Callahan Reservoir: I. Sediment and Nutrient Trap Efficiency

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ABSTRACT

SMALL reservoirs remove and trap significant amounts of sediment and nutrients from storm runoff. Callahan Reservoir, a small flood-detention reservoir in central Missouri, which permanently stores 1 cm of runoff from its 1,440-ha drainage area, trapped an average of 87 percent of the incoming sediment, 72 percent of the total phosphorus (P), and 30 percent of the inorganic nitrogen (N) in 1973. Sediment and P trap efficiency in this reservoir were both related to the incoming sediment particle-size; however, only sediment trap efficiency was related to detention time. The annual amount of NO_3 trapped seemed related to annual runoff volume. For 1973, the soluble nutrients, total soluble P, and NO_3 were trapped at similar rates, 32 percent and 34 percent, respectively.

We found more NH_4, dissolved organic P, and dissolved hydrolyzable P in outflow than in inflow. These increases, which are less than 2 percent of the nutrient budget, may be attributed to biological activity in the reservoir.

INTRODUCTION

Millions of dollars are spent annually constructing small reservoirs for flood control or related purposes. However, because of the recent concern for environmental pollution, millions of dollars are also being spent annually on preventing or removing pollutants from sources of public water supplies. Therefore, although these small reservoirs were constructed for flood-control, their water quality impacts are also important. The quality of water stored in and released from reservoirs like this one is a function not only of input and within-impoundment relationships but also of reservoir design. Callahan reservoir, a flood detention structure in central Missouri, offered an excellent opportunity to study the input and trap efficiency of sediment, nitrogen, and phosphorus.

Callahan reservoir, with a total drainage area of 1,460 ha and a normal surface area of 8.2 ha, has a maximum depth of 5 m and is 1,270 m long. Permanent pool storage is 1 cm depth of watershed runoff, and flood storage is 7 cm depth. About 40 percent of the drainage area, mostly upland soils, is cropland, with the remaining steeper sidehills in pasture or forest. The drainage area at the inflow gaging station is 1,150 ha, 80 percent of the total.

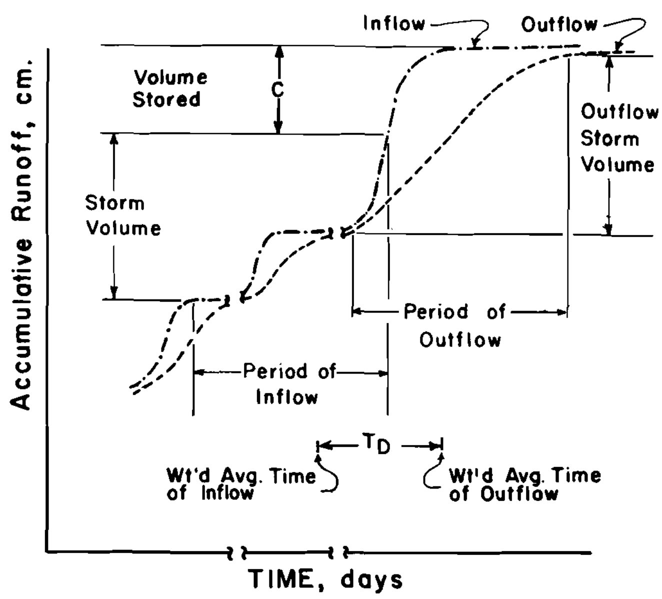

FIG. 1 Example of the average time that inflow is detained (T_D) in a reservoir of capacity (C) before it becomes an "outflow storm."

The inflow was automatically sampled at this station with a PS-66 pumping sampler, developed by the Federal Inter-Agency Sedimentation Project, St. Anthony Falls Hydraulics Laboratory, Minneapolis, MN. A 400-ml sample was taken at intervals ranging from 4 min to 2.5 hr, depending on the rate of rise and stage. To represent differences in nutrient content of inflow that varied with streamflow rate and time and still not overload the nutrient analysis laboratory, we selected 5 to 10 nutrient samples, representative of the storm hydrograph, from the many inflow samples taken. These samples were refrigerated at 4 °C until analyzed. Nutrient concentrations from these samples were used with measured streamflow to compute nutrient loads for each storm period. Outflow from the reservoir was sampled at the discharge end of the 1.07-m diameter spillway pipe with a Columbia spillway sampler (Rausch and Haden, 1974) automatically, every 2 hr when the outflow exceeded 0.57 m^3/s, and manually at lower outflows.

Simultaneous inflow and outflow samples could not be compared directly because they were separated by the volume of water stored in the reservoir (C) and the time inflow was detained before being discharged (T_D). A storm period was then defined as the beginning of a rise in reservoir stage for one storm to the beginning of a rise at the next storm. The outflow during a storm has, therefore, been detained in the reservoir T_D days before being discharged (Fig. 1), where T_D is the difference

Article was submitted for publication in March 1976; reviewed and approved for publication by the Soil and Water Division of ASAE in January 1977. Presented as ASAE Paper No. 74-2501.

Contribution of the Watershed Research Unit, North Central Region, USDA Agricultural Research Service.

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in runoff-volume weighted average time of inflow to time of outflow (Rausch and Heinemann, 1975). T_D is, therefore, a hydrologic variable and C is relatively constant for this reservoir (changes only from being filled with sediment).

Our research objectives were to determine the trap efficiency (TE) of Callahan Reservoir by measuring its sediment and associated P as well as solution-phase P and N.

SEDIMENT TE

In previous sediment TE research, Brune (1953) and Gottschalk (1965) showed that the ratio of reservoir capacity (volume) to average annual inflow (volume/year) or the C/I ratio, was the most important parameter in sediment TE of storage reservoirs. Since the units of C/I are years, it represents the average detention time (T) of predicted storm runoff. In their TE research, Churchill (1948) and Dendy (1974) recommended using a sedimentation index (SI) ($SI = T^2/L$ where T equals detention time and L equals reservoir length). Sediment TE of Callahan reservoir, as calculated by either the CI or SI method, is underestimated by 20 percent to 25 percent using actual measured inflow (I).

Because of seasonal and yearly variability in runoff and sediment yield, Rausch and Heinemann (1975) studied sediment TE on a storm basis at three reservoirs during 1972 and 1973, one of which was Callahan reservoir. They developed the following regression equation for predicting sedimentation TEof Callahan reservoir for individual storms:

$$TE = 100/e^{1.14e\,-\,0.017T_D\,-\,0.75\,\ln Q_p\,+\,0.66\,\ln Q_{tot}},$$

where T_D is the detention time (in days); $\ln Q_p$ is the natural logarithm of the peak inflow rate (in m^3/s); and $\ln Q_{tot}$ is the natural logarithm of storm runoff (in cm). For this equation, $R^2 = 0.87$ and standard error of estimate is ± 5 percent. Actual TE values ranged from 60 percent to 99.6 percent. This equation indicates that TE increases as T_D and Q_p increase and as Q_{tot} decreases. They used Q_p because it was closely correlated with the percentage of inflowing suspended sediment finer than 5μ. Q_{tot} represents the flushing or dilution effects of storm runoff on TE.

NITROGEN TE

We analyzed four years (1970 through 1973) of data on inorganic N in the inflow and outlflow of this reservoir. The nitrate (NO_3-N) and ammonium (NH_4-N) concentrations were measured with ion electrodes on the unfiltered sample. The NO_3-N was measured first, followed by a NaOH addition which increased the pH to 11.0, and thus converted NH_4 to gaseous NH_3, which we then measured with the ammonia electrode. Thus, measured NH_3-N included any NH_4-N liberated from the sediment exchange complex.

We computed the total quantities of inflow and outflow NO_3-N and NH_4-N by storms and on an annual basis. The amounts trapped during individual storms were erratic and not apparently related to any of the hydrologic variables, like T_D, Q_p, and Q_t.

The annual amount of NO_3-N in the inflow and outflow varied proportionately with the volume of annual runoff (Fig. 2). The amount trapped, the difference between inflow and outflow, varied with runoff volume

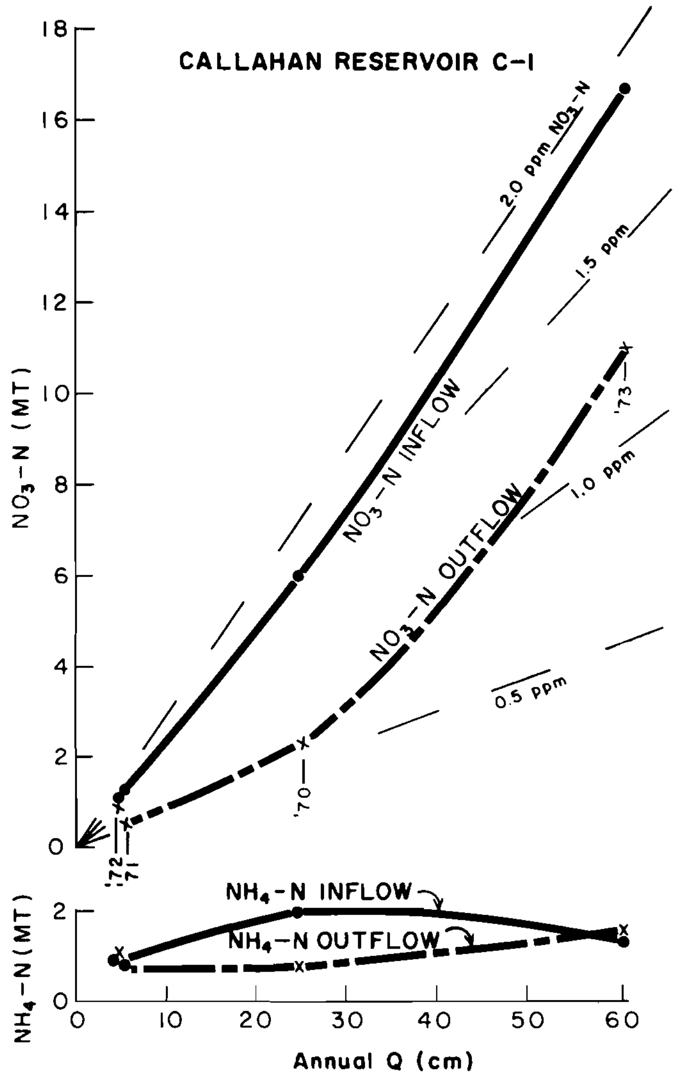

FIG. 2 Annual inflow and outflow of NO_3-N and NH_4-N for Callahan Reservoir.

but seemed to approach an upper limit of 5,700 kg at 62 cm of runoff. Although the amount increased slightly with runoff volume, the percentage trapped decreased with runoff volume because of a greater increase in the amount of NO_3-N in the inflow. Concentration grids are also included on Fig. 2 so annual amounts can be converted to average concentrations. This shows that the inflow averaged less than 2.0 ppm NO_3-N and the outflow was less than 1.25 ppm NO_3-N.

Inflow and outflow NH_4-N were relatively constant with runoff volume, with very little of it trapped (Fig. 2). However, in 1973 with 62 cm of runoff, NH_4-N in outflow exceeded inflow by 28 percent (-28 percent TE, Table 1). In part, we could attribute this increase in outflow NH_4-N to biological degradation of organic matter resulting in the release of NH_4-N.

PHOSPHORUS TE

We analyzed P in the forms: ortho, hydrolyzable, and organic P of the solution phase (FWPCA, 1969), and total, organic, inorganic (Mehta et al., 1954), and P^{31} (isotopically exchangeable with P^{32}) in the sediment phase, and labile P (P^{31} + ortho). Table 1 summarizes the amounts of inflow and outflow and the TE of each form. The negative percentages for dissolved organic and

TABLE 1. ANNUAL PHOSPHORUS, SEDIMENT, AND NITROGEN TRAP EFFICIENCIES (TE) OF CALLAHAN RESERVOIR, 1973

	In	Out	TE
	--kg--	--kg--	percent
Phosphorus			
In Solution			
Dissolved organic	56	101	- 80
Dissolved hydrolyzable	14	45	-220
Ortho-	420	190	55
Total soluble	490	335	32
In Sediment			
Inorganic	6,600	1,600	76
Organic	3,900	1,300	67
Total	10,500	2,900	72
p31	780	140	82
Labile P	1,200	330	72
Sediment (MT)	26,120	3,450	87
Nitrogen			
NO_3-N	16,660	11,000	34
NH_4-N	1,130	1,450	- 28

hydrolyzable P indicate that more of these two dissolved P forms left than entered into the reservoir. This possibly could be attributed to biological activity in the reservoir which may have utilized ortho-P and released organic and hydrolyzable P. Thus, the P-TE values indicated that the quality of outflow from this agricultural impoundment was better than the inflow, since the quantities of the most readily available P forms, i.e., ortho-P and P^{31}, were decreased significantly, even though the volume of inflow was 148 percent above normal. Rainfall for the water year (November 1972 to October 1973) was 152 cm as compared with the normal 97 cm, with 62 cm of runoff as compared with the normal 25 cm. Also, substantial amounts of P in association with the sediment were trapped. Data (Olness and Rausch, 1977) seemed to indicate that the trapped sediment P did not become desorbed into the above water column.

Of the P entering or leaving the reservoir, 96 percent and 90 percent respectively, was associated with the sediment phase. Thus P-TE was expected to be affected by the same factors affecting sediment TE; however, T_D (storm detention time), which was significant at the 1 percent (using the t-test) in the trapping of sediment, was not statistically significant (at the 10 percent level) for any of the final equations for the trapping of the sediment P. T_D is the runoff-volume weighted average of the actual residence times of each increment of runoff. The T_D values varied only from 1 to 32 days for the storms in 1973. T_D correlated with sediment P-TE at a $r^2 = 0.20$, N = 18. Sediment TE was analyzed from 2 yr of data (1972 and 1973), and correlated with T_D values, which varied from 1 to 184 days at a $r^2 = 0.58$, N = 19. If the T_D values used for P-TE had a wider variation, T_D may have had a significant effect on P-TE.

We used two basic model equations in analyzing P-TE—one where TE values varied from 0 to 100 percent.

$$[TE = 100/e^{\gamma e^{\beta_1 x_1} + \cdots} \quad \text{(Gompertz Equation)}]$$

and the other when TE values varied from -400 percent to + 100 percent

$$[TE = 100 - \gamma X_1^{\beta_1} \cdot X_2^{\beta_2} \cdot \ldots \quad \text{(Exponential Equation)}]$$

Both equations can be transformed into linear forms for regression analysis. The values shown in Tables 2 and 3 were determined using the linear forms of these equations. The equations listed in Table 2 were the most significant ones found using the following procedure.

TABLE 2. EQUATIONS FOR PREDICTING PHOSPHORUS TRAP EFFICIENCY (TE) OF CALLAHAN RESERVOIR ON A STORM BASIS.

Equation No.	TE Equation	Range in observed TE	R^2	N	S.E.E.
	Percent	percent			percent
1	Dissolved Organic P TE = $100 - 169 \cdot Q_{tot}^{0.74} \cdot P_{ORG}IN^{-0.856}$	-400 to 51	0.64	18	±63
2	Dissolved Hydrolyzable P TE = $100 - 172 \cdot P_{HYDRI}IN^{-0.296}$	-150 to 31	0.76	11	37
3	Ortho-P TE = $100 - 109 \cdot Q_p^{-0.36}$	- 50 to 91	0.29	18	34
4	Total Sed. P TE = $100 - 40 \cdot SECOUT^{0.505} \cdot P_{tot \cdot SED}IN^{-0.495}$	- 33 to 87	0.71	18	17
5	Inorganic Sed. P TE = $100/e^{0.686e^{-0.00018\,SEDCIN + 0.022\,Q_p - 0.00014\,P_{IS}IN}}$	25 to 89	0.85	16	9
6	Organic Sed. P TE = $100/e^{2.301e^{-0.26\,\ln SEDCIN + 0.0168\,Q_p + 0.27\,Q_{tot} - 0.0039\,P_{OS}IN}}$	34 to 86	0.88	15	6
7	P^{31} TE = $100/e^{70e^{-0.00016\,SEDCIN + 3.76\,\ln Q_{tot} - 1.85\,\ln P^{31}IN + 3.50}}$	23 to 99	0.94	16	9
8	Labile P TE = $100 - 3.7 \times 10^6 \cdot SEDCIN^{-1.94} \cdot Q_{tot}^{1.32} \cdot P_{Labile}IN^{0.40}$	- 33 to 98	0.88	18	23

Q_{tot} is the total runoff (in cm) during storm period.

$P_X IN$ is the amount (kg) of phosphorus entering the reservoir in form X.

Q_p is the peak rate of inflow (in m^3/s) during storm period.

SECOUT is the average sediment concentration (in ppm) in the outflow during storm.

SEDCIN is the average sediment concentration (in ppm) in the inflow during storm.

The Gompertz equation was used in the analysis with and without logarithm transforms of the independent variables (first part of Table 3). The form of the variable that gave the best t-test (lowest value listed) was used in the stepwise regression analysis (SW entries in Table 3), using the Gompertz and exponential equations.

The TE equations were computed on a storm basis for the eight forms of P and are shown in Table 2. P-TE equations [1] through [4] and [8] were analyzed, using the exponential equation, because the TE values vary from less than 0 to 100 percent. Equations [5] through [7] were analyzed using the Gompertz equation, since the TE values vary from 0 to 100 percent. The range of these equations agreed with the observed range of TE's. The equations indicated that:

P-TE increased as:

1 Sediment inflow concentration (SEDCIN) increases, because higher sediment concentration usually means larger particles that will be deposited more rapidly along with the associated P; also the total quantity of P added by total sediment mass becomes more important than the decreasing concentration of sediment P ($\mu g/g$), as sediment concentration increases (Schreiber et al., 1976).

2 Sediment outflow concentration (SECOUT) decreases, because P is attached to the outflow sediment.

3 The amount of P inflow in the form being considered (P_XIN) increases, because more P is available to be trapped by the sediment or biomass.

4 Peak inflow rate (Q_p) decreases, because the percent clay increases and a higher percentage of P is adsorbed on the clay and trapped.

5 Total inflow (Q_{tot}) decreases, because less P is flushed through the reservoir.

In summary, SEDCIN and the amount of P_XIN were directly related to trapping one or more forms of P; while Q_p, Q_{tot}, and SECOUT were inversely related to P-TE.

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TABLE 3. SUMMARY OF P-TE STATISTICS.

Form of P (P_X)	Type of analysis*	Log transforms†	N	R^2	Results of t-test, Probability (β=0)‡ T_D	SEDCIN	Q_p	Q_{tot}	SECOUT	P_XIN
Model: $TE = 100/e^{\gamma e^{\beta_1 X_1 + \beta_2 X_2 + \dots}}$										
$P_{Organic}$ Soluble	All	No	12	0.76	0.85	0.14	0.04	0.57	0.32	0.15
	All	Yes	12	0.85	§0.39	0.03	0.037	0.24	0.09	0.14
	SW	Yes	12	0.53		0.0075				
P_{Hydro}	All	No	14	0.77	0.27	0.02	0.22	0.19	0.07	0.01
	All	Yes	14	0.67	0.93	0.06	0.67	0.10	0.41	0.09
	SW	Mixed	14	0.31						0.037
P_{Ortho}	All	No	14	0.53	0.32	0.13	0.50	0.41	0.21	0.10
	All	Yes	14	0.43	0.80	0.21	0.90	0.31	0.65	0.54
	SW	Mixed	14	0.19						0.116
$P_{Tot. Sed.}$	All	No	17	0.68	0.66	0.20	0.08	0.68	0.69	0.08
	All	Yes	17	0.65	0.70	0.69	0.66	0.58	0.07	0.09
	SW	Mixed	17	0.61			0.09			0.003
$P_{Inorg. Sed.}$‖	All	No	16	0.85	0.66	0.04	0.01	0.81	0.81	0.006
	All	Yes	16	0.74	0.44	0.64	0.98	0.27	0.21	0.12
	SW	Mixed	16	0.85		0.02	0.0025			0.0003
$P_{Org. Sed.}$‖	All	No	15	0.90	0.03	0.83	0.003	0.006	0.19	0.0002
	All	Yes	15	0.65	0.88	0.70	0.60	0.07	0.37	0.05
	SW	Mixed	15	0.88		0.04	0.0006	0.0022		0.0001
p31	All	No	16	0.79	0.85	0.01	0.95	0.04	0.67	0.35
	All	Yes	16	0.93	0.48	0.70	0.65	0.0002	0.47	0.003
	SW	Mixed	16	0.94		0.76		0.0001		0.0001
Labile P	All	No	17	0.77	0.85	0.003	0.56	0.39	0.41	0.55
	All	Yes	17	0.69	0.44	0.03	0.40	0.17	0.58	0.69
	SW	Mixed	17	0.68		0.0002		0.011		
Model: $TE = 100 - \gamma (X_1^{\beta_1} \cdot X_2^{\beta_2} \cdot X_3^{\beta_3} \dots)$										
$P_{Org. Sol.}$‖	SW	Yes	18	0.64				0.0158		0.0004
P_{Hydro}‖	SW	Yes	11	0.76						0.0007
P_{Ortho}‖	SW	Yes	18	0.29			0.02			
$P_{Tot. Sed.}$‖	SW	Yes	18	0.71					0.027	0.0004
$P_{Inorg. Sed.}$	SW	Yes	17	0.64		0.0003				
$P_{Org. Sed.}$	SW	Yes	17	0.71				0.073	0.032	0.001
p31	SW	Yes	19	0.91		0.0733		0.0001		0.0001
Labile P‖	SW	Yes	18	0.88		0.0001		0.0005		0.0885

* Type of analysis indicates whether all variables were considered at once in one model (all) or individually in stepwise regression (SW).

† Indicates whether logarithm transforms were used on independent variables.

‡ Values in table indicate the probability that the regression coefficients (β) equal zero. No correlation is indicated by 1.0; significant values are less than 0.10.

§ Underlined values indicate variables used in stepwise regression (mixed).

‖ Indicates most significant analysis, equation given in table 2.

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COMPARISON OF TE'S

When we compared the TE's of sediment, N, and P for the year of greatest runoff (1973), we found many similarities and differences (Table 1). The sediment TE was similar to that for total sediment P, 87 percent vs 72 percent. Thus, 13 percent of the inflowing sediment carried through the reservoir 28 percent of the total sediment P, because the sediment leaving the reservoir is very fine clay (<2μ) with a higher concentration of P (840 μgP/g) as compared with the inflow average concentration (400 μgP/g).

Nitrate and ortho-P are both soluble and readily used in algae growth. During 1973, 24.6 times more NO_3N was trapped than ortho-P. The N/P weight ratio normally found in algae is 7:1. Thus, this reservoir either has an excess of NO_3 or is deficient in ortho-P.

SUMMARY

Small reservoirs remove and trap significant amounts of sediment, sediment-P, and soluble nutrients from storm runoff. In 1973, Callahan reservoir in central Missouri trapped 87 percent of the incoming sediment, 72 percent of the total sediment P, 55 percent of the ortho-P, and 30 percent of the inorganic N. High percentages of nutrients were trapped, even though runoff was 2.5 times normal. The sediment passing through the reservoir was very fine clay with about twice the P concentration of incoming sediment. Since 96 percent of the P in the inflow was associated with the sediment, the trapping of P is related to the trapping of fine clays.

The annual amount of NO_3 trapped seemed related to annual runoff volume. For 1973, the soluble nutrients—total soluble P and NO_3—were trapped at similar rates, 32 percent and 34 percent, respectively.

As significant quantities of the most readily available forms of P were trapped by the reservoir, the outflow quality was thus improved.

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