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 NO₃ trapped seemed related to annual runoff volume. For 1973, the soluble nutrients, total soluble P, and NO₃ were trapped at similar rates, 32 percent and 34 percent, respectively.

We found more NH₄ 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 steep sidehills in pasture or forest. The drainage area at the inflow gaging station is 1,150 ha, 80 percent of the total.

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 m³/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

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

Our research objectives were to determine the trap effi-
ciency (TE) of Callahan Reservoir by measuring its sedi-
ment 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 reser-
voirs during 1972 and 1973, one of which was Callahan
reservoir. They developed the following regression equa-
tion for predicting sedimentation TE of Callahan reser-
voir for individual storms:

\[ \text{TE} = 100e^{1.14 - 0.017T_D - 0.75 \ln Q_p + 0.66 \ln Q_{tot}} \]

where TD is the detention time (in days); lnQ_p is the
natural logarithm of the peak inflow rate (in m^3/s); and
lnQ_{tot} is the natural logarithm of storm runoff (in cm).

For this equation, \( R^2 = 0.87 \) and standard error of esti-
mate is \( \pm 5 \) percent. Actual TE values ranged from
60 percent to 99.6 percent. This equation indicates that
TE increases as TD 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 outflow of this reser-
voir. 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
\( \text{NH}_3 \), which we then measured with the ammonia electrode. Thus,
measured \( \text{NH}_3 \)-N included any \( \text{NH}_4 \)-N liberated from
the sediment exchange complex.

We computed the total quantities of inflow and out-
flow 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 TD, Q_p, and Q_t.

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

<table>
<thead>
<tr>
<th>Equation Range in Dissolved Hydrolyzable P TE</th>
<th>In Solution</th>
<th>Out Solution</th>
<th>TE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phosphorus -kg- -kg- percent</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In Solution</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dissolved organic</td>
<td>56</td>
<td>101 - 80</td>
<td></td>
</tr>
<tr>
<td>Dissolved hydrolyzable</td>
<td>14</td>
<td>45 - 220</td>
<td></td>
</tr>
<tr>
<td>Ortho</td>
<td>420</td>
<td>190</td>
<td>33</td>
</tr>
<tr>
<td>Total soluble</td>
<td>490</td>
<td>322</td>
<td>32</td>
</tr>
<tr>
<td>In Sediment</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inorganic</td>
<td>6,600</td>
<td>1,600</td>
<td>76</td>
</tr>
<tr>
<td>Organic</td>
<td>3,900</td>
<td>1,200</td>
<td>67</td>
</tr>
<tr>
<td>Total</td>
<td>10,500</td>
<td>2,800</td>
<td>72</td>
</tr>
<tr>
<td>pH</td>
<td>780</td>
<td>140</td>
<td>82</td>
</tr>
<tr>
<td>Labile P</td>
<td>1,200</td>
<td>330</td>
<td>72</td>
</tr>
<tr>
<td>Sediment (MT)</td>
<td>26,120</td>
<td>3,450</td>
<td>87</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>16,660</td>
<td>11,000</td>
<td>34</td>
</tr>
<tr>
<td>NO₃-N</td>
<td>1,130</td>
<td>1,450</td>
<td>-28</td>
</tr>
<tr>
<td>NH₄-N</td>
<td>33 to 98</td>
<td>0.88</td>
<td>23</td>
</tr>
</tbody>
</table>

hydrolyzable P indicate that more of these two dissolved P forms left than entered into the reservoir. This possibility 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 P₅, 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 of 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

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

<table>
<thead>
<tr>
<th>Equation No.</th>
<th>TE Equation</th>
<th>Range in observed TE</th>
<th>R²</th>
<th>N</th>
<th>S.E.E.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Dissolved Organic P TE = 100 - 169 × Qₕₒₜ × 0.74 - PORGIN × 0.806</td>
<td>-400 to 51</td>
<td>0.64</td>
<td>18</td>
<td>63</td>
</tr>
<tr>
<td>2</td>
<td>Dissolved Hydrolyzable P TE = 100 - 172 × P₅ × 0.296</td>
<td>-150 to 31</td>
<td>0.76</td>
<td>11</td>
<td>37</td>
</tr>
<tr>
<td>3</td>
<td>Ortho-P TE = 100 - 109 × Qₕ</td>
<td>-50 to 91</td>
<td>0.39</td>
<td>18</td>
<td>34</td>
</tr>
<tr>
<td>4</td>
<td>Total Sed. P TE = 100 - 40 × SECOUT × 0.565 × Pₕₒₜ × SEDCNN × 0.495</td>
<td>-33 to 87</td>
<td>0.71</td>
<td>18</td>
<td>17</td>
</tr>
<tr>
<td>5</td>
<td>Inorganic Sed. P TE = 100 × 0.686 × 0.00018 × SEDCNN + 0.022 × Qₕ + 0.00014 × Pₕₒₜ</td>
<td>25 to 89</td>
<td>0.85</td>
<td>16</td>
<td>9</td>
</tr>
<tr>
<td>6</td>
<td>Organic Sed. P TE = 100 × 0.320 × 0.06 × lnSEDCNN + 0.0168 × Qₕ + 0.27 Qₕₒₜ + 0.0039 × Pₕₒₜ</td>
<td>34 to 86</td>
<td>0.88</td>
<td>15</td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td>p²1 TE = 100 × 0.00016 × SEDCNN + 3.76 × lnQₕₒₜ - 1.65 lnQₕ + 0.50</td>
<td>23 to 99</td>
<td>0.94</td>
<td>16</td>
<td>9</td>
</tr>
<tr>
<td>8</td>
<td>Labile P TE = 100 - 3.7 × 10³ × SEDCNN × 1.32 × Pₕₒₜ × 0.40</td>
<td>-33 to 98</td>
<td>0.88</td>
<td>23</td>
<td>98</td>
</tr>
</tbody>
</table>

Qₕₒₜ is the total runoff (in cm) during storm period.
Pₕₒₜ is the amount (kg) of phosphorus entering the reservoir in form X.
Qₕ is the peak rate of inflow (in m³/s) during storm period.
SECOUT is the average sediment concentration (in ppm) in the outflow during storm.
SEDCNN 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 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 (µg/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 (PₓIN) 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 PₓIN were directly related to trapping one or more forms of P; while Q_p, Q_tot, and SECOUT were inversely related to P-TE.

(Continued on page 290)

### Table 3. Summary of P-TE Statistics.

<table>
<thead>
<tr>
<th>Form of P</th>
<th>Type of analysis*</th>
<th>Log transform**</th>
<th>N</th>
<th>R²</th>
<th>TD</th>
<th>SEDCIN</th>
<th>Q_p</th>
<th>Q_tot</th>
<th>SECOUT</th>
<th>PₓIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_Org</td>
<td>All</td>
<td>No</td>
<td>12</td>
<td>0.70</td>
<td>0.85</td>
<td>0.14</td>
<td>0.04</td>
<td>0.57</td>
<td>0.22</td>
<td>0.15</td>
</tr>
<tr>
<td>Soluble</td>
<td>All</td>
<td>Yes</td>
<td>12</td>
<td>0.76</td>
<td>0.29</td>
<td>0.03</td>
<td>0.19</td>
<td>0.19</td>
<td>0.24</td>
<td>0.09</td>
</tr>
<tr>
<td>P_Hydro</td>
<td>All</td>
<td>No</td>
<td>14</td>
<td>0.70</td>
<td>0.27</td>
<td>0.03</td>
<td>0.24</td>
<td>0.19</td>
<td>0.07</td>
<td>0.01</td>
</tr>
<tr>
<td>SW</td>
<td>Mixed</td>
<td>14</td>
<td>0.31</td>
<td>0.30</td>
<td>0.30</td>
<td>0.30</td>
<td>0.30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P_Ortho</td>
<td>All</td>
<td>No</td>
<td>14</td>
<td>0.53</td>
<td>0.32</td>
<td>0.13</td>
<td>0.50</td>
<td>0.21</td>
<td>0.10</td>
<td>0.09</td>
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<tr>
<td>SW</td>
<td>Mixed</td>
<td>14</td>
<td>0.19</td>
<td>0.19</td>
<td>0.19</td>
<td>0.19</td>
<td>0.19</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P_Lab</td>
<td>All</td>
<td>No</td>
<td>17</td>
<td>0.68</td>
<td>0.66</td>
<td>0.20</td>
<td>0.20</td>
<td>0.68</td>
<td>0.68</td>
<td>0.90</td>
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<tr>
<td>SW</td>
<td>Mixed</td>
<td>17</td>
<td>0.61</td>
<td>0.61</td>
<td>0.61</td>
<td>0.61</td>
<td>0.61</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>P_Inorg</td>
<td>All</td>
<td>No</td>
<td>16</td>
<td>0.85</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
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<tr>
<td>SW</td>
<td>Mixed</td>
<td>16</td>
<td>0.85</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
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<td></td>
</tr>
<tr>
<td>P_Org, Soluble</td>
<td>All</td>
<td>No</td>
<td>15</td>
<td>0.90</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>SW</td>
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<td>15</td>
<td>0.88</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
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<tr>
<td>p21</td>
<td>All</td>
<td>No</td>
<td>16</td>
<td>0.79</td>
<td>0.85</td>
<td>0.91</td>
<td>0.91</td>
<td>0.91</td>
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<tr>
<td>SW</td>
<td>Mixed</td>
<td>16</td>
<td>0.84</td>
<td>0.76</td>
<td>0.76</td>
<td>0.76</td>
<td>0.76</td>
<td>0.76</td>
<td>0.76</td>
<td></td>
</tr>
<tr>
<td>Labile</td>
<td>All</td>
<td>No</td>
<td>17</td>
<td>0.77</td>
<td>0.85</td>
<td>0.002</td>
<td>0.002</td>
<td>0.002</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td>SW</td>
<td>Mixed</td>
<td>17</td>
<td>0.68</td>
<td>0.0002</td>
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<td>0.0002</td>
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<td></td>
</tr>
</tbody>
</table>

* 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 (b) equal zero. No correlation is indicated by 1.0; significant values are less than 0.10.

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

|| Indicates most significant analysis, equation given in Table 2.
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 (<2μm) 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 NO₃⁻ 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 NO₃⁻ 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 NO₃⁻ trapped seemed related to annual runoff volume. For 1973, the soluble nutrients—total soluble P and NO₃⁻—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.

References