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PHOSPHORUS DYNAMICS IN AN ARKANSAS RESERVOIR: THE IMPORTANCE OF SEASONAL LOADING AND INTERNAL RECYCLING

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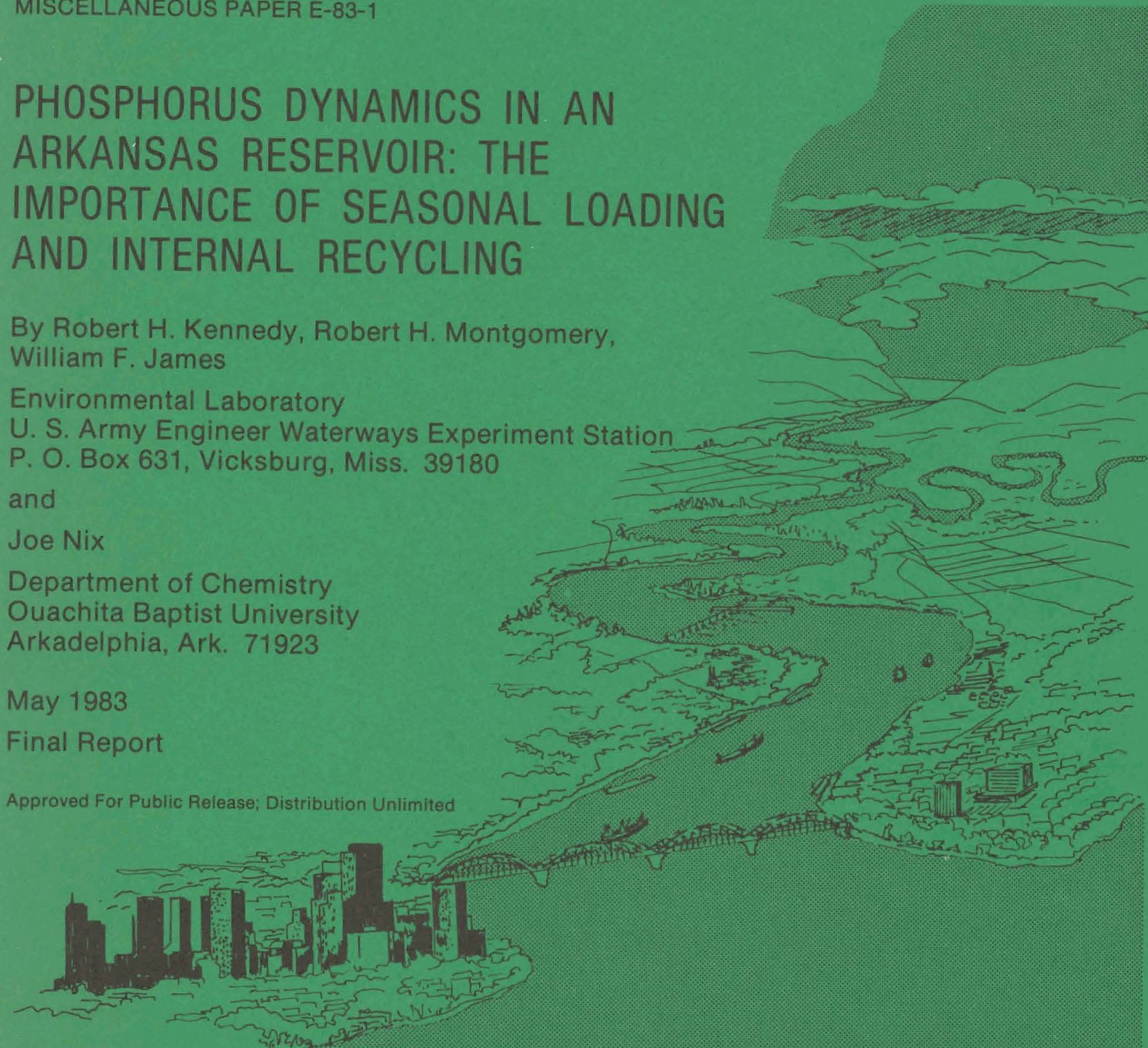

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DeGray Lake, a large U. S. Army Corps of Engineers impoundment on the Caddo River in south-central Arkansas, receives the majority of its material loads during fall, winter, and spring, when flows are highest. During summer stratified months, when loads are minimal, anoxic conditions develop in the upstream portion of the hypolimnion. Longitudinal differences in water-column phosphorus and iron concentrations indicate that processes occurring in this region of the lake play an important role in determining the fate and ultimate impact of materials input from the river. Headwater sediments, (Continued)

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which store allochthonous loads during fall, winter, and spring, act as a source for phosphorus and iron during anoxic periods. Deepening of the thermocline in late summer leads to losses of phosphorus and iron. These occurrences are also suggested by changes in the chemical compositions of sedimenting material collected in sediment traps.

This study represents one part of an effort to better define the impacts of Corps reservoir design and management on water quality.

PREFACE

The work described in this report is part of the Environmental and Water Quality Operational Studies (EWQOS) Work Unit VIIA, Reservoir Field Studies, conducted by the U. S. Army Engineer Waterways Experiment Station (WES) for the Office, Chief of Engineers, U. S. Army (OCE). The study was completed by the Aquatic Processes and Effects Group (APEG), Environmental Research and Simulation Division (ERSD), Environmental Laboratory (EL), WES. The OCE Technical Monitors for EWQOS were Mr. Earl Eiker, Mr. John Buchanan, and Mr. James L. Gottesman.

The report was prepared by Dr. Robert H. Kennedy and Messrs. Robert H. Montgomery and William F. James, APEG, and Dr. Joe Nix, Department of Chemistry, Ouachita Baptist University, under the supervision of Mr. Donald L. Robey, Chief, ERSD, and Dr. John Harrison, Chief, EL. Dr. Jerome L. Mahloch was Program Manager of EWQOS.

Commander and Director of WES during the study and preparation of this report was COL Tilford C. Creel, CE; Mr. F. R. Brown was Technical Director.

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CONTENTS

PHOSPHORUS DYNAMICS IN AN ARKANSAS RESERVOIR: THE IMPORTANCE OF SEASONAL LOADING AND INTERNAL RECYCLING

PART I: INTRODUCTION

1. Large elongated lakes and reservoirs often receive a majority of their water and material loads via a single large tributary located some distance from the lake's discharge. These waterbodies often exhibit marked longitudinal gradients in water quality (Gloss et al. 1980, Thornton et al. 1982, Peters 1979, Kennedy et al. 1982). Longitudinal changes in channel morphology (i.e., increased width and depth) reduce riverine influences within the lake and promote sedimentation of suspended loads in the upper reaches of the lake (see, for example, Kennedy et al. 1981). Concomitant losses of nutrients result in the establishment of chemical gradients which are often reflected by differences in phytoplankton production along the lake's major axis (e.g., Kennedy et al. 1982). In such cases, the frequently applied assumption that allochthonous loads are completely and instantaneously mixed upon entering the lake may be inappropriate. Internal processes such as transport, deposition, and recycling may determine the fate of influent materials and their ultimate impact on the lake.

2. This study represents one part of a major program conducted by the U. S. Army Corps of Engineers (CE) in an effort to better define the impacts of reservoir design and management on water quality. Specific objectives of this study were: (a) to evaluate the importance of seasonal variability in phosphorus loading and (b) to identify within-lake processes of potential importance in determining the limnological impact of these loads.

Study Site

3. DeGray Lake is a CE reservoir created during 1969-70 by the impoundment of the Caddo River in south-central Arkansas (Figure 1).

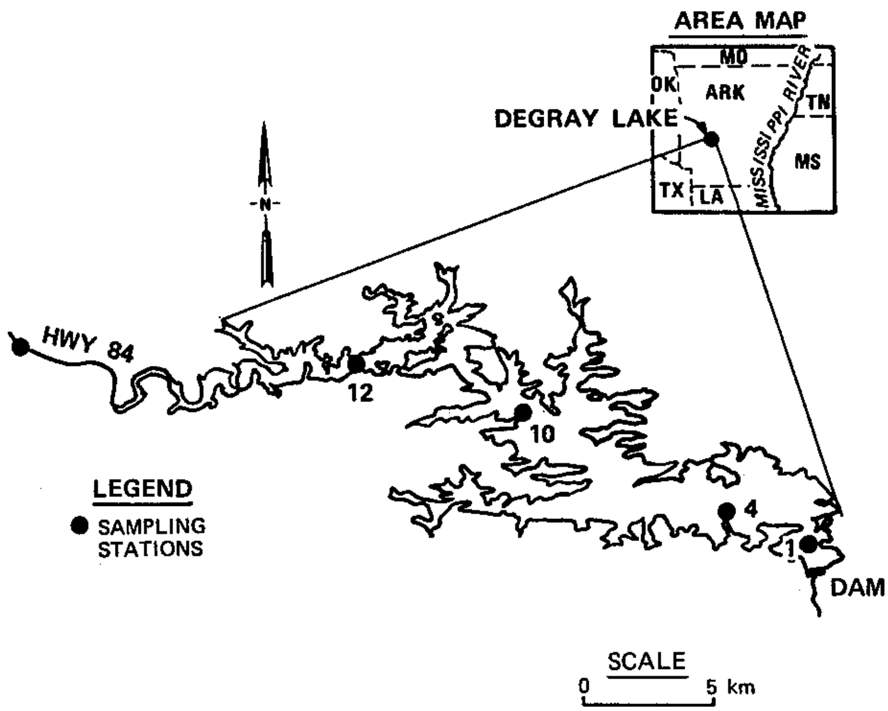


Figure 1. Locations of sampling stations in DeGray Lake, Arkansas

The lake is large (52.6 km^2), long (27 km), morphologically complex (i.e., with a shoreline development ratio of 12.8), and strongly stratifed during summer. Mean and maximum lake depths are 9 m and 60 m, respectively. Reservoir purposes include power generation, flood control, and recreation.

4. The Caddo River drains a predominately forested watershed and enters the extreme upstream end of the lake. It is the dominant tributary to DeGray Lake, supplying approximately 70 percent of the total inflow to the lake. Small secondary tributaries enter the lake through coves along the lake's length. Overflow, underflow, and interflow density currents, which are commonly observed following storm events (Ford and Johnson 1981, Nix 1977), influence water quality in the upstream portions of the lake (Nix 1981, Thornton et al. 1982).

Methods

5. DeGray Lake and its watershed have been extensively studied

since filling, and previously established sampling stations were incorporated in this study. These included (a) a river station at Highway 84 (34 river km above the dam), (b) a lake station near the dam (Station 1), and (c) lake stations 5 km (Station 4), 12 km (Station 10), and 19 km (Station 12) above the dam (Figure 1).

6. Lake samples for iron and phosphorus determinations were collected biweekly in 1980 at 2-m intervals above and 5-m intervals below the thermocline at Stations 4, 10, and 12. Samples for total phosphorus were stored on ice in acid-washed polyethylene bottles and returned to the laboratory for acid-persulfate digestion and colorimetric analysis (American Public Health Association 1976). Total soluble and soluble reactive phosphorus were determined for 0.45-μ-filtered samples. Particulate phosphorus was calculated as the difference between total and total soluble phosphorus. Samples for dissolved iron determination were filtered anaerobically in the field through a 0.1-μ membrane, acidified with nitric acid, and analyzed using standard atomic absorption techniques (American Public Health Association 1976). Biweekly oxygen and temperature profiles at Stations 1, 4, 10, and 12 were obtained using a YSI (Yellow Springs Instruments) dissolved oxygen analyzer or a Hydrolab Model 8000 dissolved oxygen analyzer.

7. River samples for phosphorus determination were collected approximately biweekly during 1978-1980 near midchannel at the Highway 84 bridge. Additionally, phosphorus concentrations were intensively monitored during 11 storm events over the period 1976-1980. Samples during storms were collected at intervals ranging from 1 to 24 hr, depending on flow conditions, and analyzed for total phosphorus as described above; sample collection was most frequent during periods of maximum rates of change in streamflow. Streamflow was obtained from a continuous stage recorder located at Highway 84.

8. Sedimenting seston was collected at Stations 10 and 12 in triplicate cylindrical plexiglass containers suspended at depths of 5 m (in or immediately above the thermocline) and 15 m. Material removed from traps at monthly intervals during March-September 1980 was analyzed for total phosphorus and iron following acid digestion. Methods used are described in James and Kennedy (1983).

PART II: RESULTS AND DISCUSSION

9. Phosphorus concentrations in the river were low (0.01-0.03 mg P/L) during nonprecipitation periods, but increased markedly during storm events. Changes following a moderate rainfall event on 6 March 1978 (Figure 2) were typical. Particulate phosphorus concentration increased sharply on the rising limb of the hydrograph, with the peak concentration preceding maximum flow; phosphorus concentrations returned to prestorm levels more rapidly than did flow. Total soluble phosphorus increases were less pronounced, and the peak concentration occurred later in the hydrograph. This pattern of change was consistent among storms and could have resulted from the scour and transport of phosphorus-containing particulates accumulated on the streambed during baseflow periods, from wash-off from the watershed, or both. Particulate phosphorus represented a larger percentage of total phosphorus during storm events than during periods of baseflow in the Caddo River.

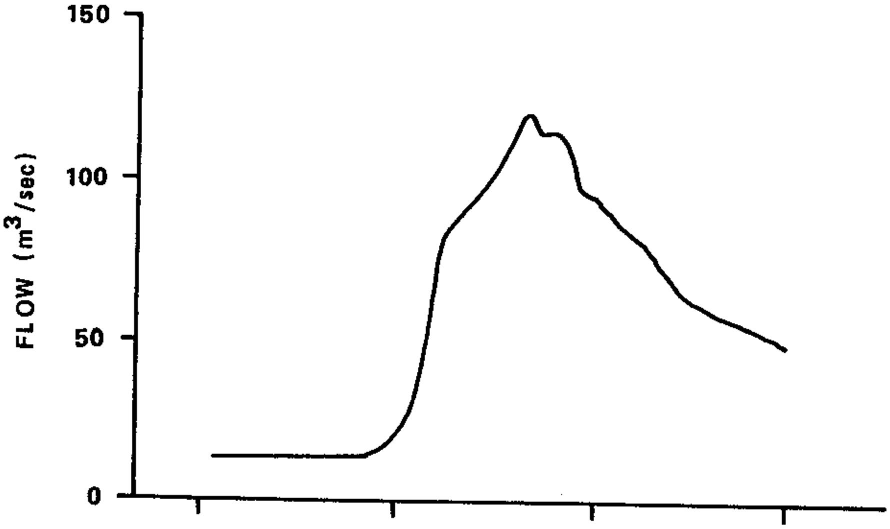
10. Phosphorus loads from the Caddo River during 1980 were estimated using relationships between instantaneous loads (i.e., the product of concentration and flow) and flow. The following regression equations provided the best fit ($R^2 = 0.77$ and 0.94, respectively) for baseflow (Equation 1) and storm event (Equation 2) data. Based on a review of the flow record, baseflow was subjectively defined as flow less than 12 m^3/sec.

$$\text{Total phosphorus load} = 2.0136\ (\text{flow}) \qquad (1)$$

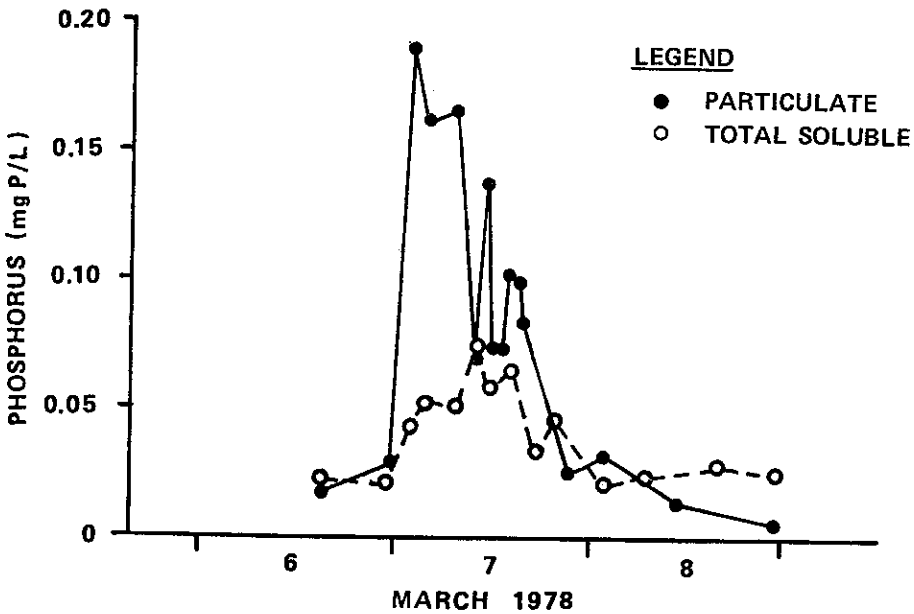
$$\text{Total phosphorus load} = 9.5316\ (\text{flow}) + 0.0277\ (\text{flow})^2 \qquad (2)$$

Estimates of daily phosphorus loading (kg P/day) were obtained using these relationships and flow data obtained from the river gage at Highway 84.

11. Phosphorus loads from the Caddo River in 1980 were seasonally variable (Figure 3), with storm events accounting for the majority of the total annual phosphorus load. Late winter and spring storm events



a. Changes in streamflows



b. Changes in phosphorus concentrations

Figure 2. Changes in Caddo River (a) flow and (b) particulate and total soluble phosphorus concentrations following the occurrence of a storm event in March 1978

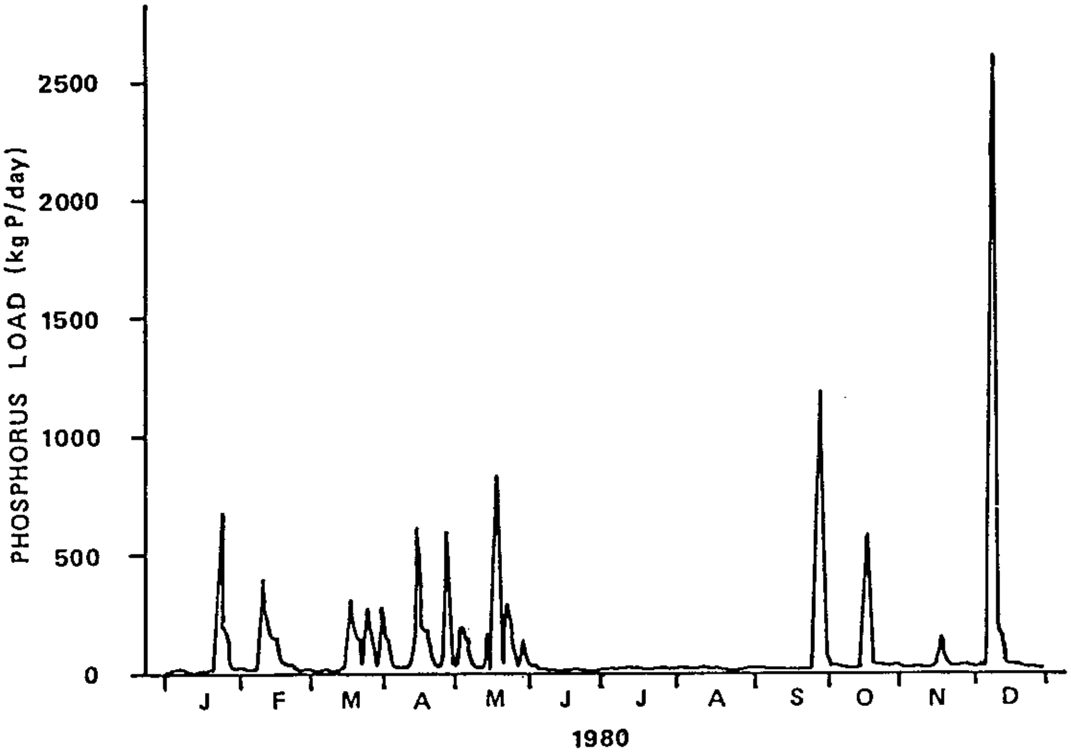


Figure 3. Daily total phosphorus loads for the Caddo River in 1980

contributed 51 percent of the total annual load, with an additional 37 percent supplied from three major events in fall and early winter. The largest single loading event occurred during a 6-day period in December and accounted for 22 percent of the river's annual phosphorus load. The importance of storm events is clear since they accounted for 88 percent of the river's annual phosphorus load during a total of only 73 days. Phosphorus loads during the summer stratified period were minimal.

12. Epilimnetic total phosphorus concentrations also varied spatially as well as in response to seasonal changes in loading (Figure 4). Pronounced longitudinal gradients occurred in winter and spring, and again in late summer and fall. During both periods, total phosphorus concentration decreased with increased distance downstream from the lake's headwaters (i.e., from Station 12 to Station 4). Station differences were most pronounced between Stations 12 and 10, while concentrations at Station 4 were low (5-10 μg P/L) and relatively constant

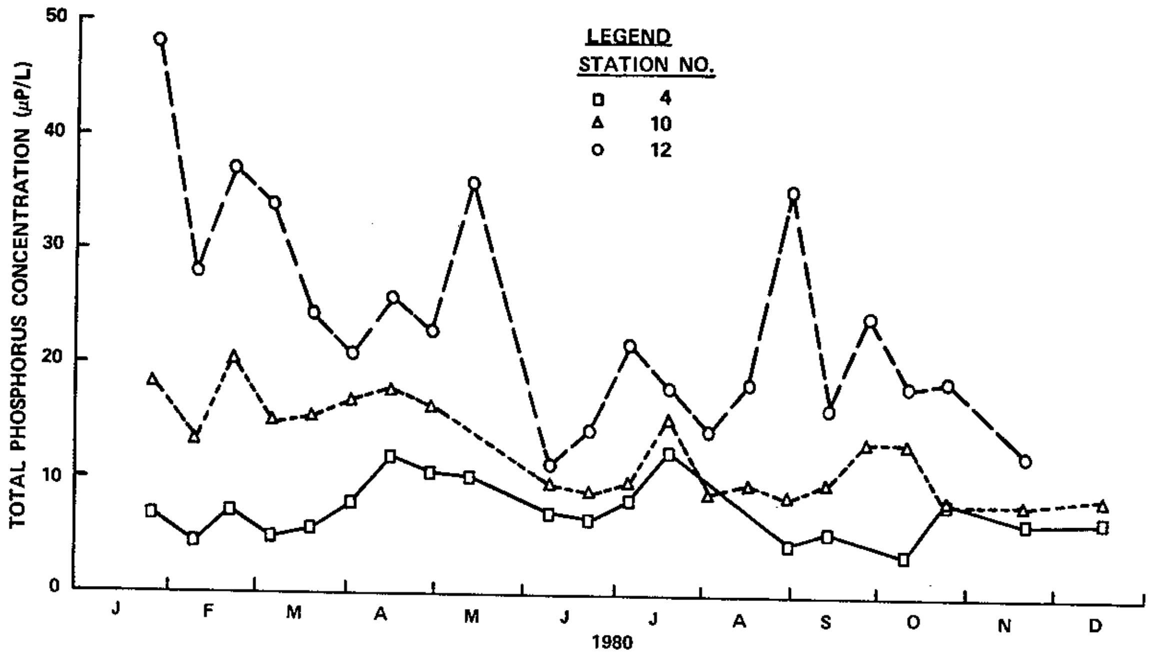


Figure 4. Changes in mean epilimnetic total phosphorus concentration at Stations 4, 10, and 12 in DeGray Lake during 1980

throughout the year. Station differences were minimal immediately prior to the onset of stratification (late May).

13. Although high epilimnetic total phosphorus concentrations in winter coincided with elevated loading rates, concentrations at Station 12, and to a lesser extent at Station 10, declined steadily from January through late May. Concentrations at Station 12 increased in summer following stratification despite the lack of significant loading from the Caddo River, and, as will be discussed below, may have been influenced by internal recycling. Concentrations in fall were little affected by periodically intense loading events.

14. Headwater areas experienced progressive hypolimnetic anoxia (≤ 0.5 mg O_2/L) and marked increases in hypolimnetic total phosphorus concentrations following the onset of thermal stratification (Figure 5). Although lake total phosphorus concentrations were low (<10-30 µg P/L) and relatively uniform on 27 May, by 24 June anoxic conditions were observed below 6 m and 17 m at Stations 12 and 10, respectively, with

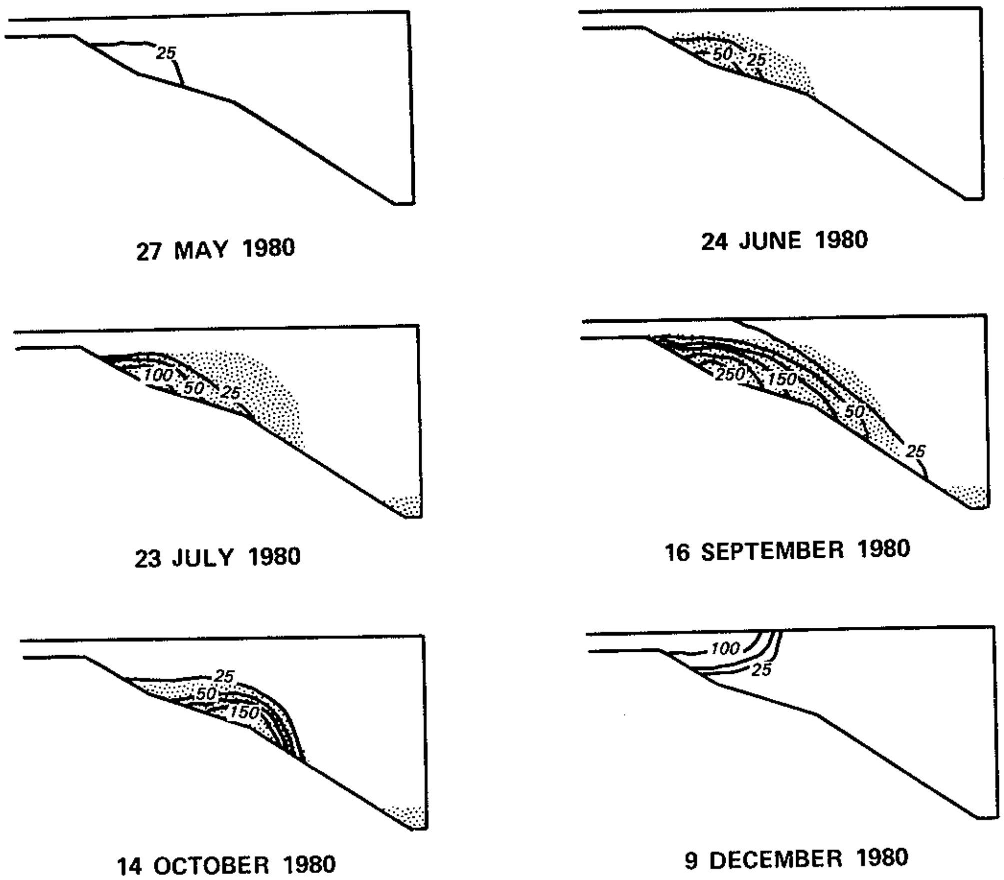


Figure 5. Distribution of total phosphorus concentrations (μg P/L) in DeGray Lake on selected dates in 1980 (shading represents areas of anoxia (DO ≤ 0.5 mg/L)

maximum hypolimnetic total phosphorus concentrations exceeding 50 μg P/L at Station 12. On 16 September, hypolimnetic total phosphorus concentrations at Station 12 ranged from 50 μg P/L immediately below the thermocline to 250 μg P/L above bottom sediments. A large percentage of the upstream portion of the lake exhibited hypolimnetic anoxia. Anoxic conditions in downstream areas developed in midsummer, but were restricted to a small volume of deep water immediately upstream from the dam. During this period, phosphorus concentrations in the lake's surface waters, and throughout the water column at Station 4, remained relatively low.

15. Increased mixing associated with elevated flows and a deepening of the thermocline in late September and early October

resulted in a dramatic decrease in hypolimnetic phosphorus concentrations at Station 12. Phosphorus concentrations downstream at Station 10 remained high and relatively unchanged until destratification occurred at this station in late October. Phosphorus concentrations were low (<25 μg P/L) on 9 December 1980, with the exception of surface waters at Station 12 where high phosphorus concentrations were associated with the entrance of turbid storm water. Complete vertical circulation was not observed at Station 1 until 20 January 1981, 84 days after Station 12.

16. Anoxic sediments appeared to be a significant source of phosphorus in the upper portion of the lake in summer. A conservative estimate of their importance was made by comparing external loading with rates of hypolimnetic phosphorus increase in the portion of the lake above Station 10. Advective transport of phosphorus downstream was assumed to be negligible. Phosphorus increases in the hypolimnion averaged 5.71 mg P/m^2/day from June through September, while inputs from the Caddo River averaged only 2.97 mg P/m^2/day during the same period. The difference, 2.74 mg P/m^2/day, estimates the average net sediment phosphorus release rate; thus, recycling of phosphorus from anoxic sediment may have accounted for at least 50 percent of the summer phosphorus increase in the lake's upstream areas during 1980.

17. Concomitant increases in soluble iron and soluble reactive phosphorus immediately above the sediments at Station 12 (Figure 6) strengthen the hypothesis that anoxic sediments play an important role in phosphorus dynamics in the lake's headwater area. Dissolved iron concentration increased following the onset of anoxia in early June and reached a maximum in late August. Although delayed until late June, soluble reactive phosphorus concentration also increased steadily during anoxia and reached a maximum in mid-September. The ratio of iron to phosphorus during this period remained relatively constant at 25, which corresponds with a ratio of 33 determined for DeGray Lake surfacial sediments (Gunkel et al. 1982). If sediment phosphorus were associated with hydrous iron oxides (Mortimer 1971), ferric iron (III) reduction following the onset of anoxia would result in concomitant increases in phosphorus and ferrous iron (II); this appears to be the case for DeGray

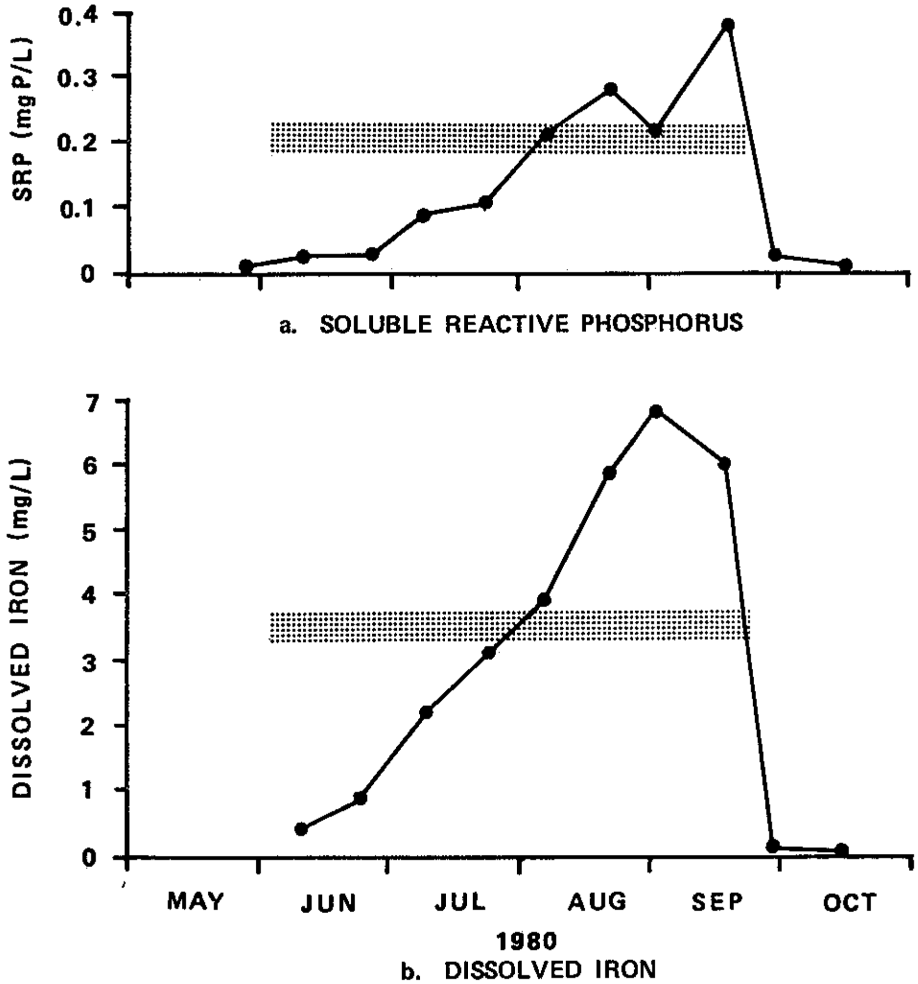


Figure 6. Changes in soluble reactive phosphorus and dissolved iron concentrations above Station 12 sediments (periods of anoxia are indicated by shading)

Lake. Rapid reductions in the concentrations of iron and phosphorus immediately following destratification and reoxygenation of bottom waters at Station 12 in late September suggest the precipitation of phosphorus with hydrous iron oxides.

18. The significance of spring loading events and the potential importance of interactions between iron and phosphorus are reflected in the sediment trap data (Figure 7). Total phosphorus sedimentation rates determined for Station 12 exhibited two distinct peaks: one in late spring coincident with storm-related maxima in phosphorus loading from the Caddo River and a second in September coincident with the loss of

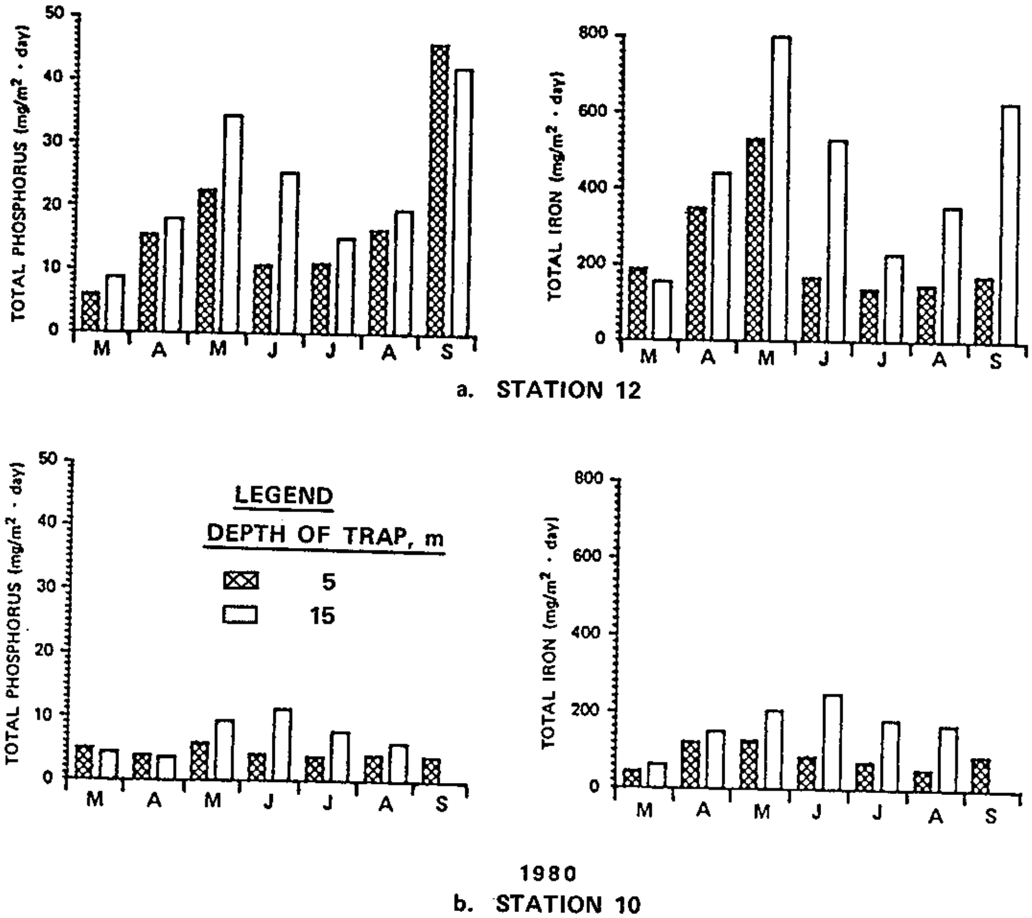


Figure 7. Phosphorus (left) and iron (right) sedimentation rates at 5 m and 15 m at Stations 12 and 10

thermal stratification in the headwater areas of the lake. Phosphorus deposition recorded by traps located downstream from Station 12 (i.e., at Station 10) was considerably less and did not exhibit seasonal maxima, indicating that this reach of the lake was less affected by spring loading events and late-summer mixing at upstream areas. Differences in calculated total phosphorus sedimentation rates between traps at 5 and 15 m at Station 12 in May and June seem reasonable, since the occurrence of a pronounced interflow following the onset of stratification--as did happen in DeGray Lake (Ford and Johnson 1981)--would introduce riverborne phosphorus loads to depths within the thermocline (approximately 10 m) and thus below the 5-m trap. Differences in the sediment trap data between the 5- and 15-m traps at Station 12 in September, when phosphorus sedimentation rates were again high, were minimal. Since phosphorus inputs from the river continued to be low from June until late September (Figure 3), increased deposition in traps at both depths must have resulted from the redistribution by mixing and subsequent settling of the hypolimnetic phosphorus. The fact that rates observed at the 5-m depth were high indicates significant vertical transport to surface waters.

19. Seasonal and station differences for iron sedimentation rates were similar to those for phosphorus (Figure 7). Rates calculated for Station 12 were high in spring and late summer, while low and relatively uniform at Station 10. A notable difference was the dissimilarity between rates calculated for 5- and 15-m depth in August and September at Station 12. Unlike phosphorus sedimentation, the increase in the iron sedimentation rate during this period was recorded for only the 15-m trap; thus, there appear to be differences in the extent of redistribution of hypolimnetic phosphorus and hypolimnetic iron following destratification. This observation may be related to (a) the rate at which insoluble hydrous iron oxides are formed and/or (b) the uptake of phosphorus by phytoplankton. Since the formation of hydrous iron oxides occurs relatively rapidly, the introduction of significant quantities of hypolimnetic iron to surface waters (i.e., strata above the 5-m trap) during the deepening and eventual loss of the thermocline in late summer would be prevented by oxidation and precipitation. Phosphorus not immediately removed by coprecipitation with iron would be redistributed to surface waters and thus increase phosphorus accumulation in the 5-m trap. In addition, the uptake of readily available phosphorus by phytoplankton, the standing crop of which was at a maximum during this period (Kennedy, unpublished data), could account for the increased phosphorus sedimentation rates recorded for the 5-m depth.

PART III: SUMMARY AND CONCLUSIONS

20. The storage of river-borne phosphorus in headwater sediments and its eventual release during stratification provide a mechanism coupling spring loading events with summer phosphorus increases in DeGray Lake (Figure 8). During winter and spring, the majority of the annual phosphorus load enters the lake associated with storm inflows. Phosphorus losses by sedimentation of allochthonous material in upstream reaches of the lake result in the establishment of longitudinal concentration gradients. In early summer, decreases in flow and external phosphorus loading coincide with the onset of thermal stratification. The isolation of a small volume of hypolimnetic water above these sediments rich in autochthonous and allochthonous organic matter leads to the establishment of anoxic conditions in upstream areas, the release of phosphorus and iron, and the establishment of marked vertical gradients. Phosphorus and iron concentrations in oxic downstream portions of the hypolimnion remain low. Entrainment of density inflows in or near the thermocline, convective mixing, and seiche activity provide the potential for material transport across the thermocline, which may account for euphotic zone phosphorus increases observed in the upstream end of the lake during summer. Phosphorus inputs from the river directly to the epilimnion during summer are minimal. Losses of phosphorus occur by particulate settling and by precipitation as ferric hydroxide/phosphate complexes. Major phosphorus fluxes during summer occur from sediment to overlying water and between epi- and hypolimnion. Advective transport downstream, in the absence of summer storm events, is minimal.

21. In late summer, destratification begins in shallow upstream areas and proceeds downstream accompanied by precipitation of iron and phosphorus. External phosphorus loads increase with increased runoff and, frequently, intense storms. The major phosphorus flux in fall is again from water column to sediments.

22. While this scenario is appropriate for describing seasonal events in DeGray Lake, it may also provide a perspective from which to evaluate phosphorus dynamics in other lakes and reservoirs. The

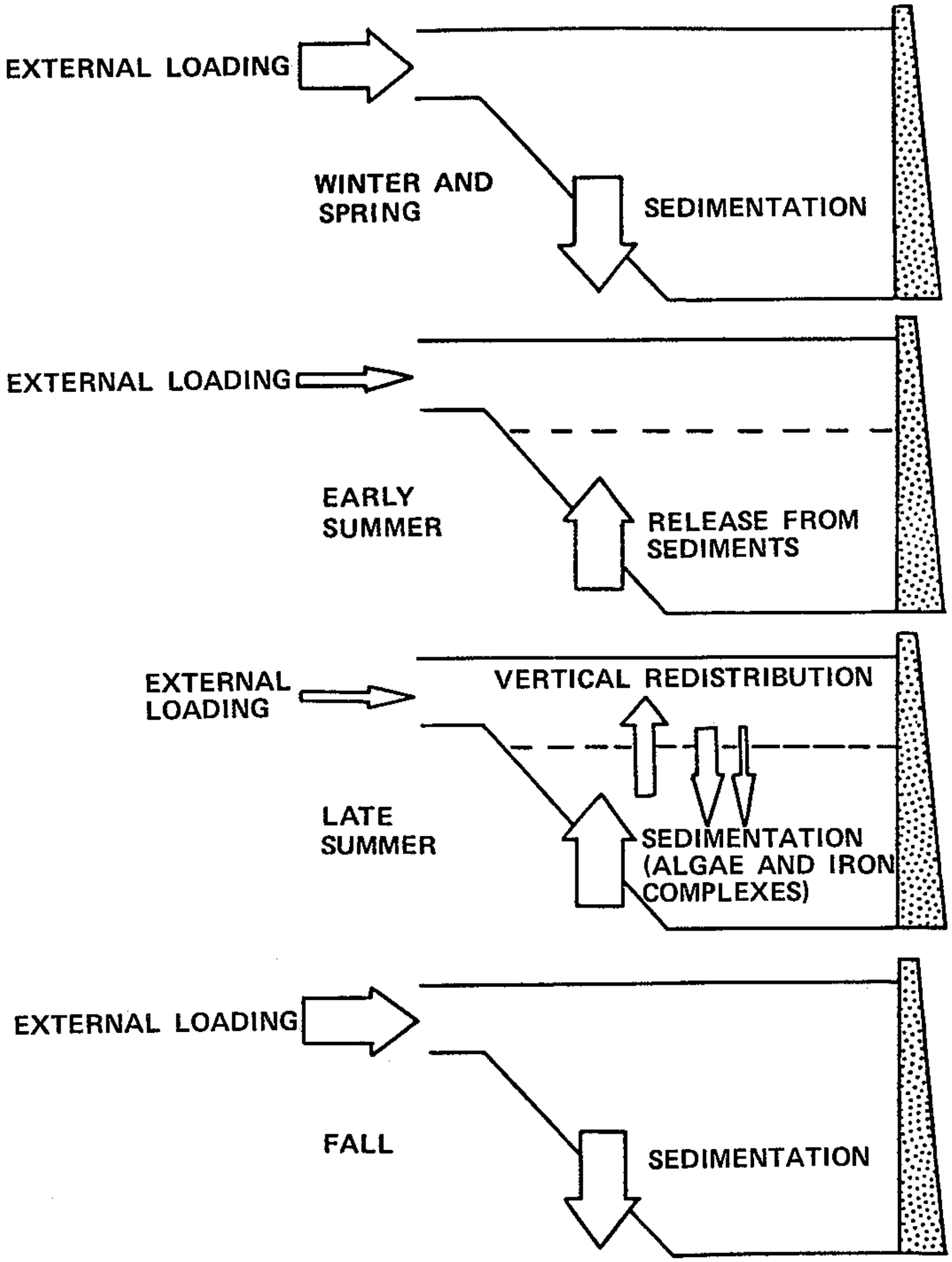


Figure 8. Generalized diagram of major phosphorus fluxes in DeGray Lake (relative importance of exchanges are indicated by arrow thickness)

ordering of events in time and along a lake's axis is of potential ecological significance, however, and the calculation of annual phosphorus loads may be inappropriate for lakes receiving seasonally variable loads; in such cases, nutrient budgets calculated over shorter intervals (e.g. season, month) may provide greater insight into the relative seasonal importance of various sources and sinks. Also, the assumption of complete and instantaneous mixing of nutrient loads may be inappropriate for lakes which, because of their morphometric and hydrologic features, exhibit marked spatial differences in limnological characteristics. Processes occurring in the headwaters of DeGray Lake influence phosphorus loadings and thus have a potentially significant effect on the ultimate impact of phosphorus loadings at downstream locations.

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