln Q_p + 0.42 \ln Q_{tot}}}$	0.76	±5%	... [4]
Callahan	$TE = 100/e^{826e^{-0.017T_D - 0.75 \ln Q_p + 0.66 \ln Q_{tot}}}$	0.87	±5%	... [5]

This improved the R^2 for Callahan C-1 reservoir to 0.76. Kinetic energy of rainfall in joule/m² (KE), sediment yield of storm in tonnes/ha (SY), capacity of reservoir in cm (C), drainage area in hectares (DA), and storm runoff volume in cm on the watershed (Q_{tot}) were also added to the regression equation to improve the prediction of TE. KE was not statistically significant for any of the three reservoirs. Q_{tot} was signifnicant for one individual reservoir and all three combined. The coefficients of determination and levels of significance of each coefficient for each of the three reservoirs and all three combined are shown in Table 2.

The most significant equation for all three reservoirs combined is:

$$TE = 100/e^{15.6e^{-0.018T_D - 0.32 \ln Q_p + 0.71 \ln Q_{tot} - 0.39 \ln SY - 1.6 \ln C - 0.43 \ln DA}} \quad \ldots\ldots\ldots\ldots [6]$$

$R^2 = 0.70$

Standard error of estimate (S.E.E.) = ±6.6 percent.

Although this equation is based on only three reservoirs, 48 data points were used in the regression analysis which is considered adequate. Reservoir capacity (C), watershed sediment

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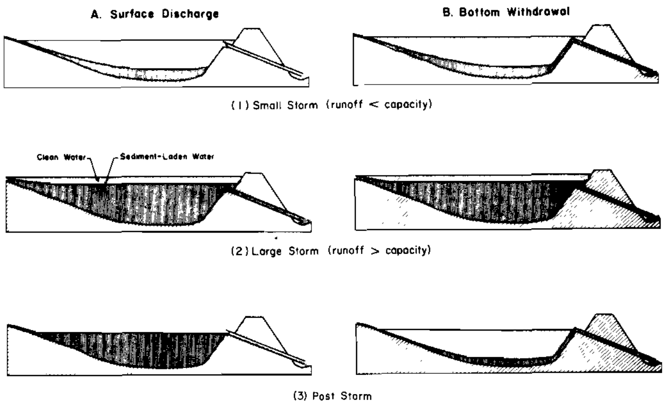

FIG. 5 Comparison of two spillways.

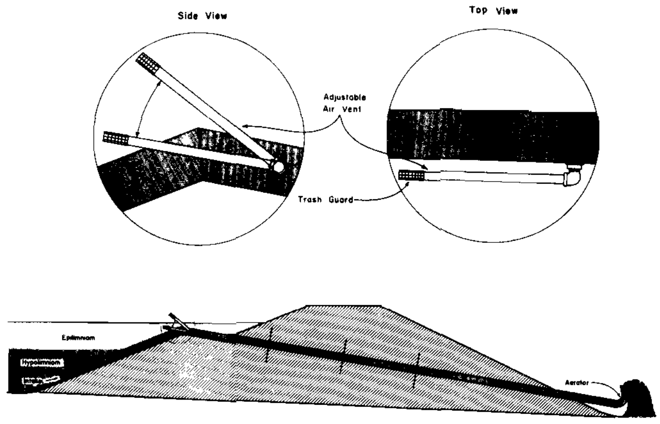

FIG. 6 Cross section of dam with bottom withdrawal spillway.

yield (SY), and drainage area (DA) are the variables that best describe the differences in TE for these three reservoirs. Caution should be used when applying equation (6) to reservoirs where characteristics are different from those included in Table 1.

CONTROLLING TRAP EFFICIENCY

The analyses show that there are three general methods of controlling TE of a given reservoir: (a) by changing the detention time, (b) by changing the peak inflow rate and/or sediment yield, because of their relationships to the sediment, and (c) by eliminating the "dead" storage (capacity below the lowest intake to the principal spillway). These three methods recognize that (a) reducing the time that sediment-laden water is in the reservoir reduces the sediment deposition in the reservoir, (b) keeping the large soil particles out of the reservoir reduces the deposition when runoff water enters the reservoir, and (c) eliminating the dead storage permits the discharge of reservoir water with the highest sediment and nutrient concentrations.

Reducing Detention Time

Changing the detention time of the storm runoff would be an effective and direct way of controlling TE. If the mean detention time of all three reservoirs, for example, was reduced from 30 to 2 days, the TE of an average storm would decrease from 90 to 82 percent; 8 percent less sediment would be trapped. In areas having finer soils, the reduction might be much greater.

The detention time of a reservoir may be decreased by (a) increasing the discharge capacity of the spillway or (b) decreasing its "dead" storage capacity. If the spillway capacity is already sufficient to discharge all the storm runoff in 2 days or less, a further increase in spillway size would have little effect on the three reservoirs in this study and on their detention times and trap efficiencies.

Changing the Particle Size of Sediment

Good soil and water conservation practices are always an asset in extending the useful life of conservation structures. Because they reduce storm runoff and the peak flows, they also reduce erosion and sediment yield. This, in turn, reduces the size of the incoming sediment particles. The larger soil particles are always the first to be deposited when sediment-laden inflow reaches the reservoir water. The fine clays usually remain in suspension for a long time, permitting more opportunity for their discharge from the reservoir before deposition.

Use of this method, however, is sometimes limited because the owner of the reservoir may not own all the land in the contributing watershed. It is frequently difficult to install and maintain conservation practices on upstream land owned by others.

Elimination of Dead Storage

Eliminating the "dead" storage in the reservoir not only reduces the amount of sediment-laden water trapped in the reservoir after each runoff event but also has the effect of reducing detention time. By reducing "dead" storage capacity—C in the previously shown equation for three reservoirs—to zero, the TE will be significantly reduced.

BOTTOM-WITHDRAWAL SPILLWAY

One type of bottom-withdrawal spillway is shown in Fig. 5b. It has several desirable features: (a) water is automatically discharged from the bottom; (b) once the spillway is primed, the reservoir water level can be lowered to any desired elevation; (c) flexibility of the operating level for the reservoir is great; and (d) "dead" storage capacity is eliminated and detention time approaches the drawndown time of the spillway, reducing the TE. By using a bottom-withdrawal spillway, TE can be reduced while still maintaining water available for other purposes.

When the reservoir water level is above the crest of the spillway pipe, the bottom-withdrawal spillway (Fig. 5B) will start discharging sediment-laden water as soon as it reaches the spillway intake. The intake should be at the lowest point in the reservoir. The cleaner surface waters remain in the reservoir unless the storm runoff is large enough to cause the surface water to flow through the emergency spillway. Following the return to near-normal stage, the bottom-withdrawal reservoir contains mostly clean water (Fig. 5-B-3) while the surface-discharge reservoir contains mostly sediment-laden water (Fig. 5-A-3).

The siphon action of the bottom-withdrawal spillway is controlled by an air vent near the apex (Fig. 6). When water is above the vent and the apex, the pipe can prime and siphoning takes place. The elevation of this vent determines when the siphoning action starts and stops and thereby controls the rate (siphon flow or orifice flow) and depth of drawdown (down to apex or below). The bottom-withdrawal spillway not only reduces TE by reducing the detention time, but also eliminates the "dead" storage capacity. This will significantly reduce the trap efficiency further, since only the large soil particles will be trapped in the reservoir.

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Reservoir Trap Efficiency

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CONCLUSIONS

1 Reduction of reservoir trap efficiency is sometimes desirable to improve the quality of water impounded and to increase the life of the reservoir.

2 Trap efficiency is dependent on reservoir detention time and particle-size distribution of the incoming sediment. The particle-size distribution is well related to peak discharge.

3 Trap efficiency can be decreased by decreasing detention time of the storm runoff, decreasing the particle size of incoming sediment, and eliminating the "dead" storage in a reservoir.

4 By using a bottom-withdrawal spillway, detention time can be decreased and "dead" storage can be eliminated while maintaining clean water stored for other purposes. Such a spillway discharges the poorest water in a reservoir while retaining the best.

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