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Reservoir sedimentation has also become important in recent years for recreational and aesthetic reasons, its impacts on water treatment costs, and the requirements of legislative acts. In 1960, sediment was assessed to be not only the major water pollutant by weight and volume but also a major carrier and catalyst for other water quality constituents such as pesticides and other organic residues, nutrients, and pathogenic organisms (13).

This paper will examine differences between reservoirs and lakes that support the importance and influence of reservoir sedimentation on water quality, develop a heuristic model to describe the effects of reservoir sedimentation on water quality, and discuss its impact on modeling reservoir ecosystems mathematically.

DIFFERENCES BETWEEN LAKE AND RESERVOIRS

The U. S. Environmental Protection Agency National Eutrophication Survey (NES) data were analyzed and compared for 309 natural lakes and 107 USAE reservoirs included in the NES program between 1972-1975 (Table 1).

TABLE 1. - A Comparison of Geometric Means on Selected Variables on Natural Lakes and CE Reservoirs

<table>
<thead>
<tr>
<th>Variable</th>
<th>Natural Lakes (N = 309)</th>
<th>CE Reservoirs (N = 107)</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drainage Area (km²)</td>
<td>222</td>
<td>2222</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Surface Area (km²)</td>
<td>5.6</td>
<td>34.5</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Maximum Depth (m)</td>
<td>10.7</td>
<td>19.8</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Mean Depth (m)</td>
<td>4.5</td>
<td>6.9</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Shoreline Development Ratio</td>
<td>2.9 (N = 346)</td>
<td>9.0 (N = 179)</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Hydraulic Residence Time (yr)</td>
<td>0.74</td>
<td>0.37</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Areal Water Load (m/yr)</td>
<td>6.5</td>
<td>19</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Drainage/Surface Area</td>
<td>33</td>
<td>93</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Secchi Depth (m)</td>
<td>1.4</td>
<td>1.1</td>
<td>&lt;0.0005</td>
</tr>
<tr>
<td>Total Phosphorus (mg/l)</td>
<td>0.054</td>
<td>0.039</td>
<td>&lt;0.02</td>
</tr>
<tr>
<td>Chlorophyll a (µg/l)</td>
<td>14</td>
<td>8.9</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>N Loading (g/m²-yr)</td>
<td>0.87</td>
<td>1.7</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>P Loading (g/m²-yr)</td>
<td>18</td>
<td>28</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

1 Hutchinson, 1957.
2 Leidy and Jenkins, 1977.

Reservoirs generally have greater drainage and surface areas, mean and maximum depths, and shoreline development ratios. The greater drainage to surface area ratio for reservoirs (approximately three times that of natural lakes), indicating the potential for greater sediment and nutrient loads, is also reflected in a shorter hydraulic residence time and greater areal water load for reservoirs.
Total phosphorus and chlorophyll $\alpha$ concentrations, on the average, are lower in reservoirs, despite higher total phosphorus and nitrogen loadings. The occurrence of lower total phosphorus concentrations could be related to the modifying effects of greater mean depth and shorter water residence time (e.g. 14) or the possibility that sedimentation rates are higher for reservoirs. Ancillary to the latter is the possibility that a larger percentage of the loadings to reservoirs are in a particulate form. This would also explain the lower average Secchi disc depth for reservoirs. If it is assumed that light attenuation is a function of phytoplankton population density (3), estimated here by chlorophyll $\alpha$ concentration, then a comparison of Secchi disc depth and chlorophyll $\alpha$ (Table 1) suggests the importance of non-algal particulates to the light regime of reservoirs.

Reservoirs exhibit pronounced longitudinal gradients, a phenomenon not unexpected considering the greater advective and unidirectional flows in reservoirs (1). The long, dendritic nature of many reservoirs is characteristic of the inundated floodplain and meandering channel of impounded rivers. Many reservoirs receive a majority of their inflow from a single large tributary located a considerable distance from the outflow. This provides a suitable setting for the development of physical, chemical, and biological gradients in both time and space.

**RESERVOIR SEDIMENTATION AND WATER QUALITY - A CONCEPTUAL MODEL**

Morphologic differences between lakes and reservoirs and the importance of sedimentation form the basis for a conceptual model to describe and explain the development of longitudinal gradients in reservoirs. Although occurring along a continuum from river inflow to dam, these gradients result in the establishment of three distinct zones possessing unique physical, chemical, and ecological properties. These three zones are a riverine zone, a zone of transition, and a lacustrine zone (Fig. 1). Although velocities in the riverine zone are decreasing, this zone is relatively narrow, well mixed, and advective forces are still sufficient to transport significant quantities of finer particles, such as silts, clays, and organic particulates. Light penetration is minimal and generally limits primary production. An aerobic environment is maintained because the riverine zone is generally shallow and well mixed, even though the degradation of allochthonous organic loadings often creates a significant oxygen demand. Secondary production in this portion of the reservoir would be subsided by allochthonous material through detrital food chains.

Significant sedimentation occurs through the transition zone with a subsequent increase in light penetration. Light penetration may increase gradually or abruptly, depending on flow regime. If an overflow occurs, light penetration will increase gradually down the reservoir as sedimentation occurs. If the inflow proceeds as an inter- or underflow, light penetration in the mixed layer will increase abruptly downstream of the plunge point, a point where sediment-laden inflowing water sinks to a depth of comparable density. At some point within the mixed layer of the zone of transition, a compensation point between the production and processing of organic matter should be reached. Beyond this point, autochthonous production of organic matter within the mixed layer should begin to dominate.
The lacustrine zone is characteristic of a lake system. Sedimentation of inorganic particulates is low, light penetration is sufficient to promote primary production with the potential for nutrient limitation and production of organic matter exceeds processing within the mixed layer. Entrainment of metalimnetic and hypolimnetic water, particulates, and nutrients may occur through internal seiches or wind mixing during the passage of large weather fronts (2). Hypolimnetic mixing may be more extensive in reservoirs because of hypolimnetic or bottom withdrawal. Bottom withdrawal removes hypolimnetic water and nutrients, and may promote movement of inter- or underflows into the hypolimnion (5).

A PROTOTYPE SYSTEM

West Point Dam impounds the Chattahoochee River on the Georgia-Alabama border approximately 80 km southwest of Atlanta, Georgia. Land use in the 5000 km² watershed is approximately 70% agricultural and 30% urban. There are significant point source discharges into the Chattahoochee River from Atlanta. West Point Lake is a long, dendritic reservoir with 113 km² surface area, 0.8 km³ volume, a maximum and mean depth of 31 m and 7 m, respectively, and a length of 53 km. It has a theoretical hydraulic residence time of 0.17 yr and a shoreline development ratio of 23.0. The dynamic nature of the above three zones is evident in West Point Lake (Fig. 2). Plumes of highly turbid water were associated with elevated flows occurring in June, September, and December 1976, and March and June 1977. As flow in the Chattahoochee River decreased, the turbidity zone receded upstream. These turbidity plumes illustrate the dynamic nature of the transition zone and the importance of the hydrologic regime.

An inverse relation existed between turbidity and chlorophyll along the length of the reservoir (Fig. 2). High turbidities due to inorganic suspended solids in the upper portion of the reservoir diminished toward the dam with a concomitant increase in chlorophyll concentration. Elevated flows and, therefore, increased turbulence, transported particulate matter farther into the pool, decreased light penetration, and decreased algal production as indicated by reduced chlorophyll concentrations. During low flow, shear generated turbulence decreased, greater sedimentation occurred in the upper portion of the reservoir, light penetration increased, and chlorophyll concentrations increased upstream. While, in general, chlorophyll a concentrations increased with distance downstream, it should be noted that, with the exception of winter months, concentrations were highest at mid-reservoir immediately below turbidity plumes. Nutrient concentrations, which tended to be higher here than near the dam, and an improved light regime apparently resulted in higher algal populations.

Similar zonation was observed in Livingston Reservoir. The zone of highest carbon fixation was dictated by hydrologic conditions and productivity (10). During the high flow periods of spring and fall, productivity was greatest in the lacustrine region of the reservoir. As flow decreased during the summer and turbidity decreased in the river, the peak in productivity occurred upstream where nutrient concentrations were higher. Using stepwise discriminate analysis, turbidity was demonstrated to be the dominate factor influencing productivity in the riverine segment during high flow while phytoplankton standing crop was a discriminating factor influencing productivity in the lacustrine region (10). The highest primary productivity in the reservoir was also observed in Lake Powell (7). In the upper portions of Lake Powell, turbidity reduced the photic zone depth while nutrient depletion reduced productivity in the lower portion of the reservoir (7).

SIMULATING RESERVOIR ECOSYSTEMS

The establishment of longitudinal gradients in reservoirs may require the coupling of several models to adequately simulate these systems. Although models are developed and applied around specific objectives, a minimum combination of models can be discussed that will provide cost-effective simulations addressing many of the water quality problems in reservoirs (Fig. 1).

The riverine zone may be simulated with a longitudinally one-dimensional riverine model. Based on the characteristics of the riverine zone, the model should include algorithms for organic matter processing, sediment transport and deposition, dissolved-particle matter interactions, and nutrient dynamics for realistic simulations.

The zone of transition represents the most dynamic area of the reservoir and would be best simulated using a two-dimensional, laterally averaged reservoir ecosystem model. Physically, the model must be able to simulate the flow fields in this zone, including the proper positioning of the plunge point, and the longitudinal gradients in suspended solids. Since the highest primary production may occur downstream from the plunge point within this zone, algorithms must describe the interactions among hydrodynamics, light, temperature, nutrients, and phytoplankton. These algorithms must also incorporate the transition from the processing to the production of organic matter.
The lacustrine zone has generally been simulated using a vertically one-dimensional reservoir ecosystem model (6). The model must be capable of simulating the onset, duration and breakup of thermal stratification within the reservoir. Implicit in these algorithms is the proper simulation of the mixed layer, entrainment of metalimnetic water, nutrient dynamics and anaerobic processes. Since this zone is influenced by water control operation, realistic reservoir operation algorithms and withdrawal characteristics must be incorporated.

While many reservoir ecosystems could be simulated with a two-dimensional total reservoir ecosystem model, the data and computer requirements, as well as cost, would be prohibitive. Used in combination, the output from one model may be used to define the input to the next model. The use of the three models in combination should provide a realistic, cost-effective approach for reservoir water quality problems.

CONCLUSIONS AND SUMMARY

Reservoir sedimentation significantly affects reservoir water quality as evidenced by the development of a riverine zone, a zone of transition, and a lacustrine zone. The processing of organic matter dominates the riverine zone, while production dominates in the mixed layer of the lacustrine zone. The relation of reservoir sedimentation and water quality has been presented as a heuristic model. Sufficient circumstantial evidence supports the relationships, but more importantly, the heuristic model can be tested directly through field experimentation. The three zones imply that it may be necessary to use a one-dimensional riverine model, a two-dimensional reservoir model, and a one-dimensional reservoir model to simulate reservoir water quality in toto.

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REFERENCES