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RESERVOIR SEDIMENTATION AND WATER QUALITY - AN HEURISTIC MODEL

by

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INTRODUCTION

While reservoirs are incorporated in the formal definition of lakes, several structural and functional differences between lakes and reservoirs make reservoirs unique ecological systems. Structural differences include greater reservoir shoreline development ratios, shorter retention times, and pronounced longitudinal gradients (1). One of the obvious differences is the outflow depth or zone of withdrawal and the capability of selectively altering this outflow depth in reservoirs.

While hydrodynamics are important in both lakes and reservoirs, dominant mixing processes may be different in reservoirs. In lakes, the controlling factors are generally the interactions of solar insolation and wind (11). In reservoirs, the advective forces of inflow and outflow and density differences caused by solids concentrations play an equally important role in hydrodynamics. Inflow and outflow mixing, while separated spatially, have a profound effect on reservoir dynamics by dictating the initial distribution of influent water and associated material and by influencing the quantity and rate at which materials are discharged downstream.

A dominate process in reservoirs is sediment transport. The transport of sediment into reservoirs and its eventual deposition are of concern since the original purpose of a reservoir is to store water for flood control, water supply, irrigation, power production or other uses. For reservoirs built prior to 1935 in the midwest, Great Plains States, the southeastern and southwestern United States, 33% have lost from one-fourth to one-half their original capacity; 14% have lost from one-half to three-quarters of their original capacity; and about 10% have had all usable storage depleted by sediment deposition (12). This impact of sediments has led to the use of routine reservoir sediment surveys, calculations of trap efficiency, and other procedures designed to provide a better basis for making water quantity management decisions.

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Reservoir sedimentation has also become important in recent years for recreational and esthetic 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

Variable (1)	Natural Lakes (N = 309) (2)	CE Reservoirs (N = 107) (3)	Probability Means Are Equal (4)
Drainage Area (km^2)	222	3228	<0.0001
Surface Area (km^2)	5.6	34.5	<0.0001
Maximum Depth (m)	10.7	19.8	<0.0001
Mean Depth (m)	4.5	6.9	<0.0001
Shoreline Development Ratio	2.9 (N = 34)†	9.0 (N = 179)‡	<0.001
Hydraulic Residence Time (yr)	0.74	0.37	<0.0001
Areal Water Load (m/yr)	6.5	19	<0.0001
Drainage/Surface Area	33	93	<0.0001
Secchi Depth (m)	1.4	1.1	<0.0005
Total Phosphorus (mg/ℓ)	0.054	0.039	<0.02
Chlorophyll a (μg/ℓ)	14	8.9	<0.0001
P Loading (g/m^2-yr)	0.87	1.7	<0.0001
N Loading (g/m^2-yr)	18	28	<0.0001

† Hutchinson, 1957.

‡ 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 a 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 a concentration, then a comparison of Secchi disc depth and chlorophyll a (Table 1) suggests the importance of nonalgal particulates to the light regime of reservoirs.

Reservoirs exhibit pronounced longitudinal gradients, a phenomenon not unexpected considering the greater advective and undirectional 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 subsidized 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.

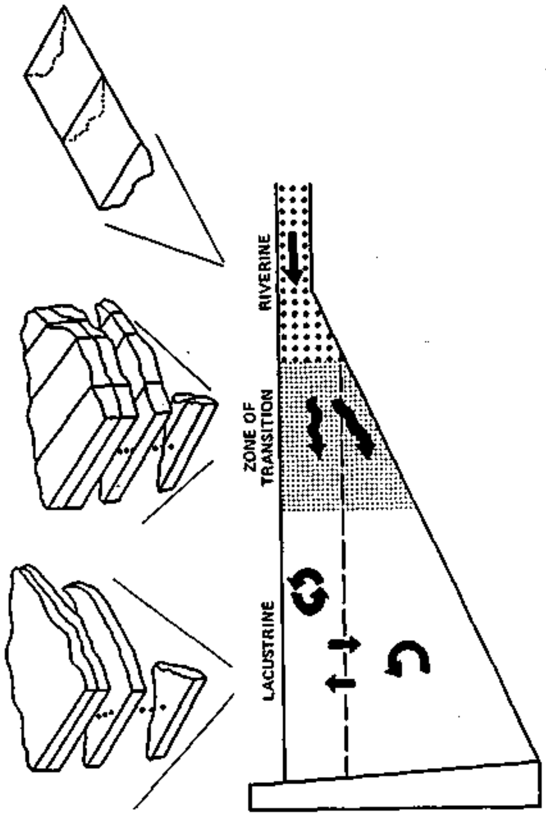

Fig. 1. - Reservoir zonation and appropriate simulation models. Arrows indicate dominant transport processes.

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 6000 km^2 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 km^2 surface area, 0.8 km^3 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

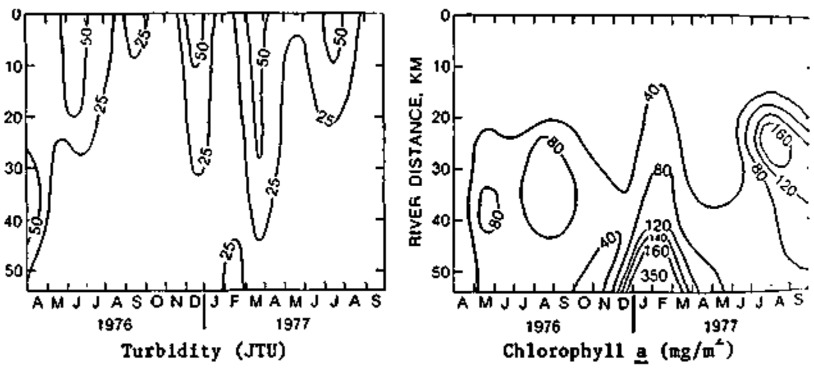

Fig. 2. - Turbidity and chlorophyll gradients in West Point Lake, Ga. River distance measured from headwater to dam. Data from Davies et al. (4).

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 turbidity (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 stepwide 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 midreservoir 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-particulate 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 reservior model to simulate reservoir water quality in toto.

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