RESERVOIR LIMNOLOGY: ECOLOGICAL PERSPECTIVES

Edited by

Kent W. Thornton
FTN Associates, Ltd.
Little Rock, Arkansas

Bruce L. Kimmel
Environmental Sciences Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee

Forrest E. Payne
FTN Associates, Ltd.
Little Rock, Arkansas

A Wiley-Interscience Publication
John Wiley & Sons, Inc.
New York / Chichester / Brisbane / Toronto / Singapore

CHAPTER 5

Reservoir Nutrient Dynamics

ROBERT H. KENNEDY AND WILLIAM W. WALKER

Limiting a discussion of nutrient dynamics to reservoirs risks the implication that there are inherent differences between nutrient-related processes occurring in reservoirs and those occurring in other types of aquatic systems. This is certainly not the intent of this chapter. However, there are a number of substantive differences between reservoirs, as a group, and most other lakes (Kennedy et al. 1985, Ryder 1978, Thornton et al. 1981), as has been discussed in preceding chapters in this volume.

The body of knowledge upon which our present understanding of nutrient dynamics is based has been acquired primarily from studies of small natural lakes. Since significant differences in flow regime and morphology do exist between reservoirs and small, natural lakes, it seems prudent to evaluate the relative importance of the various processes affecting nutrient distribution and availability in reservoirs. These processes include nutrient loading (external and internal), sedimentation, flow, mixing, and discharge. The intent of this chapter is to explore relations between these processes and nutrient conditions in reservoir ecosystems.

LOADINGS

Reservoir water quality and productivity are controlled to a large extent by the quantity and quality of external nutrient loadings. The nature of these nutrient inputs reflect, in turn, climatic regime and various watershed characteristics, including morphology, soil type, and land use. The strong regional variations in total phosphorus concentrations, reported by Omernik (1977) in his analysis of data from U.S. streams not impacted by point sources, reflect geographic variations in climatic and watershed characteristics. Streamflow, erosion rates, parent soil characteristics, and stream sediment transport properties are also regional in character and have potentially important effects on nutrient loadings and reservoir responses.

Canfield and Bachmann (1981) observed statistically significant differences between lakes and reservoirs in the parameters of an empirical model for predicting phosphorus sedimentation rate. They suggested that these differences might be attributed to "qualitative differences in the phosphorus inputs related to geographic location," specifically referring to the fact that most of the reservoirs included in their analysis were located in regions where large percentages of the phosphorus loadings were in particulate form.

The latitudes of 309 natural lakes in the United States sampled by the Environmental Protection Agency's (EPA) National Eutrophication Survey (U.S. Environmental Protection Agency 1978) are compared with the latitudes of 106 Corps of Engineers (CE) reservoirs also sampled by the EPA in Figure 5.1. The distribution of natural lakes is bimodal, with peaks in the North (glacial lakes) and the South (Florida lakes). Most of the CE reservoirs are located at intermediate latitudes (23–40 degrees N), where there are relatively few natural lakes. These latitudinal distributions are consistent with Canfield and Bachmann's suggestion, particularly since most of the CE reservoirs are located in unglaciated regions with high soil erodability and high watershed nutrient export.

WITHIN-LAKE PROCESSES

Flow

In reservoirs longitudinal gradients in physical, chemical, and biological factors result from the combined influence of hydrodynamics and basin morphology. While physical characteristics vary widely among reservoirs, reservoirs are often long and narrow and, unlike drainage lakes, receive water and nutrient inputs from a single, large tributary distant from the point of discharge. Although riverine effects dissipate with changes in basin width and depth along the axis of the reservoir, riverine influences

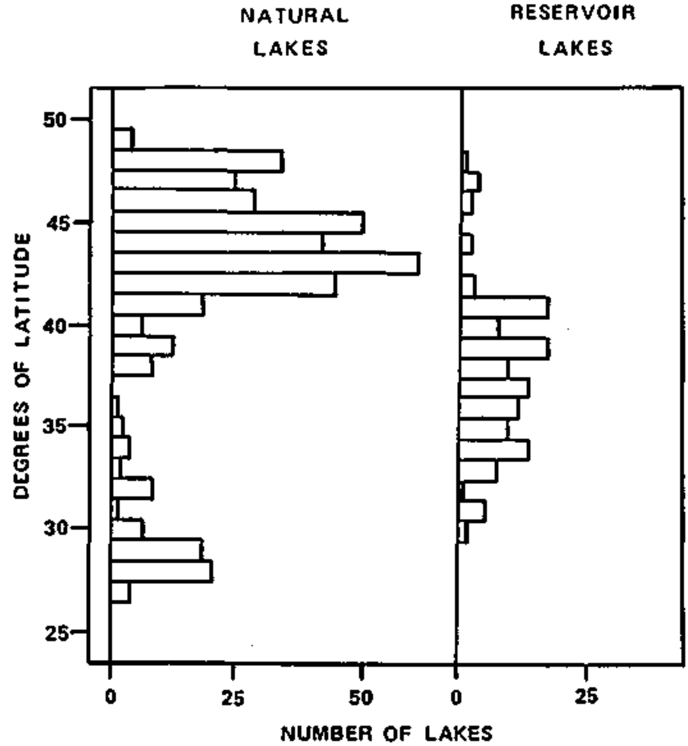

Figure 5.1 Latitudinal distributions of natural lakes and reservoir lakes sampled during EPA's National Eutrophication Survey (based on Walker 1981).

may often persist for great distances within some reservoirs. Thus, chemical and biological processes occur in a physical environment greatly influenced by flow regime, and as a result, processes acting to modify inflow water quality are ordered along a dynamic time/distance continuum governed by flow. This is in marked contrast to most natural lakes, in which vertical gradients resulting from thermal stratification predominate. Therefore, the relative importance of advective forces is one of the major distinctions between reservoirs and most other lakes.

The potential importance of interactions between hydrodynamic and morphometric characteristics and within-lake processes affecting nutrient-related attributes are most easily explored by considering idealized examples. For instance, consider the behavior of a nonconservative substance (e.g., phosphorus) in two nonstratified reservoirs of similar hydrology but dissimilar morphologies, one broad and deep and the other narrow and

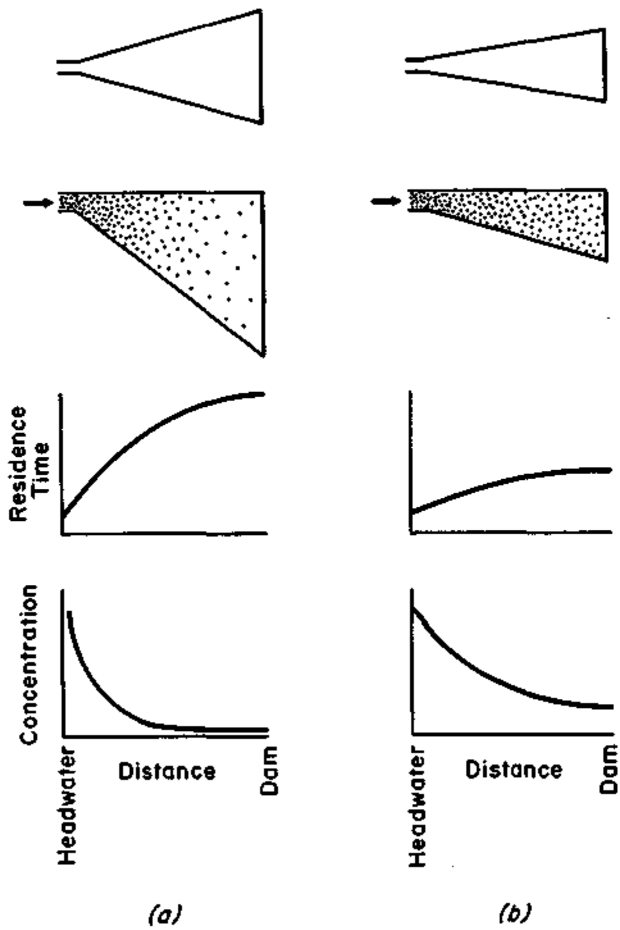

Figure 5.2 Distribution of inflow material (shading) and changes in water residence time and material concentration with distance from headwater to dam in two reservoirs receiving similar input but differing morphologic characteristics, one broad and deep (*a*) and the other narrow and shallow (*b*).

shallow (Figure 5.2). For the purpose of this discussion we assume that the nonconservative nature of the substance results from the occurrence of a first-order decay process. Since flows are similar, differences in water residence time are dictated by differences in basin morphology, with the broad, deep basin having a longer residence time. Therefore, the quantity of material retained in this basin would, based on residence time, be greater than that retained in the narrow, shallow basin. Of equal importance would be differences in concentration along the lake's length. In this example distance downstream from the river mouth is a surrogate measure of time. Therefore, concentrations along the length of the broad, deep lake would decline more sharply and to a greater extent than in the narrow, shallow basin.

This view of the establishment of gradients in nutrient concentration is, in general, consistent with observation (Peters 1979, Gloss et al. 1980, Thornton et al. 1981, Kennedy et al. 1982), suggesting that simple decay models may provide a means for describing concentration changes along gradients (Higgins and Kim 1981). Kennedy et al. (1982) were able to identify relics of previous hydrologic events along an otherwise predictable turbidity gradient in the reservoir West Point Lake (Atlanta, Georgia). These results suggest that longitudinal gradients in reservoirs reflect patterns resulting from both inflow history and reservoir operations.

The potential effects of inflow history are apparent if, in the above example, the inflow concentration is allowed to vary through time. Consider two nonstratified reservoirs with similar morphologies and inflows but dissimilar loading histories (Figure 5.3). In the reservoir receiving constant material input concentrations would, assuming a constant decay rate and a nondispersive flow regime, decline with distance along the length of the reservoir. However, concentrations along the length of the reservoir receiving inputs of variable concentration would exhibit a pattern reflecting loading history. Parcels of inflow water with low initial concentrations would follow and precede parcels of water with higher initial material concentrations. Although material concentrations for individual parcels of water would decline through time (and thus with distance), the decline in concentration along the length of the reservoir would be nonuniform.

The pattern becomes more complex under more realistic conditions of changing flow and concentration. In Figure 5.4 patterns in concentration observed at three points in time are more easily explained when viewed in a historical context. During baseflow, when inflow concentrations and flow rate are low, concentrations immediately below the headwater decline sharply and reach relatively low levels in downstream portions of the reservoir. Following a hydrologic event that increases both flow and inflow concentration, nutrient concentrations along the length of the reservoir increase as parcels of inflow water of higher initial concentration progress through the reservoir. Concentrations near the discharge,

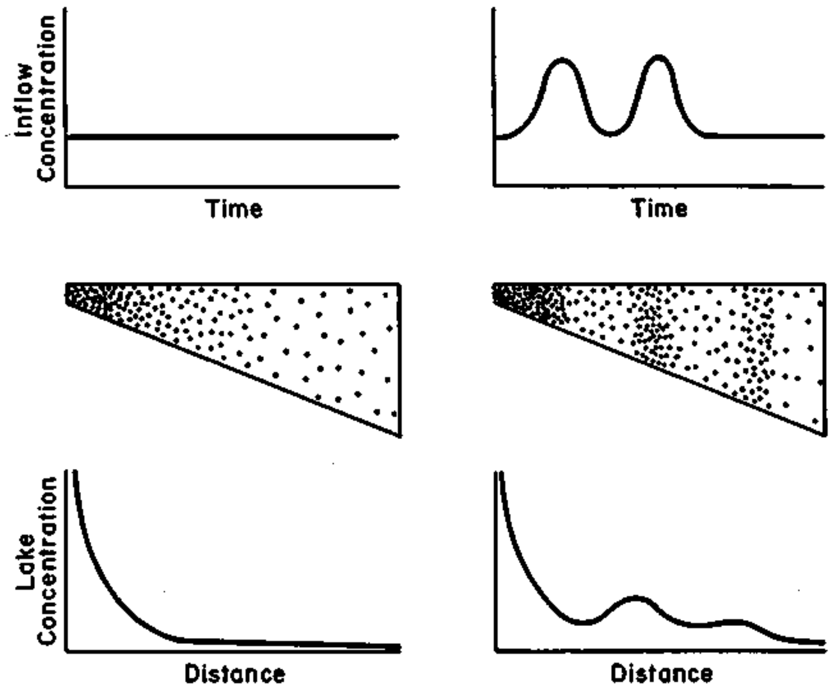

Figure 5.3 Material distributions along a reservoir receiving inflows with constant concentration (left) and a similar reservoir receiving inflows with variable concentration (right).

although still relatively low, would be higher than during baseflow. If reservoir conditions are again observed following the return of the tributary to baseflow conditions, remnants of earlier events would be recognized as areas of elevated concentration in the lower portion of the reservoir. Kennedy et al. (1982, 1981) documented such patterns in the reservoir Lake Red Rock (Iowa) following storm-related increases in nutrient and suspended solid loads from the Des Moines River. Although a general pattern of decreasing phosphorus concentration was observed from headwater to dam, elevated concentrations occurred at midlake coincident with the passage of the peak of the hydrograph.

Dispersion, assumed to be minimal in the preceding discussions, also influences the distribution of nutrients and the establishment of longitudinal gradients. As advective influences decrease with distance from the tributary inflow or because of increases in basin width and/or depth, wind-generated mixing becomes increasingly more important in distribut-

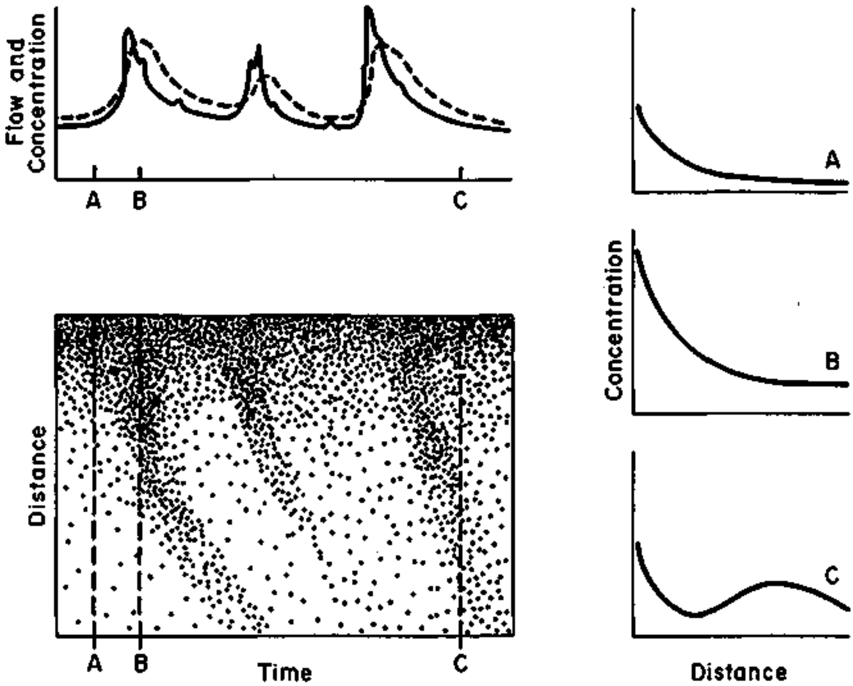

Figure 5.4 The combined effects of changes in tributary concentration and flow (upper left) on the spatial and temporal distribution of materials (shading) in the receiving reservoir (lower left). Longitudinal gradients in material concentration observed at three points in time (A, B, and C) are also depicted (right).

ing nutrients. In general, longitudinal gradients in nutrient concentrations are most pronounced in lakes in which advective or plug-flow conditions predominate, and gradients in lakes in which dispersion predominates are minimal. Walker (1982a) suggests a means by which reservoirs with a high potential for the development of longitudinal gradients can be distinguished from reservoirs that would be more completely mixed. Discriminatory factors include residence time, phosphorus sedimentation, and the relative importance of advection and dispersion as longitudinal transport processes (Figure 5.5). Maximal gradients would develop in reservoirs with long residence times, high sedimentation rates (i.e., high phosphorus retention), and an advectively dominated flow regime. Minimal longitudinal gradients would develop in reservoirs with short residence times, low sedimentation rates, and dispersive flow regimes.

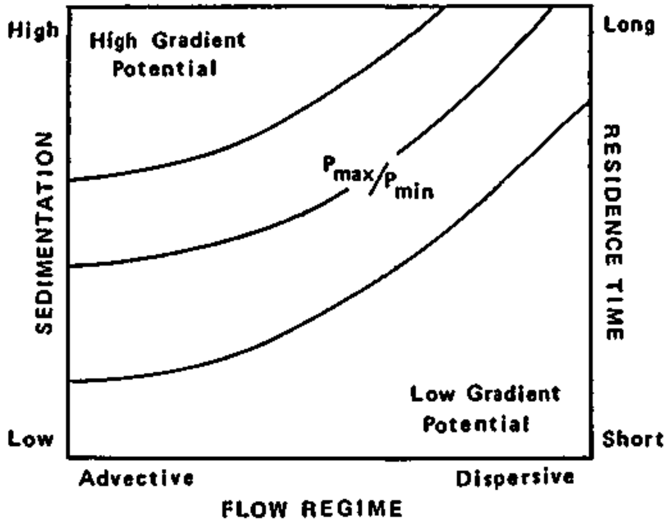

Figure 5.5 The dependence of phosphorus gradient potential on sedimentation rate, residence time, and flow regime. Lines of equal P_{max}/P_{min} (the ratio of maximum to minimum observed phosphorus concentration) are plotted. (Based on Walker 1982a.)

Density flows (see Chapter 2) also influence the distribution of nutrients in stratified reservoirs. During periods of thermal stratification vertical differences in density and the density difference between the inflowing river and reservoir water strata dictate the vertical placement of tributary inflows and thus the nutrients they transport. While riverine inflow patterns differ somewhat with changes in latitude, a general seasonal progression from overflows in fall, winter, and spring to interflows or underflows in summer is apparent (Wunderlich 1971, Carmack et al. 1979). While as yet incompletely evaluated these density-related phenomena have a significant impact on nutrient dynamics in stratified lakes and reservoirs.

If river inflows enter a lake, sink to a depth of comparable density, and then progress through the lake as an interflow at or below the thermocline, it seems reasonable to assume that the biological impact of riverborne ntutrients will be greatly diminished. During periods of interflow the epilimnion is at least partially isolated from an advected nutrient supply, and nutrient concentrations established prior to stratification would be expected to decline due to sedimentation losses. An increasingly limited supply of nutrients has obvious implications for summer phytoplankton production. Ultimately, the degree to which the epilimnion is isolated depends on the degree of density difference, the magnitude of flow, and basin morphology.

Field observations suggest that while nutrient loading to epilimnia may be greatly reduced during periods of interflow, mixing of riverine and epilimnetic water does occur. Kennedy et al. (1982) documented the movement of Chattahoochee River water through the upstream reach of West Point Lake using fluorescent dye as a water-mass tracer. During a nonstratified period river water mixed vertically and progressed through the reservoir as a plug flow. When the reservoir was stratified inflows progressed to the plunge point as a well-mixed plug flow and then were confined to a zone near the thermocline. While maximum dye concentrations were observed near the thermocline, significant quantities of dye were also found in surface waters, indicating the mixing of river water into the epilimnion. Kennedy et al. (1982) also observed the entrainment of nutrient-rich hypolimnetic water by the riverine interflow. Similar observations were made in Slapy Reservoir by Hrbacek et al. (1966). Thus, mixing across turbulent interfaces between the riverine layer and the epilimnion or between the shallow upstream portion of the hypolimnion and the riverine layer provides a mechanism by which nutrients may be redistributed vertically (Figure 5.6).

Carmack and Gray (1982) suggest another means by which nutrients transported by an interflowing riverine layer may enter the epilimnion during stratified periods. In Kootenay Lake, a long, deep, natural lake of the Columbia River System, nutrient-laden waters from the Kootenai and Duncan Rivers enter from opposite ends of the lake and, during summer months, are confined to a riverine-layer interflow located immediately above the thermocline. Exchanges between the riverine layer and the euphotic zone occur only following episodic mixing events. Internal seiche motion displaces the riverine layer upward where, under the influence of wind-generated mixing, water and nutrients of the riverine layer are entrained into the euphotic zone. Thus, nutrient concentrations in the euphotic zone, established at the onset of thermal stratification, decline during the summer because of a lack of nutrient inputs from the

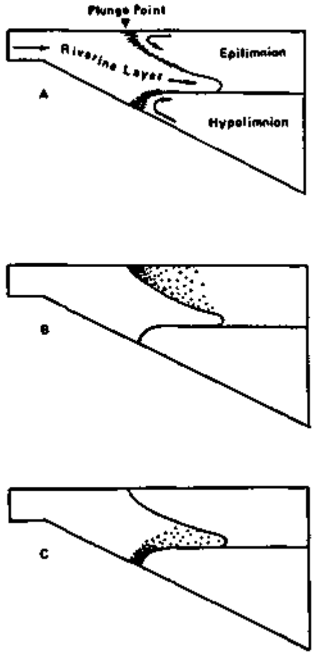

Figure 5.6 Turbulent interfaces (zigzag line) between epilimnion, hypolimnion, and an interflowing riverine layer (*a*). Exchanges of material from riverine layer to epilimnion (*b*) and from hypolimnion to riverine layer (*c*) are also indicated (shading).

river until such time that conditions favor entrainment of riverine water. These episodic events then augment dwindling epilimnetic nutrient supplies (Figure 5.7).

Sedimentation

Sedimentation and subsequent sediment-water interactions are major regulatory processes influencing the nutrient status of lakes and reservoirs. Sedimentation of nutrients, which can occur by the settling of particles or by the association of dissolved substances with settling biotic and abiotic particles, results in a loss of nutrients from the water column. Once deposited, sedimented materials may buffer or otherwise modify nutrient concentrations in overlying water. Both regulatory processes are influence by flow regime, reservoir morphology, tributary loading, trophic state, and the presence of gradients.

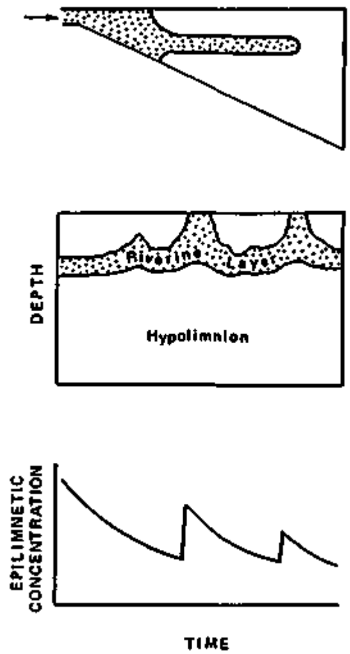

Figure 5.7 The effects of internal mixing of nutrient-rich riverine water (shading) and epilimnetic water on epilimnetic nutrient concentrations (based on Carmack and Gray 1982).

Differences in the relative contributions of particulate loads to reservoirs are reflected in higher sedimentation rates for reservoirs than for natural lakes. Canfield and Bachmann (1981), in comparing over 700 lakes and reservoirs, suggest that differences in phosphorus sedimentation may be due to the association of phosphorus with readily settleable allochthonous particulates. Higgins and Kim (1981) found similar differences when applying empirical loading-response models to Tennessee Valley Authority reservoirs. The apparent settling velocity of phosphorus for these lakes was nine times that for other types of lakes. They also identified differences between reservoir types. Tributary storage reservoirs, which are deeper and have longer residence times, retained a higher percentage of inflowing phosphorus than did shallower, more rapidly flushed reservoirs.

Sedimentation, like other nutrient-related processes in flow-dominated lakes and reservoirs, exhibits longitudinal gradients, with the highest sedimentation rates generally occurring in the portion of the nearest inflow. A majority of the material loads to Lake Red Rock, a short-retention-time reservoir on the sediment-laden Des Moines River, is retained in headwater areas near the river inflow (Kennedy et al. 1981). Significant losses (>75%) of inflow phosphorus occurring coincident with sedimentation of suspended solids resulted in relatively low concentrations in downstream areas, even during storm events. Sedimentary losses of phosphorus, nitrogen, and carbon are of greatest significance in the immediate vicinity of the inflow of the Caddo River to DeGray Lake, a long-retention-time storage improvement in south-central Arkansas. Sediment trap data reported by James et al. (1987) indicate that the greatest losses of allochthonous and autochthonous nutrients, metals, and organic matter occurred uplake near the river mouth. Differences between sedimentation rates for vertically arranged sets of traps also suggest higher sedimentation below the riverine layer during periods of interflow. Sedimentation losses are the prime cause for observed nutrient gradients in this lake (Thornton et al. 1981).

Seasonal trends in sedimentation are also observed. Nutrient-containing material collected by sediment traps deployed during spring in Lake Memphremagog was primarily inorganic, suggesting allochthonous inputs as the primary source (Spiller 1977). During summer and fall losses of nutrients were associated with sedimentary losses of autochthonous organic material. Similar seasonal trends were concluded from sediment trap data from DeGray Lake (James et al. 1987). Sedimentation patterns may also be influenced by seasonal changes in flow regime. In Lake Mojave cold, upstream releases from Lake Mead progress through the lake in summer as underflow, intercepting sedimenting autochthonous matter and transporting it downlake. Subsequent decomposition results in marked hypolimnetic gradients in inorganic nitrogen concentrations (Priscu, Verduin, and Deacon 1981). High nitrogen concentrations in Hoover Dam hypolimnetic releases from Lake Mead may also account for nitrogen gradients in Lake Mojave.

Patterns in sediment quality, important for understanding exchanges between bottom sediments and overlying water, result from interactions between hydrodynamic, morphometric, loading, and trophic state characteristics (Gunkel et al. 1984). Here again, longitudinal gradients are apparent. Hyne (1978) contrasts the distribution of organic matter in two midwestern reservoirs: Fort Gibson Lake, which receives low sediment inputs, and Lake Texoma, a productive reservoir receiving high sediment inputs. In Fort Gibson Lake organic materials are deposited in deep downlake areas. Deposits in Lake Texoma occur in shallow upstream areas as well as in deep areas of the lake, reflecting the combined influences of allochthonous organic matter inputs from the Red and Washita Rivers and autochthonous production.

Sediment characteristics in Lake Mulwala, an impoundment of the Murray River, Australia, are related to flow characteristics (Hart et al. 1976). Sediments underlying riverine areas of the lake are characteristically low in organic matter and total phosphorus. Sediments in areas little affected by river flow are high in organic matter and phosphorus, indicating the potential importance of flow and nutrient particle associations in the sorting of deposited materials. This result is supported by a comparative evaluation of the sediment characteristics of four CE reservoirs of varying trophic state and flow regime (Gunkel et al. 1984). In general, sediments along riverine reaches of these lakes were high in inorganic carbon but low in nutrients, metals, and organic carbon. In West Point Lake, the largest of the four reservoirs examined, sediment nutrient concentrations were highest downlake from the area of maximum phytoplankton production and the area influenced by riverine inflows. Coincident with increases in nutrient and organic content were increases in sediment moisture content.

Hakanson (1977) compared data for sediment samples collected from various locations in Lake Vanern and concluded that the nature of sedimentary environments can be deduced from sediment moisture content. Sediments in flow-dominated or high-energy areas (e.g., near inflows or areas of mixing) had low moisture content and low organic matter concentrations, indicating areas of sediment erosion and transport. Sediments in deeper areas or in areas less affected by turbulence had high moisture content and high organic matter concentrations, indicating that these are areas of sediment accumulation. Adopting similar criteria, Gunkel et al. (1984) were able to differentiate between sediments from advectively dominated areas of reservoirs and those from areas where nutrient accumulation in sediments occurs.

Relations between nutrient loading, sedimentation, flow, productivity, and sediment quality can be suggested (Figure 5.8). Inflow nutrient concentrations decline along a gradient from headwater to dam due to sedimentary losses. The losses result initially from the reduced carrying capacity for suspended particulates in uplake portions of the reservoirs, but later and further downlake because of phytoplankton uptake and settling. Phytoplankton production may be low in the headwaters due to

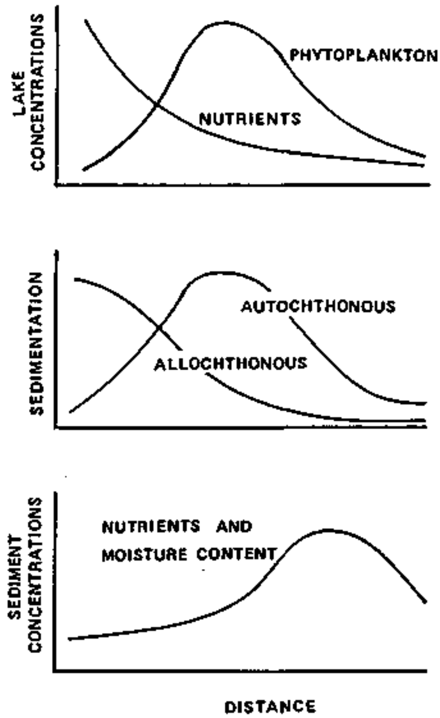

Figure 5.8 Changes in nutrient and phytoplankton (upper), autochthonous and allochthonous sedimentation rates (middle), and sediment and nutrient content (lower) with distance from headwater to dam.

inorganic turbidity and flushing but often increases downlake. Coincident with headwater declines in nutrient concentrations and mid- or downlake increases in phytoplankton production would be peaks in allochthonous and autochthonous sedimentation rates, respectively. Settling organic detritus and small inorganic particulates (e.g., clays and fine silts), both of which are often enriched with nutrients, are displaced downlake by advection. The net result of these processes is the accumulation of organic, nutrient-rich sediments of high moisture content in deeper downlake areas.

Internal loading

Seasonal releases of nutrients from storage sites within a lake or reservoir (e.g., from the sediments) can have a pronounced impact on lake nutrient status, particularly during periods when inputs from external sources are minimal (Cooke et al. 1977). Despite the dominance of river-borne nutrient inputs internal nutrient recycling is also of ecological significance in reservoirs. And, considering the establishment of gradients in sediment characteristics, large differences in the degree of ecological significance may occur between locations within a particular reservoir. Occoquan Reservoir in northern Virginia, for instance, exhibits longitudinal differences in sediment phosphorus concentrations and differences in the degree of exchange between sediments and the overlying water (To and Randall 1975). Surficial uplake sediments in this reservoir have higher phosphorus concentrations and release rates than do sediments at downlake locations. Differences are also apparent for release/absorption threshold concentrations. Phosphorus releases from the anoxic uplake sediments ceased at water column concentrations above 1.75 mg P/l while downlake sediments sorbed phosphorus from bottom water when concentrations exceeded only 0.5 mg P/l.

Thus, internal loading from sediments is related to trophic state, oxygen dynamics, and sedimentary history. DeGray Lake, because of a history of variable conditions, provides an instructive example of these relationships (Kennedy and Nix 1987). Timber, forest litter, and other organic detritus in the reservoir basin were left relatively undisturbed prior to impoundment, and exerted a significant demand on dissolved oxygen supplies. Anoxic conditions developed immediately following the onset of stratification, and the entire hypolimnion exhibited anoxia during summer. Hypolimnetic nutrient concentrations, despite relatively low external loads, were high during this early period, suggesting the potential for significant exchanges of dissolved materials across the thermocline by mixing diffusion. In subsequent years, as pre-impoundment organic deposits were exhausted, oxygen conditions improved. Summer increases in hypolimnetic nutrient concentrations also diminished. Conditions are now more consistent with the lake's low loading rate and moderate productivity. However, internal loading still occurs in the headwater areas of the lake (Kennedy et al. 1986). Particulate organic loads from the Caddo River, which supplies a majority of the lake's nutrient and organic loads, are deposited on headwater sediments, resulting in the establishment of anoxic conditions during summer months. Coincident increases in hypolimnetic nutrient concentrations also occur. Sediment trap data suggest that exchanges of nutrients from this shallow headwater portion of the hypolimnion to the epilimnion may influence the establishment of maximal chlorophyll standing crops in the lake's headwater area.

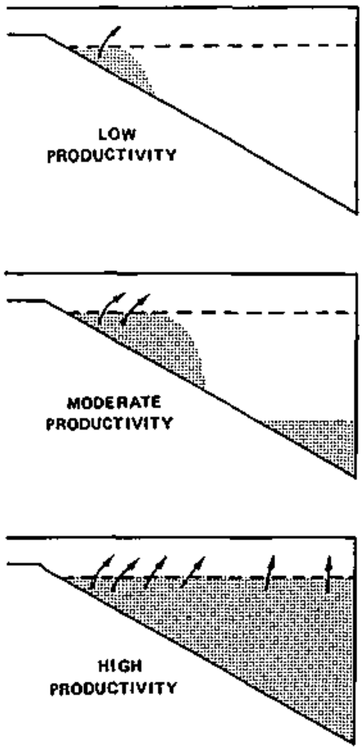

Figure 5.9 Longitudinal occurrences of hypolimnetic anoxia and nutrient increases (shading), and upward exchanges of nutrients (arrows) in reservoirs of differing productivity and loading.

Generalizations concerning potential longitudinal differences in the occurrence and significance of internal loading in reservoirs of similar hydrology and morphology, and its relation to reservoir trophic conditions, are presented in Figure 5.9. In unproductive reservoirs low allochthonous organic inputs and low autochthonous production may lead to anoxic conditions of limited extent (see Chapter 4). Releases from anoxic headwater sediments and turbulent mixing would lead to the possible introduction of nutrients to surface waters. In highly productive stratified reservoirs inputs of both allochthonous and autochthonous organic matter can result in a completely anoxic hypolimnion and consequent increases in nutrient releases. Concentration gradients across the thermocline could result in the introduction of nutrients to the epilimnion at downlake locations. Internal loadings of intermediate significance would occur in reservoirs of moderate productivity.

RESERVOIR OPERATION

The manner in which water is discharged differs in natural lakes and reservoirs. Differences are also apparent in the degree of daily or seasonal fluctuation in water level. Natural lakes discharge water at the surface and, since discharges are uncontrolled, lake level changes are seldom extreme. Reservoirs, on the other hand, are designed to modify or control river flows and therefore often experience significant changes in water level. In hydropower reservoirs levels can fluctuate dramatically over diel cycles. While surface releases do occur, subsurface discharges are more common for large reservoirs. Reservoir operation might, therefore, be expected to influence nutrient dynamics.

Wright (1967) hypothesized that surface-discharge lakes trap nutrients and dissipate heat while subsurface-discharge lakes dissipate nutrients and store heat. Martin and Stroud (1973) and Martin and Arneson (1978) provided supporting evidence by comparing reservoirs of differing operation, and a reservoir and natural lake, respectively. Total organic carbon and total phosphorus concentrations were proportionately higher in the tailwater of Nolin Lake, a hypolimnetic-discharge reservoir, than in the Barren River Reservoir, which discharges epilimnetic water. Similar differences were demonstrated for Heglen Lake, a deep-discharge reservoir, and Quake Lake, a surface-discharge landslide lake.

Many nonhydropower reservoirs operate during summer months (when flows are seasonally low) as epilimnetic- or surface-discharge lakes. However, when flood waters are discharged, releases must be made using large hypolimnetic floodgates. The impact of such an operational change can often be dramatic. The use of hypolimnetic floodgates at Lake Red Rock following a summer storm event influenced flow patterns in the reservoir and resulted in the "short-circuiting" of inflowing nutrient-laden storm water. The actual residence time of storm water in the reservoir was half the theoretical residence time estimated from flow and lake volume data (Kennedy et al. 1981).

If nutrients accumulate in the reservoir hypolimnion, then hypolimnetic discharges, either by the release of flood waters or during hydropower generation, result in nutrient losses from the reservoir. The management implications of such losses are worthy of consideration. If the residence times of various depth strata can be manipulated by the operation of the outlet structure (e.g., by selective withdrawal), then reservoir managers could exert some control over nutrient-related processes occurring in reservoirs. For instance, nutrients transported by the riverine layer in stratified reservoirs could be "drained off" by withdrawing water from the depth of interflow. Simiarly, nutrients that enter reservoirs following storm events or those that accumulate in deep water during stratification could be selectively flushed from the reservoir, thus minimizing their impacts on algal production, as shown by Elser and Kimmel (1985). However, nutrient releases from one reservoir may constitute nutrient inputs to reservoirs located downstream and thus influence the productivity of these downstream systems.

Lake level changes also influence nutrient conditions. In addition to changes in water residence time, fluctuating water levels can increase nutrient exchanges between littoral and pelagic zones. Metabolic activities in the macrophyte-infested littoral zone of Kremenchug Reservoir increased nitrogen and phosphorus concentrations during periods of constant lake level (Zimbalevskaya et al. 1976). During hydropower releases lake level dropped and nutrients were drawn from the littoral to the pelagic zone, where they were available for phytoplankton. The return of Quabbin Reservoir to a normal level after a six-year drought resulted in the inundation of newly established terrestrial vegetation around the perimeter of the lake. Miner (1974) calculated nitrogen and phosphorus loads from the decoposition of this material to be 1.3 g N/m^2 and 0.1 g P/m^2, respectively. Nutrient exchanges of this type are probably of greatest significance in reservoirs with high shoreline development ratios.

GENERALIZATIONS

Reservoirs, like all lakes, are dynamic aquatic ecosystems of which we have only a limited understanding. However, based on the preceding discussions we can offer several generalizations about nutrient dynamics in reservoirs. The organization of these ideas is aided by the suggestion that reservoirs can be divided into riverine, transition, and lacustrine zones, but it must be emphasized that the boundaries between zones are often difficult to delineate and that the locations of zones are temporally unstable.

An advective flow regime in combination with a long, narrow basin morphology results in the spatial ordering of nutrient-related processes and the establishment of gradients from headwater to dam. Nutrient loads, a large percentage of which are often associated with suspended particulates, progress through the riverine zone and are deposited downlake as flows diminish. Nutrient availability for phytoplankton production is reduced by sedimentation losses and in stratified water columns by the downward displacement of density flows in the transition zone. Nutrient utilization by phytoplankton is potentially greatest in this zone near the boundary between the transition and riverine zones. Nutrient availability is further diminished in the lacustrine zone, and vertical exchanges may provide important nutrient supplies for phytoplankton growth. The spatial distribution of nutrients, which is also affected by outlet operation, may in turn be reflected by patterns in sediment quality.

IMPLICATIONS FOR EMPIRICAL MODELING

Nutrient loading models were originally developed from northern lake data and designed to predict the eutrophication of a water body as a function of three primary variables:

P_i = annual inflow total phosphorus concentration (mg/m^3)
Z = mean depth (m)
T = annual mean hydraulic residence time (years)

Most published models can be expressed in combinations of the above terms (Vollenweider 1968, 1976, Chapra 1975, Larsen and Mercier 1976, Jones and Bachmann 1976, Canfield and Bachmann 1981).

The models are empirical in nature and should not be used outside the range of the data set used for model calibration. The application "range" refers not only to the three explicit variables mentioned but also to other characteristics (including impoundment type and region) that may influence nutrient dynamics and are therefore implicit in the model formulation.

Lake-reservoir differences of potential significance to the development and use of loading models include:

1. Reservoirs tend to have shorter hydraulic residence times, which may indicate the need to formulate nutrient and water balances on seasonal, as opposed to annual, bases.
2. Because of regional geographic factors, reservoirs tend to have higher percentages of particulate phosphorus loadings and higher

sediment accumulation rates, both of which may influence the parameter estimates of phosphorus retention models.

3. Reservoirs tend to have greater concentrations of allochthonous suspended solids, which influence phosphorus-chlorophyll and chlorophyll-transparency relationships.
4. Reservoir morphometric and hydrodynamic characteristics are more conducive to the development of spatial gradients in phosphorus and related trophic-state indicators; predictions of spatially averaged conditions may not adequately describe many reservoirs.
5. Hydrodynamic factors (underflows, interflows, bottom outlets, fluctuations in pool level) influence nutrient responses. These factors are not directly accounted for in existing model formulations.

These differences, which may have important effects on model formulations, parameter estimates, monitoring, and data-reduction procedures, must be considered if appropriate reservoir eutrophication assessments are to be developed.

Empirical studies by Clausen (1980), Canfield and Bachmann (1981), Higgins and Kim (1981), Walker (1982b, 1982c, 1985), and Mueller (1982) have shown that the parameter estimates of phosphorus retention models originally developed from northern lake data require significant adjustments when the models are recalibrated to reservoir data sets. These adjustments generally reflect higher phosphorus sedimentation rates in reservoirs as compared with natural lakes for a given inflow concentration, mean depth, and hydraulic residence time.

REFERENCES

Canfield, D. E. and R. W. Bachmann. 1981. Prediction of total phosphorus concentrations, chlorophyll-a and Secchi disc in natural and artificial lakes. *Can. J. Fish. and Aq. Sci.* 38:414–423.

Carmack, E. C., C. B. J. Gray, C. H. Pharo, and R. J. Daley. 1979. Importance of lake-river interactions on seasonal patterns in the general circulation of Kamloops Lake, British Columbia. *Limnol. Oceanogr.* 24:634–644.

Carmack, E. C. and C. B. J. Gray. 1982. Patterns of circulation and nutrient supply in a medium residence time reservoir Kootenay Lake, British Columbia. *Can. Wat. Res. J.* 7:51–70.

Chapra, S. C. 1975. Comment on "An empirical method of estimating the retention of phosphorus in lakes" by W. B. Kirchner and P. J. Dillon. *Wat. Resourc. Res.* 11:1033–1034.

Clausen, J. 1980. OECD Cooperative Programme for Monitoring Inland Waters — Regional Project — Shallow Lakes and Reservoirs. Organization for Economic Cooperation and Development.

Cooke, G. D., M. R. McComas, D. W. Waller, and R. H. Kennedy. 1977. The occurrence of internal phosphorus loading in two small, eutrophic, glacial lakes in northeastern Ohio. *Hydrobiol.* 56:2, 129–135.

Elser, J. J. and B. L. Kimmel. 1985. Nutrient availability for phytoplankton production in a multiple-impoundment series. *Can. J. Fish. Aquat. Sci.* 42: 1359–1370.

Gloss, S. P., D. E. Kidd, and L. M. Mayer. 1980. Advective control of nutrient dynamics in the epilimnion of a large reservoir. *Limnol. Oceanogr.* 24:219–228.

Gunkel, R. C., R. F. Gaugush, R. H. Kennedy, G. E. Saul, J. H. Carroll, and J. Gauthey. 1984. A comparative study of sediment quality in four reservoirs. Technical Report E-84-2. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Hakanson, L. 1977. The influence of wind, fetch, and water depth on the distribution of sediments in Lake Vanern, Sweden. *Can. J. Earth Sci.* 14:397–412.

Hart, B. T., R. J. Mcgregor, and W. S. Perriman. 1976. Nutrient status of the sediments in lake mulwala. *I. Total Phosphorus. Aust. J. Mar. Freshwat. Res.* 27:129–135.

Higgins, J. M. and B. R. Kim. 1981. Phosphorus retention models for Tennessee Valley Authority reservoirs. *Wat. Resourc. Res.* 17:571–576.

Hrbacek, J., L. Prochazkova, V. Straskraboua-Prokesova, and C. O. Junge. 1966. The relationship between the chemical characteristics of the Vlstara River and Slapy Reservoir with an appendix: Chemical budget for Slapy Reservoir. *Hydrobiol. Stud.* 1:41–84.

Hyne, N. J. 1978. The distribution and source of organic matter in reservoir sediments. *Env. Geol.* 2:279–287.

James, W. F., R. H. Kennedy, R. H. Montgomery, and J. Nix. 1987. Seasonal and longitudinal variations in apparent deposition rates within an Arkansas Reservoir. *Limnol. Oceanogr.* 32:5, 1169–1176.

Jones, J. R. and R. W. Backmann. 1976. Prediction of phosphorus and chlorophyll levels in lakes. *J. Wat. Poll. Contr. Fed.* 48:2176–2182.

Kennedy, R. H., K. W. Thornton, and J. H. Carroll. 1981. Suspended sediment gradients in Lake Red Rock. Pages 1318–1328 in H. G. Stefan, ed. Proceedings of the symposium on surface water impoundments. Amer. Soc. Civil Engr., New York, NY.

Kennedy, R. H., K. W. Thornton, and R. C. Gunkel, Jr. 1982. The establishment of water quality gradients in reservoirs. *Can. Wat. Res. J.* 7:71–87.

Kennedy, R. H., R. H., K. W. Thornton, and D. Ford. 1985. Characterization of the reservoir ecosystem. In D. Gunnison, ed. Microbial processes in reservoirs. Dr. W. Junk Publishers, Boston, MA.

Kennedy, R. H., R. H., W. F. James, R. H. Montgomery, and J. Nix. 1986. The influence of sediments on the nutrient status of DeGray Lake, Arkansas. In P. G. Sly, ed. Sediments and water interactions. Springer-Verlag Publishers, New York, NY.

Kennedy, R. H., R. H., and J. Nix, eds. 1987. Proceedings of the DeGray Lake Symposium. Technical Report E-87-4. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Larsen, D. P. and H. T. Mercier. 1976. Phosphorus retention capacity of lakes. *J. Fish. Res. Bd. Con.* 33:1742–1750.

Martin, R. G. and R. H. Stroud. 1973. Influence of reservoir discharge location on water quality, biology and sport fisheries of reservoirs and tailwaters. 1968–1971. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Martin, R. G., D. B. and R. D. Arneson. 1978. Comparative limnology of a deep-discharge reservoir and a surface-discharge lake on the Madison River, Montana. *Freshwat. Biology.* 8:33–42.

Miner, N. H. 1974. The potential for impact for inundation of terrestrial vegetation on the water quality of Quabbin Reservoir — Commonwealth of Massachusetts. *Wat. Res. Bul.* 10(6):1288–1297.

Mueller, D. K. 1982. Mass balance model estimation of phosphorus concentrations in reservoirs. *Wat. Res. Bull.* 18:377–382.

Omernik, J. M. 1977. Nonpoint source-stream nutrient level relationships: A nationwide study. Corvallis Environmental Research Laboratory. EPA-600/3-77-105, U.S. Environmental Protection Agency.

Peters, R. H. 1979. Concentration and kinetics of phosphorus fractions along the trophic gradient of Lake Memphremagog. *J. Fish. Res. Board Can.* 36:970–979.

Priscu, J. C., J. Verduin, and J. E. Deacon. 1981. The fate of biogenic suspersoils in a desert reservoir. Pages 1657–1667 in H. G. Stefan, ed. Proceedings of the symposium on surface water impoundments. Amer. Soc. Civil Engr., New York, NY.

Ryder, R. A. 1978. Ecological heterogenity between north-temperate reservoirs and glacial lakes systems due to differing succession rates and cultural uses. *Verh. Int. Verein. Limnol.* 20:1568–1574.

Spiller, G. B. 1977. A mathematical model of seasonal and spatial variation in phosphorus concentrations in the surface waters of Lake Memphremagog, Quebec. M.S. Thesis, Biology Dept., McGill University, Montrea, Quebec.

Thornton, K. W., R. H. Kennedy, J. H. Carroll, W. W. Walker, R. C. Gunkel, and S. Ashby. 1981. Reservoir sedimentation and water quality — an heuristic model. Pages 654–661 in H. G. Stefan, ed. Proceedings of the symposium on surface water impoundments. Amer. Soc. Civil Engr., New York, NY.

To, Y. S. and C. N. Randall. 1975. The effect of sediment on reservoir water quality. Pages 590–597, in proceedings of the Second National Conference on Complete Wateruse, Amer. Inst. Chem. Eng.

U.S. Environmental Protection Agency. 1978. National Eutrophication Compedians Working Papers 474–477. Corvallis Environmental Research Laboratory and Las Vegas Environmental Monitoring and Support Laboratory, U.S. Environmental Protection Agency.

Vollenweider, R. A. 1968. The scientific basis of lake and stream eutrophication, with particular reference to phosphorus and nitrogen as eutrophication factors. Technical Report DAS/DSI/68. Organization for Economic Cooperation and Development, Paris.

Vollenweider, R. A. 1976. Advances in defining critical loading levels for phosphorus in lake eutrophication. *mem. Ist. Ital. Idrobiol.* 33:53–83.

Walker, W. W. 1982a. A simplified method for predicting phosphorus gradient potential in reservoirs, prepared for Environmental Laboratory. EWQOS Work Unit 1-E, Working paper No. 10. USAE Waterways Experiment Station, Vicksburg, MS.

Walker, W. W., W. W. 1982b. Empirical methods for predicting eutrophication in impoundments. Report 2: Model Testing, prepared for Office Chief of Engineers, U.S. Army, Washington, DC. Technical Report E-81-9. U.S. Army Corps of Engineers. Waterways Experiment Station, Vicksburg, MS.

Walker, W. W., W. W. 1985. Empirical methods for predicting eutrophication in impoundments. Report 3: Model Refinements, prepared for Office, Chief of Engineers. U.S. Army, Washington, DC. Technical Report E-81-9. U.S. Army Corps of Engineers. Waterways Experiment Station, Vicksburg, Ms.

Wright, J. C. 1967. Effect of impoundments on productivity, water chemistry, and heat budgets of rivers. Pages 188–199 in Reservoir Fishery resources. Am. Fish. Soc., Washington, DC.

Wunderlich, W. O. 1971. The dynamics of density-stratified reservoirs. Pages 219–231 in G. E. Hall, ed. Reservoir fisheries and limnology. Spec. Pub. 8th Amer. Fish Soc. Washington, DC.

Zimbalevskaya, L. N., L. A. Zhuravleva, L. A. Khoroshikh, V. I. Pugach, L. E. Kostikova, M. N. Dekhtyar, and A. B. Yakubovsky. 1976. Eutrophication of the Kremenchug Reservoir shallows. *Limnologica.* 10(2):321–324.