CHANGES IN THE OXYGEN STATUS OF A NEWLY IMPOUNDED RESERVOIR

John Myers and Robert H. Kennedy
Environmental Laboratory
US Army Engineer Waterways Experiment Station
Vicksburg, Mississippi

INTRODUCTION

River impoundment during reservoir construction inundates large amounts of organic material (e.g., topsoil, plant litter, and vegetation), decomposition of which consumes dissolved oxygen and releases nutrients (e.g., nitrogen and phosphorus) to the water column. This results in reductions in hypolimnetic dissolved oxygen concentrations, often leading to anoxia, and the proliferation of phytoplankton in years immediately following reservoir filling. As sources of organic material are exhausted, oxygen demands are reduced, nutrient inputs from internal sources are diminished and phytoplankton production declines. Baranov (1961) and Ostrofsky and Duthie (1978) referred to these stages in the limnological development of a reservoir as trophic upsurge and trophic depression, respectively.

Completion of Richard B. Russell Dam in 1983 inundated approximately 10,520 hectares of the Savannah River flood plain to form Richard B. Russell Lake. While a large portion of the flooded basin was clear-cut, nearly 3,640 hectares of forested land were inundated (Shain 1987). Submerged leaf litter and "green" vegetation (standing or freshly-cut woody and vegetative material) were estimated to be 5.0 x 10^6 kg and 5.6 x 10^8 kg fresh weight, respectively (Shain 1987). James (1987) determined that leaf litter characteristic of the basin (oak, beech, hickory, and pine) decayed quickly when experimentally incubated in the lake, especially at shallow depths, and predicted high rates of oxygen depletion. High rates of oxygen consumption, as well as nutrient releases were also reported by Gunnison et al. (1984) using laboratory microcosms containing local soil and litter samples.

Because of the large amount of material inundated and the potential adverse impacts on dissolved oxygen concentrations, an oxygen injection (diffuser) system was designed and installed. The two-staged system consisted of a continuously-operated injection system located 1.6 km upstream from the dam and a pulse injection system located immediately upstream from the power-house section of the dam (Kennedy et al. 1995). The latter system was designed to provide supplemental additions of oxygen to insure that tailwater dissolved oxygen concentrations during hydropower operation meet or exceed 6 mg/l, a negotiated target concentration for protection of downstream fish habitat. Although variable in duration of operation (generally, May or June through October or November) and rate of injection (maximum ca. 85-120 tons/day), the system has been operated routinely during summer stratification since 1985.

Here we report changes in the oxygen status of Richard B. Russell Lake during the first thirteen years of impoundment relative to reservoir aging and changes in hydrology and reservoir operation. We also evaluate the paradigm of lacustrine development of reservoirs proposed by Baranov (1961).

SITE DESCRIPTION

Richard B. Russell Lake is the second in a series of three US Army Corps of Engineers hydropower reservoirs impounding the Savannah River along the border between Georgia and South Carolina (Figure 1). Hartwell Lake, a 344-MW hydropower reservoir completed in 1962, is located immediately (2 km) upstream. J. Strom Thurmond Lake, located immediately downstream, is a 280-MW hydropower reservoir impounded in 1954. Richard B. Russell Dam, which discharges directly to J. Strom Thurmond Lake, is a 1,590-m long structure composed of a concrete gravity section, which contains the powerhouse and gated spillway, flanked by earthen embankments. The powerhouse contains eight generators (total generation capacity = 600 MW), four of which will serve as pumps following commencement of commercial pump storage operation in 1997. Releases for meeting peak hydropower demands (daily average = 143.8 m^3/sec) are through mid-level penstocks. Tests of pump storage operation, which returns water to Richard B. Russell Lake from J. Strom Thurmond Lake, were conducted during 1993-1996.

Richard B. Russell Lake is a large (surface area=107.9 km^2), moderately deep (maximum depth = 47 m; mean depth=12 m), spatially-complex (shoreline development ratio = 24.5) reservoir featuring a main basin corresponding to the old Savannah River channel and two major embayments formed by impoundment of the flood plains of Beaverdam Creek and Rocky River (Figure 1). The combined area drained by these and numerous other secondary tributaries is approximately 2,100 km^2, compared with 5,400 km^2 for the Savannah River above the headwaters of Richard B. Russell Lake.

METHODS

Six sampling stations, four along the Savannah River portion of the reservoir from Richard B. Russell Dam to the lake's headwaters below Hartwell Dam and one station each in Beaverdam Creek and Rocky River embayments, were established as a means to assess changes in limnological conditions throughout Richard B. Russell Lake (Figure 1). Station locations were chosen so as to allow characterization of distinct regions of the reservoir. These included the near-dam region in the vicinity of the oxygen injection system (Station 060B); the mid-reservoir region near the confluence of Beaverdam Creek and Rocky River embayments with the main portion of the reservoir (Station 120); the Beaverdam Creek embayment (Station 130); the Rocky River embayment (Station 140); the mid-reservoir region downstream from the direct influence of Hartwell Dam releases (Station 160); and the up-reservoir region (Station 180).

In-situ measurements of dissolved oxygen concentration and temperature were collected routinely (weekly to monthly) at 2-m intervals from surface to within 0.5 m of the bottom at each station from 1984 to 1996, using a cabled, in-situ monitor (Hydrolab Corporation, Austin, TX). Dissolved oxygen probes were calibrated prior to each sampling event and replicate samples were recorded for approximately 10 percent of the sampled depths. Dissolved oxygen values $\leq$ 0.5 mg/l were considered equivalent and indicative of anoxia.

Hypolimnetic oxygen deficit (HOD) rate, computed from temporal differences in the oxygen content, provides a direct measure of the cumulative effects of processes depleting oxygen (e.g., microbial respiration, chemical oxidation, etc.) in the hypolimnia of lakes during the summer stratified period (Wetzel 1975), and indirectly estimates autochthonous production in the euphotic zone (Cornett and Rigler 1979). Computation of HOD rate assumes isolation of the hypolimnion due to thermal stratification and a lack of reaeration. However, since density currents can transport oxygenated inflows to reservoir hypolimnia during stratification (Kennedy et al. 1985) and discharges from near-bottom ports can result in the downward displacement of warm, oxygenated water (Martin and Arneson 1978), computation of an HOD rate may be inappropriate for many reservoirs.

Therefore, the anoxic factor (AF), a statistic integrating the duration and extent of anoxia (Nürnberg 1987), was used here to describe spatial and temporal (yearly) changes in oxygen status. AF values, or the total number of days that a sediment area equal to the lake surface area is overlain by anoxic water, were computed for each reservoir region for each of the sampled years according to the following:

$$\text{Anoxic Factor (AF)} = \frac{\sum_{i=1}^{n} (t_i\, a_i)}{A}$$

where,

t_i = duration of anoxia (days)
a_i = surface area of the anoxic stratum (m^2)
n = total number of periods of anoxia
A = surface area of the reservoir or reservoir region (m^2)

AF values were computed for each region based on dissolved oxygen profiles collected at the corresponding sampling site. Periods of regional anoxia were identified when dissolved oxygen concentrations $\leq$ 0.5 mg/l were observed at one or more depths on consecutive sample dates. Regional lake surface areas and areas at the depth of anoxia were obtained from equations relating elevation and area. Relations were based on planimetric data obtained from bathymetric maps.

Pool elevation values were recorded daily at the dam. Yearly average elevation was used in the calculation when elevation values were unavailable. Since Richard B. Russell Lake pool elevation does not vary greatly, such an approximation was determined to have a limited impact on the calculation of AF values. It should be noted that for lakes whose elevation changes drastically, linear interpolation between observed data is a more appropriate method to approximate missing elevation values.

Outflow rates for Richard B. Russell and Hartwell Dams were obtained from reservoir operation records (U. S. Army Engineer District, Savannah, Georgia). Inflow rates were computed as rate of change in pool volume (based on changes in pool elevation) minus outflow rate. Temperatures of Hartwell Dam releases were continuously recorded 0.2 km downstream using an in-situ monitor (Schneider Instruments Company, Cincinnati, Ohio).

RESULTS

Filling of Richard B. Russell Lake was initiated in December 1983 with closure of bottom gates used to pass river water during construction. Pool elevation increased rapidly and full operational level was reached by May 1984. Thermal stratification led to the formation of a well-defined thermocline located between 5-10 m at all stations by mid-summer 1984 (Figure 2). Dissolved oxygen concentrations were reduced lake-wide and anoxia existed at depths greater than 5-15 m (Figure 2). An exception was Station 180 where hypolimnetic dissolved oxygen concentrations were $\geq$4 mg/l. Delayed completion of the oxygen injection system precluded amelioration of severe dissolved oxygen conditions near the dam, thereby delaying initiation of hydropower releases until after autumnal turnover to avoid adverse impacts to downstream areas. Summer and fall releases were instead from near-surface gates.

While thermal structure was relatively unchanged, vertical profiles of dissolved oxygen concentration were spatially heterogeneous following the initial year of impoundment. Meta- and hypolimnetic concentrations at Station 060B in July 1992, were relatively high ($\geq$ 6 mg/l) reflecting the effects of oxygen injection, whereas concentrations at Station 130 were similar to those observed in 1984 (Figure 2). Although anoxia was still observed near bottom, dissolved oxygen concentrations in the hypolimnion at Station 120 were markedly higher than those observed in 1984 (Figure 2). Hypolimnetic dissolved oxygen concentrations continued to be $\geq$4 mg/l at Station 180.

Tests of pump operation in 1993-1996 returned large volumes of surface water from J. Strom Thurmond Lake resulting in significant increases in water temperature throughout much of the downstream reach of Richard B. Russell Lake. While thermal stratification was not lost, hypolimnetic temperatures warmed by 3-7° C at downstream locations coincident with extensive pump operation during August 1996 (Figure 2). Changes in hypolimnetic dissolved oxygen concentrations were not observed in the mainstream stations (i.e., Stations 060B, 120, and 180), and hypolimnetic anoxia persisted at embayment stations (i.e., Stations 130 and 140).

AF values were spatially and temporally variable (Figure 3). Anoxia was extensive following impoundment and high AF values were computed for all but the upstream region of the reservoir (Station 180) during 1984 (Figure 3). AF values declined rapidly in 1985, particularly at Stations 060B, 120 and 160, reflecting large reductions in the volume of hypolimnetic water experiencing anoxia. AF values were highest at Stations 130 and 140 (144 and 107 days, respectively) and pronounced declines were observed over the first four years of impoundment (Figure 3).

Relative regional differences in AF values persisted throughout the study period (Figure 3). Highest values were computed for embayment stations (Stations 130 and 140), while minimal or zero values were computed for Stations 060B, 160, and 180. Intermediate values were associated with the mid-reservoir region (i.e., Station 120). Within-station differences in AF values were minimal during 1987-1995.

Pronounced declines in AF values were observed in 1996 coincident with extensive pump testing during May-October (Figure 3). While anoxia persisted at Stations 130 and 140, AF values declined by 56% and 59%, respectively, relative to those observed in 1995. Anoxia was not observed at Station 120 in 1996.

DISCUSSION

Spatial and temporal trends in the oxygen status of Richard B. Russell Lake during the thirteen years following impoundment were influenced by the inundation and subsequent catabolism of terrestrial organic material, differences in bathymetry and hydrology between major regions of the lake, and the operation of Richard B. Russell Dam. Flooding of soils high in organic material promotes high rates of oxygen demand on the overlying water column (Gunnison et al. 1983). Additional demands are exerted with the microbial decomposition of terrestrial litter, vegetation, and woody material remaining in the flooded basin of newly impounded reservoirs (Baxter 1985). Severe reductions in dissolved oxygen concentrations and the extent of hypolimnetic anoxia in Richard B. Russell Lake immediately following filling (i.e., 1984; Figure 2) were clearly related to the quantity and areal extent of flooded organic material (Shain 1987; James 1987).

Marked improvements in oxygen status 1-2 years following the initial year of impoundment, as documented by changes in AF values (Figure 3), were influenced by the depletion of oxidizable organic material, hydrology and operation of the oxygen injection system. Gunnison et al. (1980) demonstrated potentially significant influences on water quality following the filling of new reservoirs due to leaching and degradation during experiments involving flooded soils, but observed rapid losses in biologically available organic carbon (Gunnison et al. 1980). Rapid losses of organic material from terrestrial litter experimentally incubated (James et al. 1988) indicate that much of the labile organic material inundated during filling of Richard B. Russell Lake was rapidly oxidized and that oxygen demands would have declined over a relatively short period of time.

Declines in extent and duration of anoxia during early years were also influenced by hydrology and operation of the oxygen injection system (Figure 3). Releases from Hartwell Dam enter the shallow, upstream region of Richard B. Russell Lake initially as a plug flow and progress through the lake as an underflowing or interflowing density current at a depth of similar density (James et al. 1985). Temperatures of Hartwell Dam releases during summer ranged from 11 to 15° C, which correspond to temperatures (and, therefore, density) at depths of 35 to 47 m at Station 060B in Richard B. Russell Lake. Since inflows determine flushing rate and introduce oxygen, the extent and rate of improvements in dissolved oxygen conditions would be affected by both inflow rate and vertical placement of density currents. Such was the case in Richard B. Russell Lake in the upstream region (Stations 180 and 160) impacted by plug flows and in the mid-reservoir region (Station 120) influenced by underflowing density currents and the transport of dissolved from upstream locations. Introductions of oxygen due to oxygen injections clearly resulted in improvements in the oxygen status further downstream in the near-dam region of the reservoir (Station 060B). Extensive operation of pumps and the return of well-oxygenated water from the surface of J. Strom Thurmond Lake in 1996 subsidized oxygen additions and introduced oxygen throughout the water column in portions of the mid-reservoir region.

Changes in the oxygen status of large embayments of Richard B. Russell Lake (Stations 130 and 140) were influenced by reductions in stores of labile organic material during the early period of reservoir aging and by hydraulic isolation. Relatively high and stable AF values (30 to 100 days) following the rapid changes observed in the initial years of impoundment (Figure 3) reflect limited flushing of the hypolimnion due to relatively low inflows from secondary tributaries and suggest a greater correspondence between autochthonous production and hypolimnetic oxygen consumption in these regions of the reservoir.

Baranov (1961) proposes that lacustrine development in newly filled reservoirs occurs in three phases of variable duration. The initial phase, or trophic upsurge phase, is characterized by extensive biochemical processes which consume dissolved oxygen in deep strata and release nutrients due to decomposition of inundated organic material resulting in increased phytoplankton production. During trophic depression, rates of organic matter decomposition slow reducing demands on oxygen supplies and plankton production is reduced. The third phase involves gradual increases in autochthonous production and a greater coupling of production and oxygen consumption through respiration.

In general, limnological developments in Richard B. Russell Lake followed this paradigm. However, processes impacting dissolved oxygen concentrations and rates of change in oxygen status were markedly influenced by hydrology. Regions of reservoirs rapidly flushed by riverine inflows and receiving oxygen inputs due to advective transport experience more moderate impacts at filling and recover more rapidly than deeper regions distant from river inflows or regions hydraulically isolated. Changes in operation, including addition of oxygen and modification of outlet deep or release volume, may further influence limnological development.

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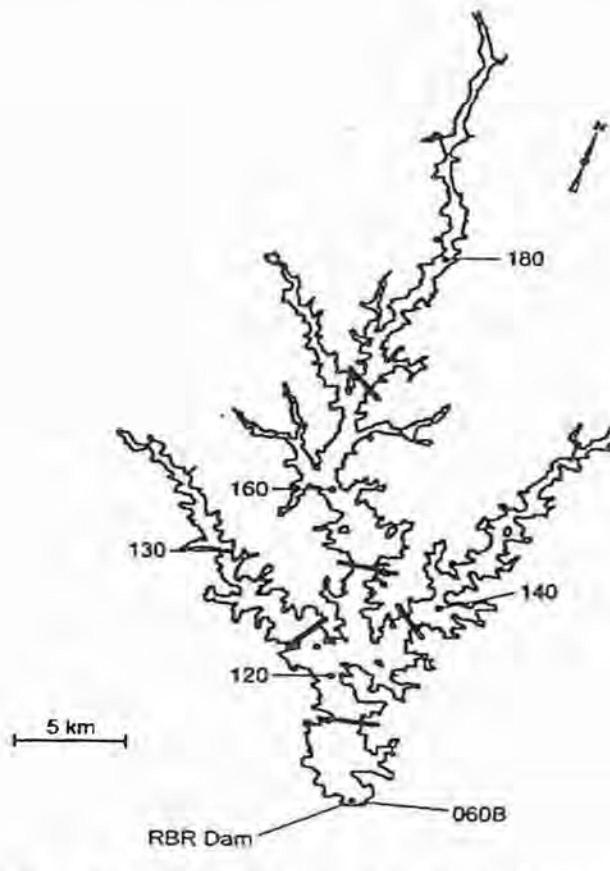

Figure 1. Map of Richard B. Russell Lake and vicinity. Numbers indicate sample station locations. Boundaries between reservoir regions are demarcated by bold lines.

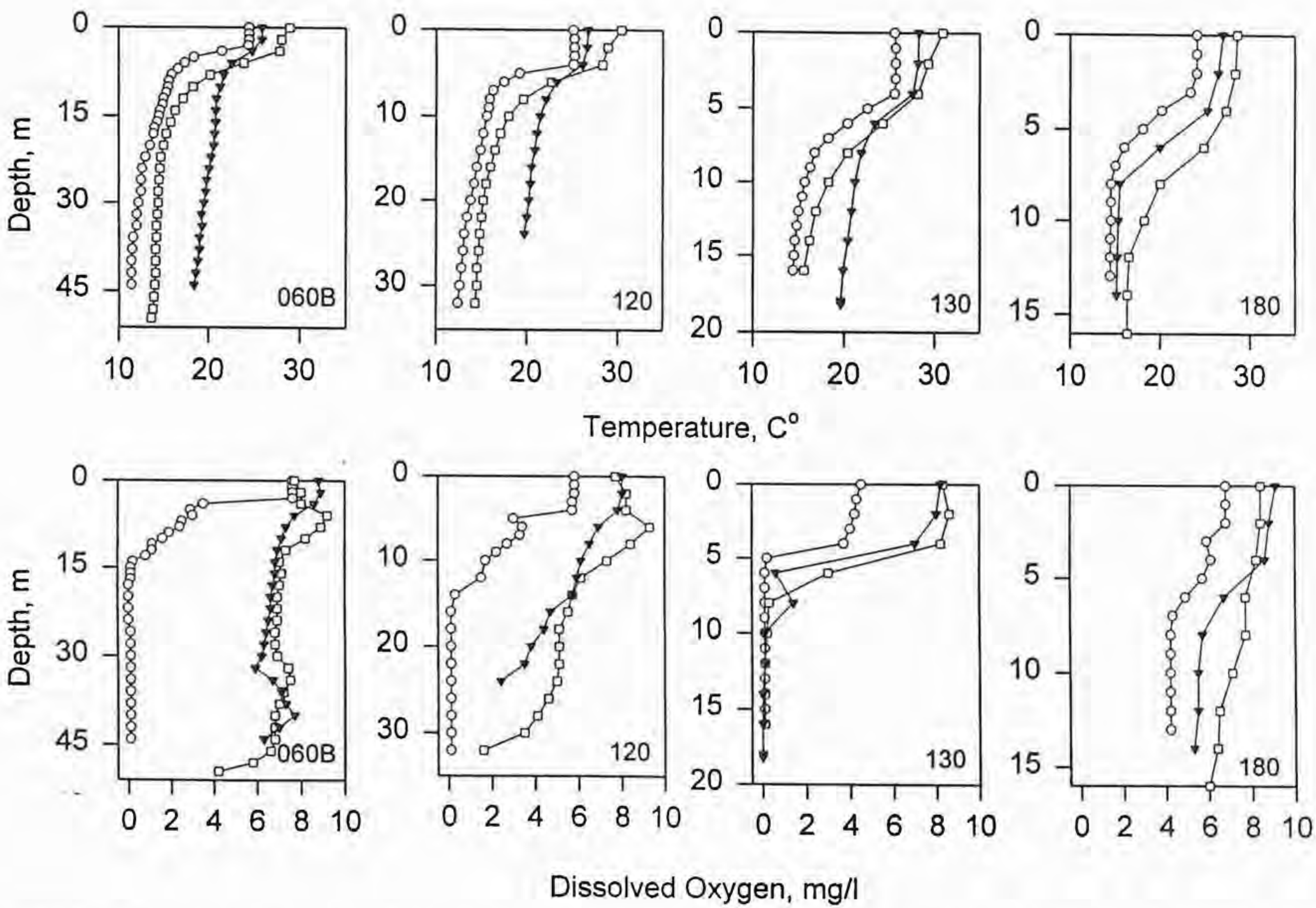

Figure 2. Profiles of temperature (upper) and dissolved oxygen concentration (lower) at Stations 060B, 120, 130 and 180 in Richard B. Russell Lake on July 30, 1984 (o), 21 July, 1992 (□), and 14 August, 1996 (▼).

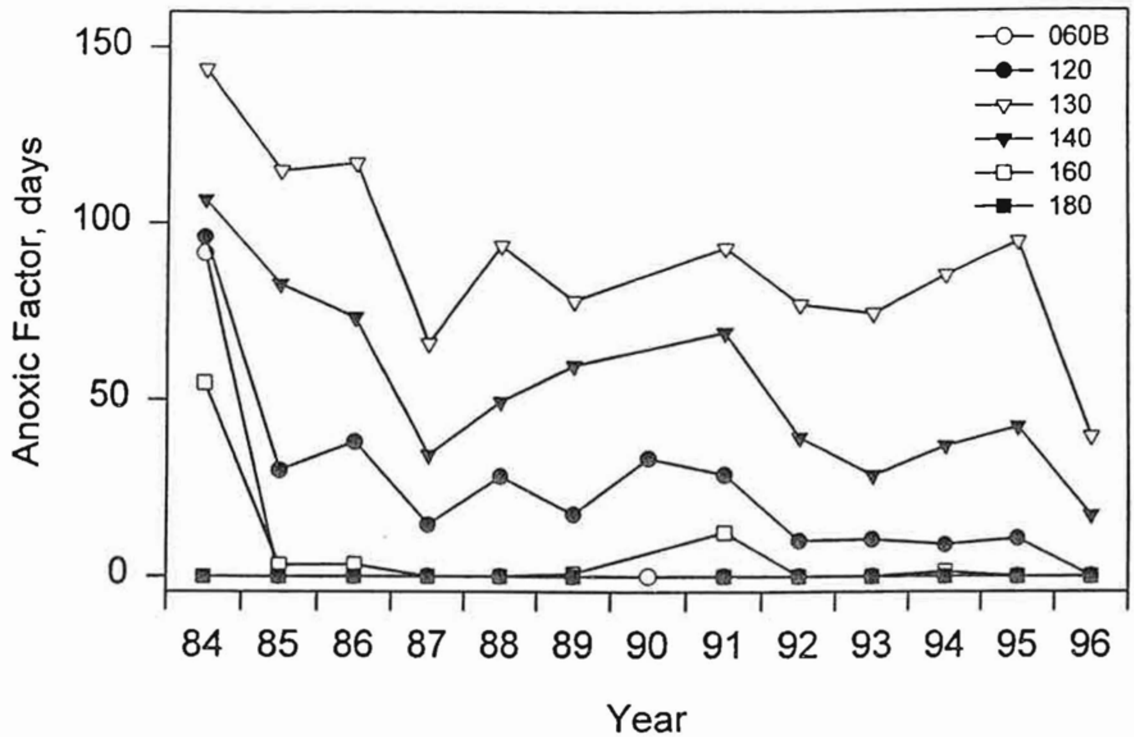

Figure 3. Annual changes in AF values for representative stations in Richard B. Russell Lake.