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WATER QUALITY STUDIES: RICHARD B. RUSSELL AND J. STROM THURMOND LAKES

FOURTH ANNUAL INTERIM REPORT

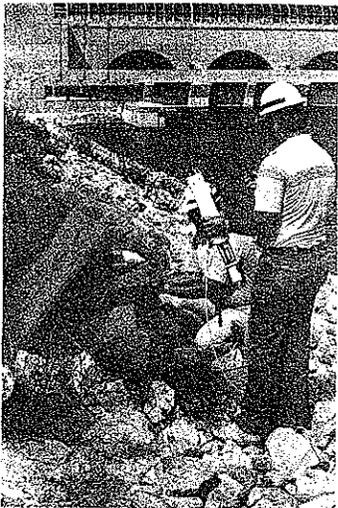
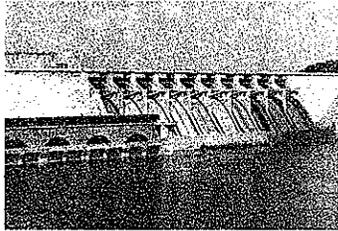
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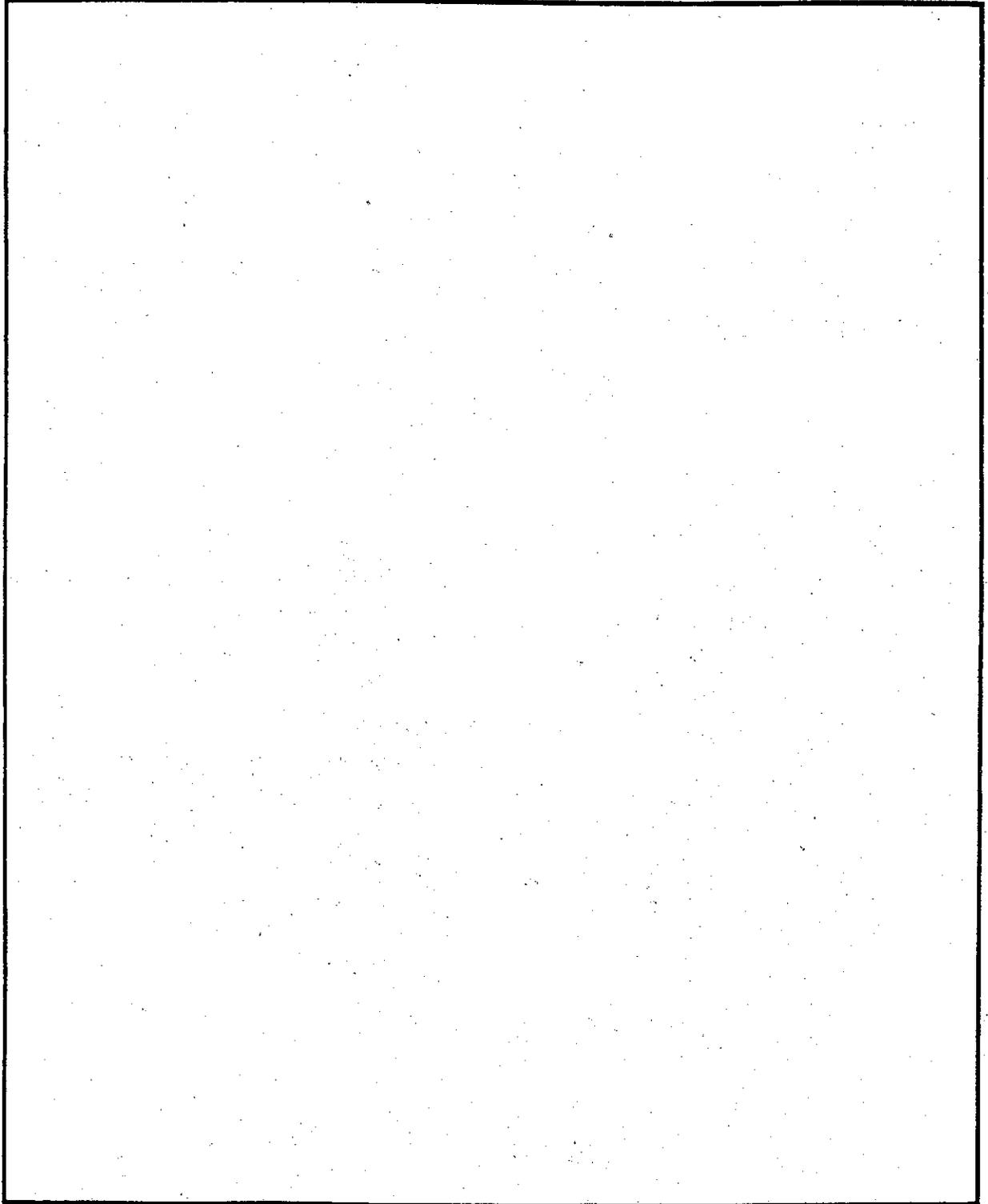
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<p>This report is the fourth annual report documenting the results of comprehensive water quality studies at Richard B. Russell and J. Strom Thurmond Lakes, Georgia and South Carolina. Study objectives were to document water quality conditions in each lake before, during, and following impoundment of Richard B. Russell Lake and to evaluate the effectiveness of an oxygenation system installed in Richard B. Russell Lake.</p>					
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SUMMARY

This report is the fourth in a series of annual interim reports documenting the results of a comprehensive water quality study at Hartwell, Richard B. Russell, and J. Strom Thurmond Lakes and pertains to the period January to December 1987. This report also summarizes the results of all studies during the 4-year period following impoundment of Richard B. Russell Lake.

Water quality conditions in Richard B. Russell Lake were markedly improved in 1987 compared with those of the preceding years. Most pronounced was a marked decline in the extent of the anoxic region in the main stem of the lake. Coincidentally, concentrations of manganese and iron in the main stem of the lake and in release waters were lower than concentrations observed in previous years. Conditions in the major tributary embayments were similar to those of previous years, however. Continued improvement in water quality is anticipated over the next several years, due to continued reduction in the decomposition of organic material inundated during impoundment.

Dissolved oxygen (DO) concentrations in Richard B. Russell Lake releases during summer months were maintained near 6 mg/l with operation of the oxygenation system.

Water quality in J. Strom Thurmond Lake was similar to previous study years; however, spatial trends in temperature and DO concentrations were observed. Cooler hypolimnetic temperatures and a more pronounced thermocline suggest that the thermal structure in the lake is more defined than that observed prior to impoundment of Richard B. Russell Lake. Hypolimnetic DO concentrations have increased in the mid and upper regions of J. Strom Thurmond Lake, but concentrations in the hypolimnion of the lower region of the lake have declined since 1984.

Manganese and iron dynamics in each lake and among the lakes continue to be the most pronounced of chemical parameters currently monitored. Transport of dissolved manganese and particulate iron in the three-lake system is apparent, but the implications of effects on water quality are less discernible.

PREFACE

A multiphase, comprehensive water quality study at Richard B. Russell, J. Strom Thurmond, and Hartwell Lakes was initiated in October 1983 as a cooperative effort by the US Army Engineer District, Savannah, and the US Army Engineer Waterways Experiment Station (WES). This report, which covers the period January to December 1987, is the fourth in a series of annual interim reports documenting findings and results. This report is submitted in accordance with the "Scope of Work: Water Quality Monitoring Program - Richard B. Russell Dam and Lake, Georgia and South Carolina" (Intra-Army Order No. PD-EI-84-07).

This report was prepared by Mr. Steven L. Ashby, Dr. Robert H. Kennedy, Mr. Joe H. Carroll, and Mr. Robert C. Gunkel, Jr., of the Environmental Laboratory (EL), WES. Participating in the study were Dr. John J. Hains of Clemson University and Mr. Michael Potter, Mr. William Jabour, Mr. Harry Eakin, Dr. Robert F. Gaugush, Dr. Stephen Schreiner, Ms. Vicki Vance, Ms. Gwen Yates, and Ms. Avis Howell of the EL. Dr. Kennedy and Mr. Carroll were responsible for the conduct of the study and for preparation of this report. The report was edited by Ms. Jessica S. Ruff of the Information Technology Laboratory, WES.

The report was prepared under the direct supervision of Dr. Thomas L. Hart, Chief, Aquatic Processes and Effects Group, and under the general supervision of Mr. Donald L. Robey, Chief, Ecosystem Research and Simulation Division, and Dr. John Harrison, Chief, EL.

Commander and Director of WES was COL Larry B. Fulton, EN. Technical Director was Dr. Robert W. Whalin.

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WATER QUALITY STUDIES: RICHARD B. RUSSELL AND J. STROM THURMOND LAKES

Fourth Annual Interim Report

PART I: INTRODUCTION

1. Management of reservoirs for multiple purposes emphasizes the ever-increasing value of reservoirs as a national resource. Historically, reservoirs have been constructed and operated primarily to provide flood control, hydroelectric power generation, and water supply. However, in recent years, utilization of reservoirs has been expanded to include fish and wildlife habitat, water quality control, and water-based recreation. Increasing emphasis on the environmental and recreational value of reservoirs has resulted in increased public demand for the protection of such a resource. This, in turn, has prompted efforts to better understand reservoir water quality processes and to develop sound management strategies for the protection of water quality.

2. Limnologists and others concerned with the management of reservoir water quality evaluate water quality processes relative to influences of reservoir operations and resultant impacts on water quality. Commonly encountered water quality management concerns are hypolimnetic anoxia, the accumulation in bottom waters of reduced metals such as iron and manganese, and excessive rates of algal production. In cases in which operational procedures require the withdrawal of water from anoxic bottom strata, downstream areas are exposed to elevated metal, nutrient, and hydrogen sulfide levels and the influx of oxygen-deficient release waters. Such conditions impact aesthetic, recreational, and water-use values and threaten fish and wildlife habitat.

3. The construction of Richard B. Russell Dam and the impoundment of the 48-km reach of the Savannah River between Hartwell Dam and J. Strom Thurmond Lake (formerly called Clarks Hill Lake) raised concerns over water quality conditions in the newly filled Richard B. Russell Lake and the potential impact of reservoir releases on the water quality of J. Strom Thurmond Lake. Accordingly, these concerns were addressed as major objectives of an intensive water quality study:

- a. To describe postimpoundment water quality conditions in Richard B. Russell Lake.

- b. To document the impacts of the new impoundment on water quality conditions in J. Strom Thurmond Lake.
- c. To evaluate the effectiveness of the oxygenation system in ameliorating potential water quality problems in Richard B. Russell Lake and its tailwater.

4. The US Army Engineer Waterways Experiment Station, through cooperative agreement with the Savannah District of the South Atlantic Division of the Corps of Engineers, began this investigation in October 1983. This document reports the results of the fourth year of the investigation and summarizes the major results of 4 years of observation regarding those objectives. The study involved a combination of routine and event- or process-oriented data collection efforts in Richard B. Russell and J. Strom Thurmond Lakes at representative sampling stations established in the lakes and their tailwaters. The forebay region and tailwater of Hartwell lake were also sampled on a routine basis. Other studies of specific events or processes influencing water quality were conducted over shorter time periods and with greater sampling intensity.

PART II: SITE DESCRIPTION

5. The Savannah River Basin is long and relatively narrow with its long axis lying in a northwest-southeast direction. The maximum length of the basin is nearly 402 km, while the maximum width is approximately 113 km. The total area of the basin is 27,400 km². The Savannah River originates on the southern slope of the Blue Ridge Mountains in North Carolina and flows in a southeasterly direction through the Piedmont Plateau and Coastal Plain along the boundary between Georgia and North and South Carolina.

6. Prompted by the need for flood control, streamflow regulation, and water supply in the basin, the US Army Corps of Engineers constructed Clarks Hill Dam (now known as J. Strom Thurmond Dam) in 1954. Hartwell Dam, completed in 1963, extended impoundment of the Savannah River into its two major tributaries, the Tugaloo and Seneca Rivers. Richard B. Russell Dam and Reservoir was authorized as Trotters Shoals Dam on 7 November 1966 by the Flood Control Act of 1966 (Public Law 89-789, Eighty-Ninth Congress House Resolution 18233) to provide power generation, incidental flood control, recreation, fish and wildlife habitat, streamflow regulation, and water supply. Richard B. Russell Dam, completed December 1983, impounds the Savannah River between Hartwell and J. Strom Thurmond Lakes (Figure 1). Major physical and morphometric features of the three impoundments are listed in Table 1. Descriptions of the basin and associated landforms are presented in Design Memorandum No. 8 for Russell Dam and Reservoir (US Army Engineer District, Savannah 1974) and summarized below.

7. Topography in the basin is characterized by gently sloping upland areas cut by gullies and stream valleys. Relief is more rugged in areas adjacent to the Savannah River where well-developed, moderately steep to steep ridges and ravines form the topography. Stream elevation varies from 274 m, referred to the National Geodetic Vertical Datum (NGVD), above Hartwell Dam to 55 m NGVD below J. Strom Thurmond Dam.

8. Rock formations of the mountain section and the Piedmont Plateau are primarily igneous or metamorphic in origin, and include granites, gneisses, schists, basic eruptives, and highly metamorphosed shales, sandstones, and limestones. On most level or gently sloping areas, the rocks are disintegrated to a depth of many meters and the surface is largely formed of residual

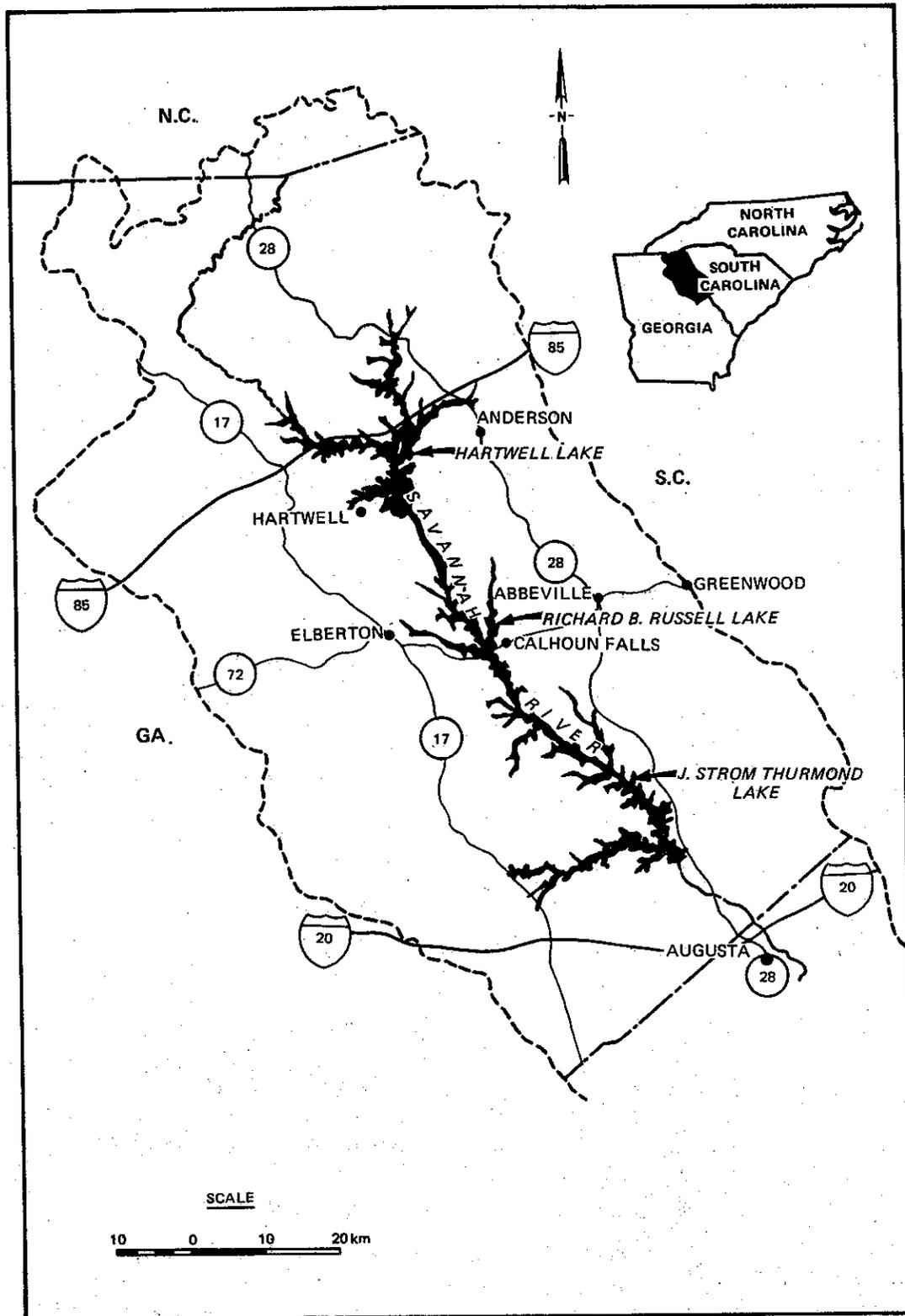


Figure 1. Locations of Hartwell, Richard B. Russell, and J. Strom Thurmond Lakes in the Upper Savannah River watershed

material. Exposed rock outcrops are mostly confined to summits, steep slopes, and stream channels.

9. The basin experiences a maritime climate with mild winters, long summers, and moderate to high rainfall (114 to 152 cm per year). While subject to continental influences, it is protected by the Blue Ridge Mountains from the more rigorous winters prevailing in the Tennessee Valley. The mean temperature for the basin is approximately 16° C. During the coldest months of the year, night temperatures frequently reach approximately -7° C. During the warmest months of the year, temperatures often exceed 32° C. At lower elevations, the winters are milder and the summer temperatures greater.

10. Land use is fairly uniform throughout the basin, with woodlands comprising 60 percent and pasture and cropland about 35 percent of the area. A small (5 percent), but growing, portion of the watershed is exposed to urban and recreational use. The wooded uplands consist of mixed pine and hardwood forest, the timber from which provides one of the major industries of the area. Cleared lands are devoted primarily to cultivated crops and pasture.

11. The waters of the Savannah River above J. Strom Thurmond Dam are relatively free of pollution. Current point sources of pollution are minimal, with most occurring in the Hartwell Lake area. Contamination with polychlorinated biphenyls in Hartwell Lake has been reported (Gaymon 1982). Numerous small wastewater treatment plants, textile mills, and various other industries discharge to streams and lakes within the study area. Surface waters tend to have low dissolved solids and alkalinity, and a low buffering capacity.

PART III: METHODS AND MATERIALS

12. Detailed descriptions of the methods and materials used during the fourth year of the study are presented in previous annual reports (James et al. 1985, 1986). The locations of primary sampling stations in Hartwell and Richard B. Russell Lakes and in J. Strom Thurmond Lake are presented in Figures 2 and 3, respectively. Data were collected monthly (in situ monitoring) and seasonally (physicochemical analyses) (Table 2). The four seasonal sampling times coincided with the spring high-flow period, the early and late stratification periods, and the period following fall mixing. Table 3 lists in situ and physicochemical parameters monitored during the study.

13. In addition to routine water quality monitoring, the area near Richard B. Russell Dam was intensively sampled to describe influences of the oxygenation system. From the onset of thermal stratification until November, weekly in situ measurements were collected at Stations 060B, 100B, 115, and 120. Monthly physicochemical data were also collected at Stations 040, 045, 050, 060B, 100B, and 120. Additional stations and dates were often included to supplement these data. Temperature, dissolved oxygen (DO), pH, specific conductance, and oxidation-reduction potential data were collected in situ using a Hydrolab Surveyor II (Hydrolab Corporation, Austin, TX). Monitoring instruments were calibrated prior to each field use. Temperature was calibrated to the nearest 0.1° C against an NBS thermometer; DO by air calibration; pH with standard buffer solutions; and specific conductivity using known standards. Because it was interpreted primarily as an indicator of reducing versus oxidizing chemical conditions, and not a quantitative measure, minimal emphasis was given to calibration for oxidation-reduction potential. In situ measurements were also collected and recorded hourly at Stations 010, 050, and 200 with Schneider Water Quality Monitors (Model RM25, Schneider Instrument Company, Madeira and Cincinnati, OH).

14. Water samples were collected using a hose and pump at selected depths throughout the water column at each lake station. Analytical methods, digestion and filtration techniques, sample holding times, and quality control statistics are presented in Appendix A. Standard methods (US Environmental Protection Agency 1979, American Public Health Association 1980) were used for laboratory analyses of water samples.

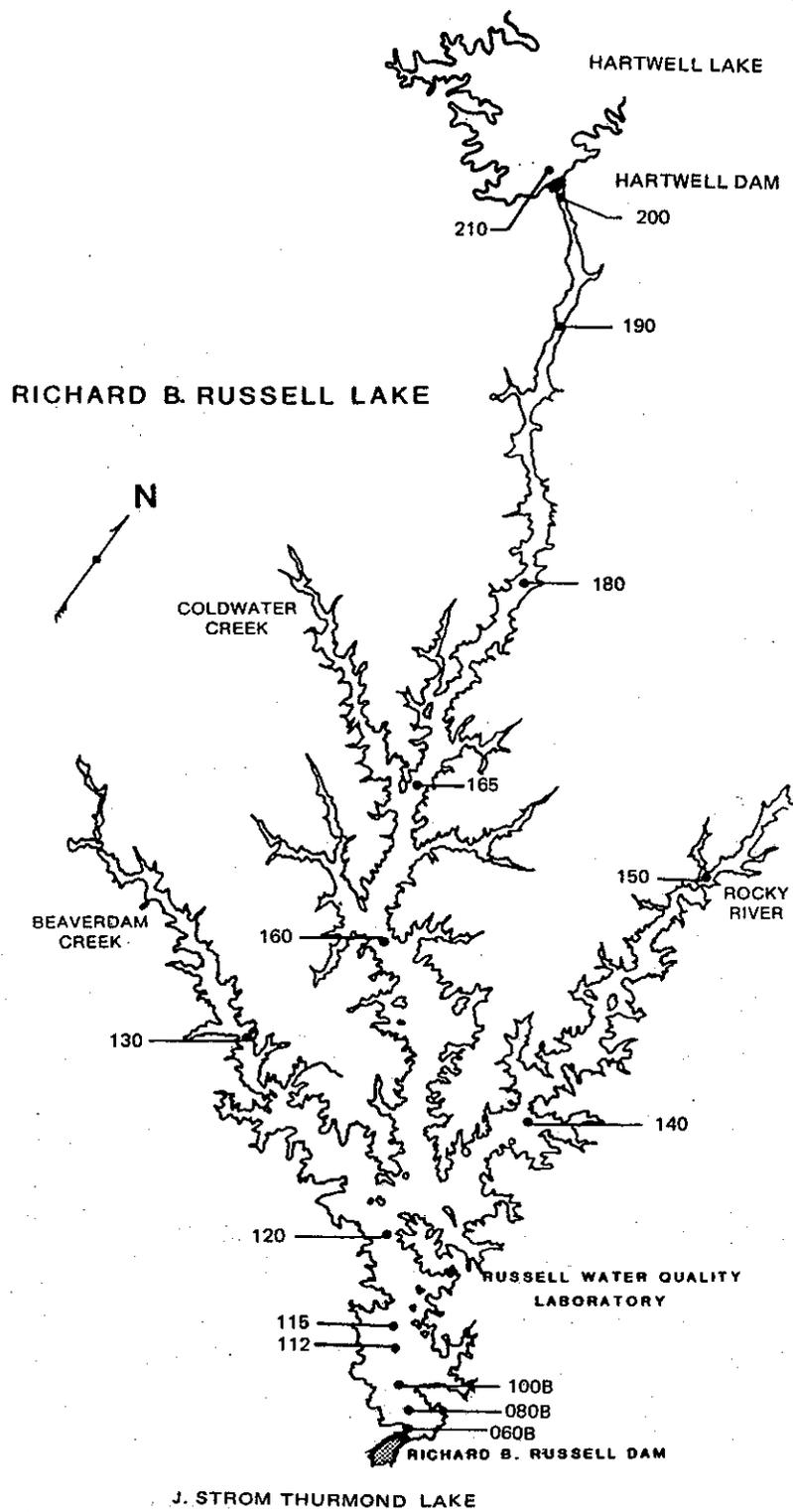


Figure 2. Locations of sampling stations on Hartwell and Richard B. Russell Lakes

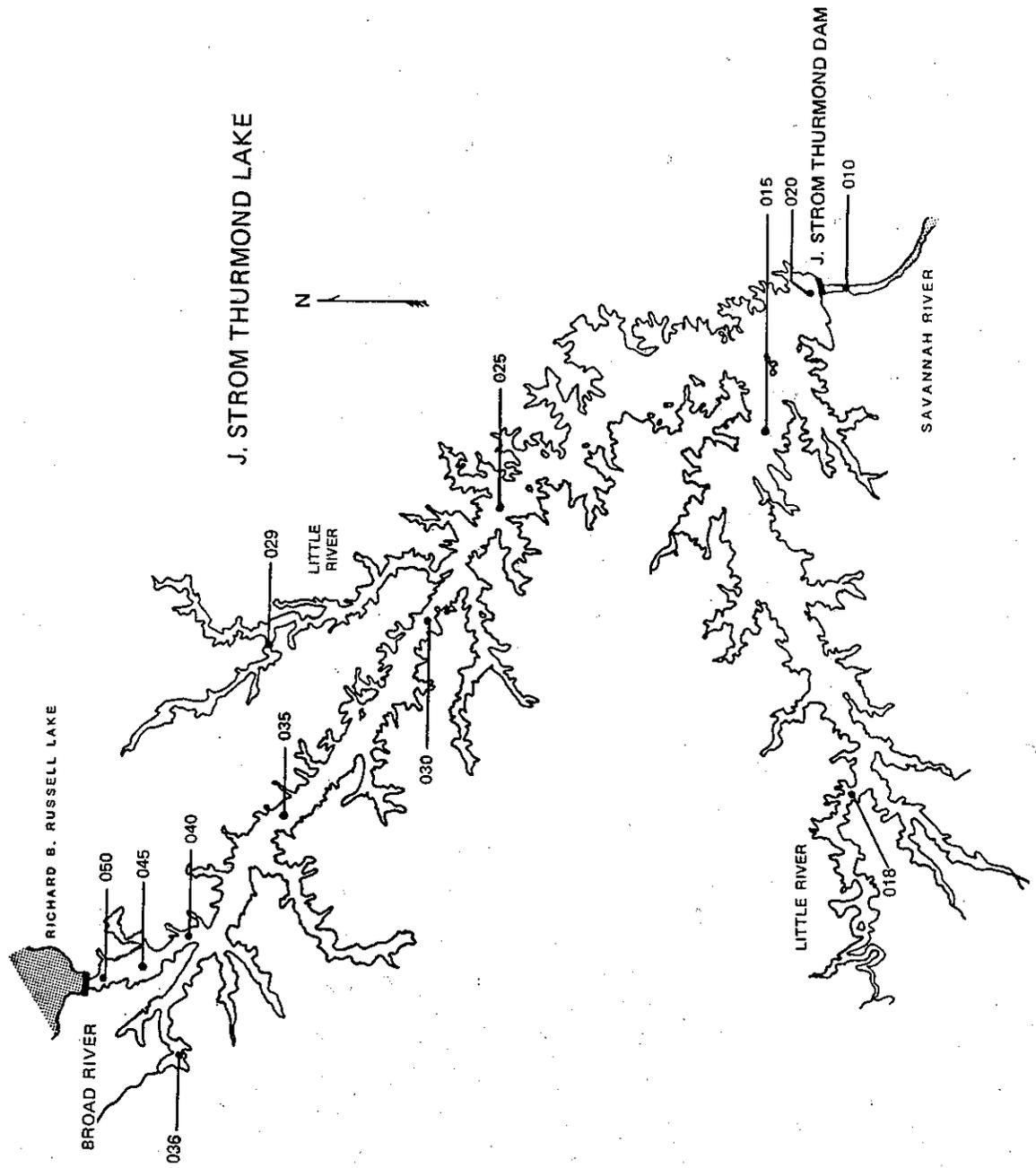


Figure 3. Locations of sampling stations on J. Strom Thurmond Lake

PART IV: RESULTS

Hartwell Lake

15. Pool elevation, precipitation, mean daily inflow, and mean daily outflow for Hartwell Lake during the period 1984-1987 are depicted in Figure 4. Hydrologic conditions were similar to those of 1986 and reflected seasonal drought conditions. While pool elevations returned to near-normal levels during the 1986-1987 winter period, levels during the summer decreased to near-1986 levels due to below-normal inflows and operational requirements for release.

16. Monthly temperature data collected during 1987 at the Hartwell Lake forebay (Station 210) depict seasonal changes in the development of vertical thermal structure in the lake (Figure 5). Isothermal conditions, with temperatures ranging from 8° to 10° C, were observed from January until mid-April. Surface warming and the onset of thermal stratification were observed by late April and early May, with establishment of a well-developed thermocline, at a depth of 6 m, occurring by late May. Continued seasonal warming of the surface waters resulted in a gradual deepening of the thermocline throughout the summer season. Maximum thermocline depth, near 18 m, was observed in late September. Hypolimnetic temperatures at this time ranged from 10° to 14° C. Seasonal cooling in late September and early October resulted in a gradual weakening of thermal structure and, by mid-November, fall mixing had returned the lake to near-isothermal conditions with temperatures between 12° and 14° C.

17. Coincident with the development of vertical gradients in temperature, seasonal trends in DO concentrations were observed at Station 210 (Figure 6). While remaining near 8 to 10 mg/l under isothermal conditions, DO concentrations began to decline in the hypolimnion as temperature gradients were established. Hypolimnetic DO concentrations decreased from 6.0 mg/l in late June to less than 0.5 mg/l in October. Anoxic conditions persisted in bottom waters until mid-December, during which time decreased oxidation-reduction potentials, indicative of reducing environments, were observed. However, following fall mixing, DO concentrations were near 8 mg/l throughout most of the water column, and complete mixing occurred by late December.

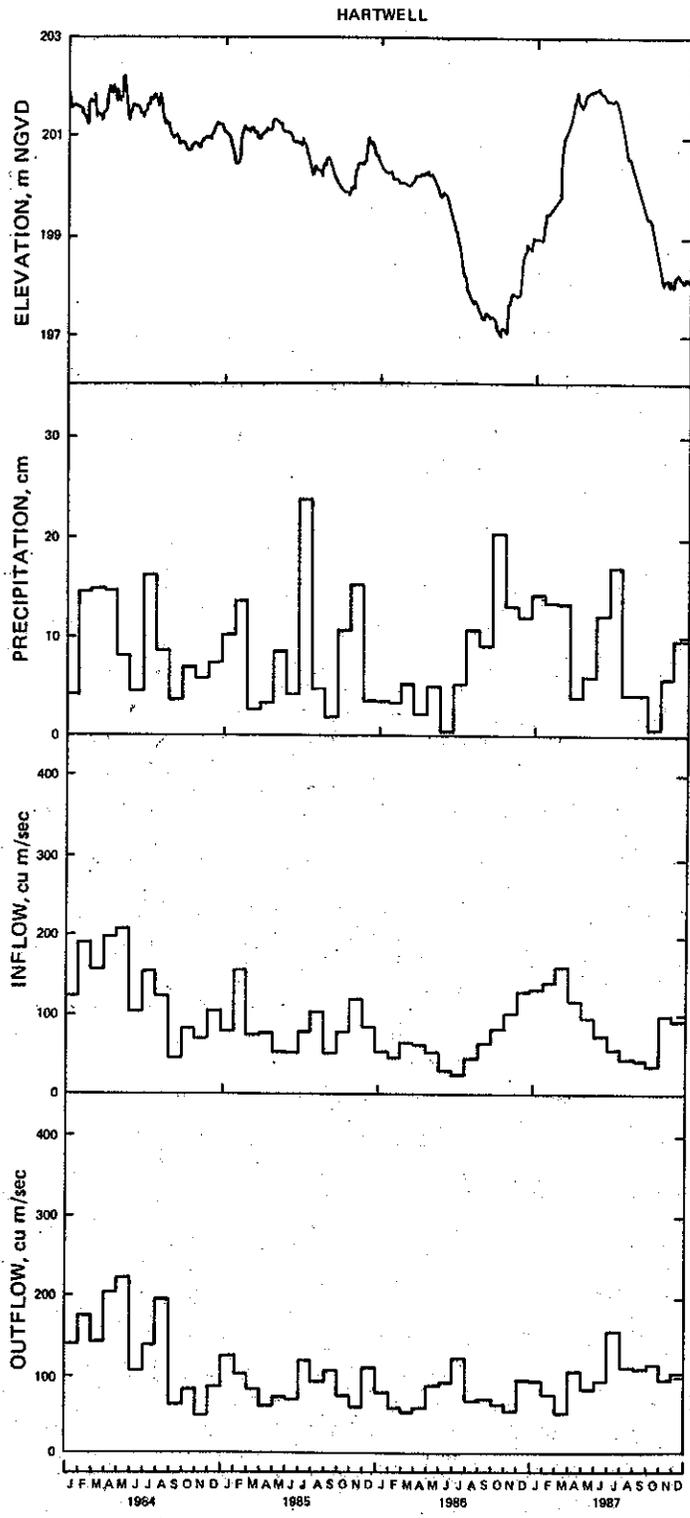


Figure 4. Pool elevation, precipitation, inflows, and outflows for Hartwell Lake, 1984-1987

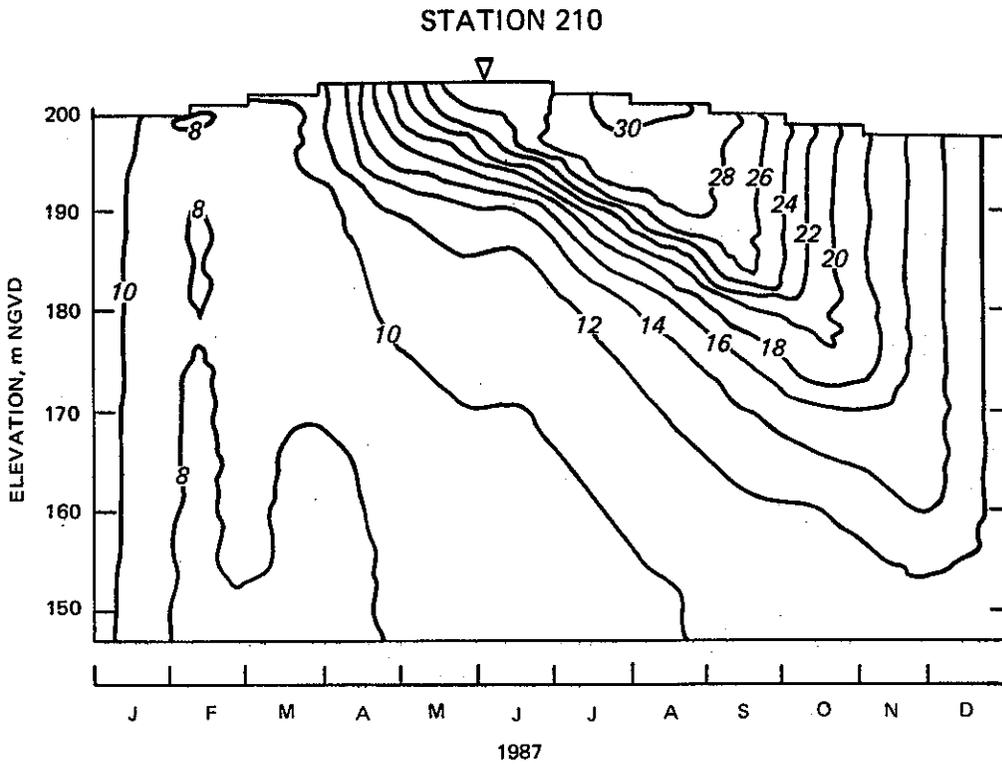


Figure 5. Temporal and vertical changes in temperature ($^{\circ}\text{C}$) in the forebay of Hartwell Lake (Station 210)

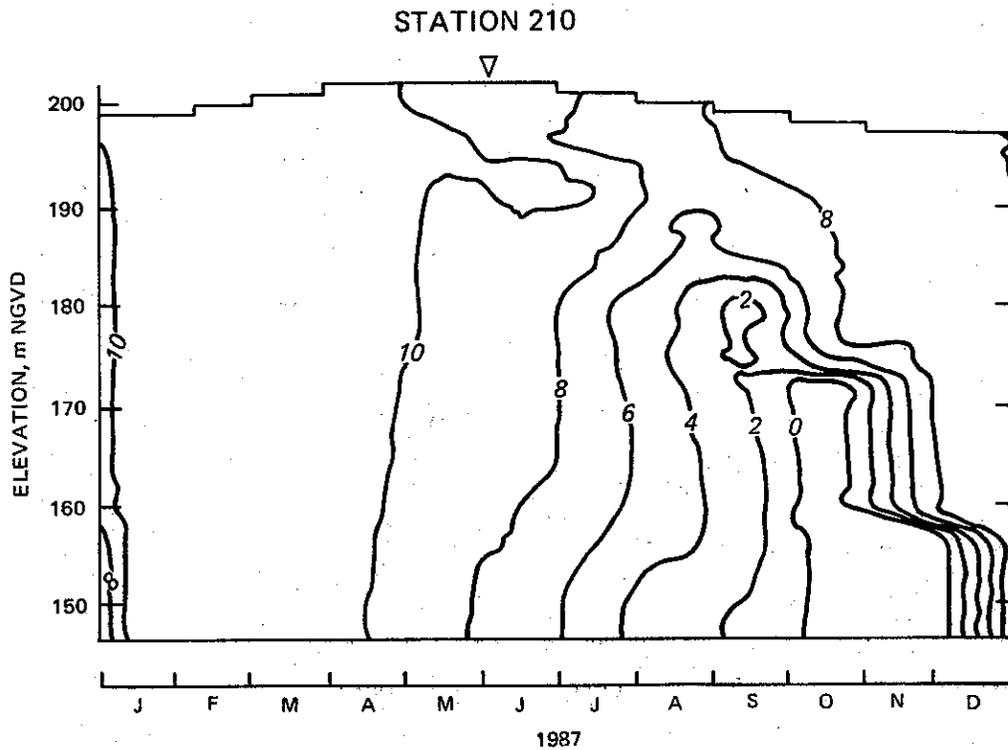


Figure 6. Temporal and vertical changes in DO concentrations (mg/l) in the forebay of Hartwell Lake (Station 210)

18. Chemical parameters at Station 210 displayed seasonal trends coincident with the development of thermal gradients and anoxic conditions. Vertical gradients in manganese and iron concentrations, associated with peak anoxic conditions, were the most pronounced. Increased concentrations of manganese (1.0 mg/l) and iron (2.5 mg/l) were observed in October in bottom waters at Station 210 (Figure 7). Maximum concentrations of manganese (1.6 mg/l) and iron (7.6 mg/l) were observed in early December, when anoxic conditions were still present in bottom waters in the forebay.

19. Manganese concentrations were greater than the detection limit (0.05 mg/l) only during stratified conditions (Figure 8), and dissolved (i.e. reduced) forms comprised the majority of the total manganese pool. In contrast, iron concentrations were mostly greater than the detection limit (0.05 mg/l) and, except during peak anoxic conditions, particulate (i.e., oxidized) forms comprised the majority of the total iron pool (Figure 9a). Dissolved forms of iron comprised the majority of the total iron pool only during the latter portion of the anoxic period (Figure 9b).

20. Moderate seasonal trends in nitrogen concentrations were apparent. Minimum concentrations of total nitrogen (0.18 mg/l) were observed in February. Concentrations began to increase in April (0.4 to 0.6 mg/l), peaked in July (0.6 to 0.9 mg/l), and decreased to 0.4 mg/l in October. A similar trend was observed for dissolved nitrogen concentrations. Dissolved nitrogen, predominantly organic forms, comprised the majority of the total nitrogen pool for most of the year. Inorganic forms of nitrogen were not detected in surface waters during the year; however, maximum concentrations of ammonia and nitrate were observed in the hypolimnion during stratification. Nitrate concentrations peaked in July (0.52 mg/l) and declined to the detection limit (0.04 mg/l) in October, coincident with the onset of anoxic conditions. Maximum concentrations of ammonia (0.22 mg/l) were observed in the hypolimnion during peak anoxic conditions.

21. Seasonal trends in concentrations of other parameters were less apparent. Phosphorus concentrations were often below the detection limit (0.005 mg/l), and observed concentrations did not exceed 0.015 mg/l. Maximum phosphorus concentrations were observed in October at the onset of anoxic conditions. Total organic carbon concentrations ranged from 0.7 to 1.9 mg/l, and dissolved organic carbon comprised the majority of the total carbon pool. Maximum organic carbon concentrations were observed in surface waters during

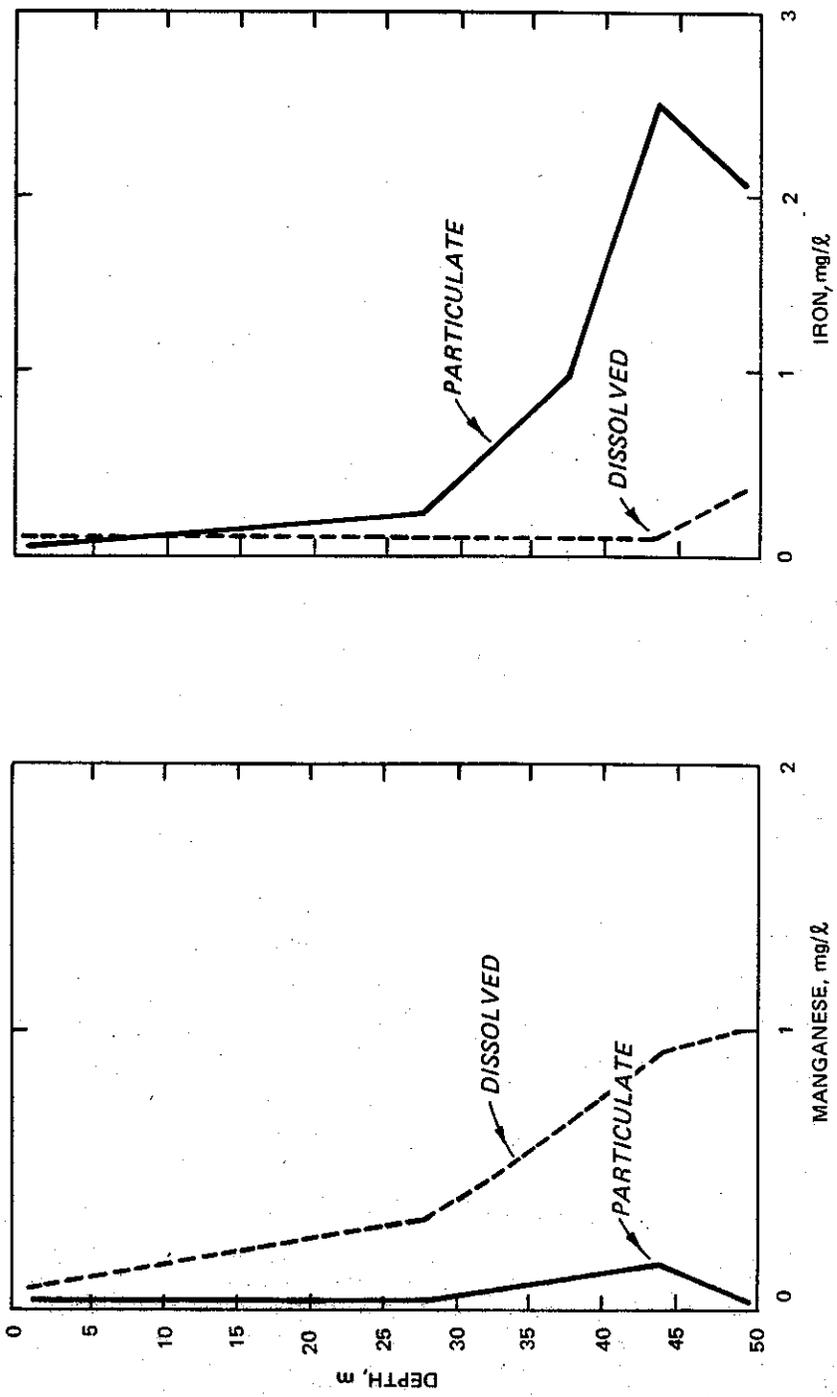


Figure 7. Concentrations of particulate and dissolved manganese and iron in the forebay of Hartwell Lake (Station 210), October 1987

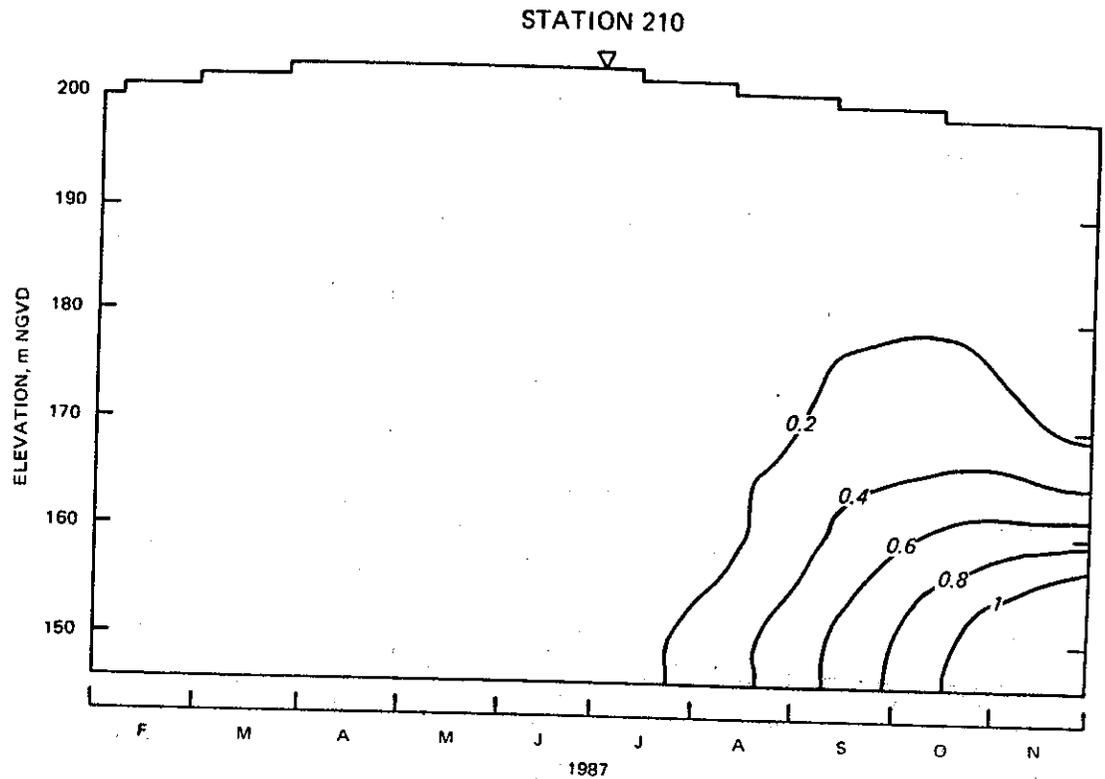
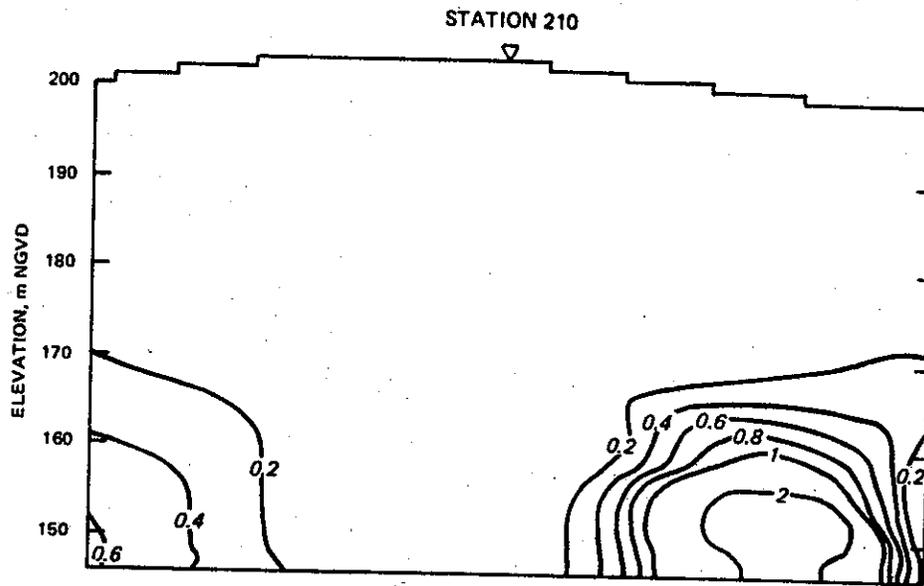


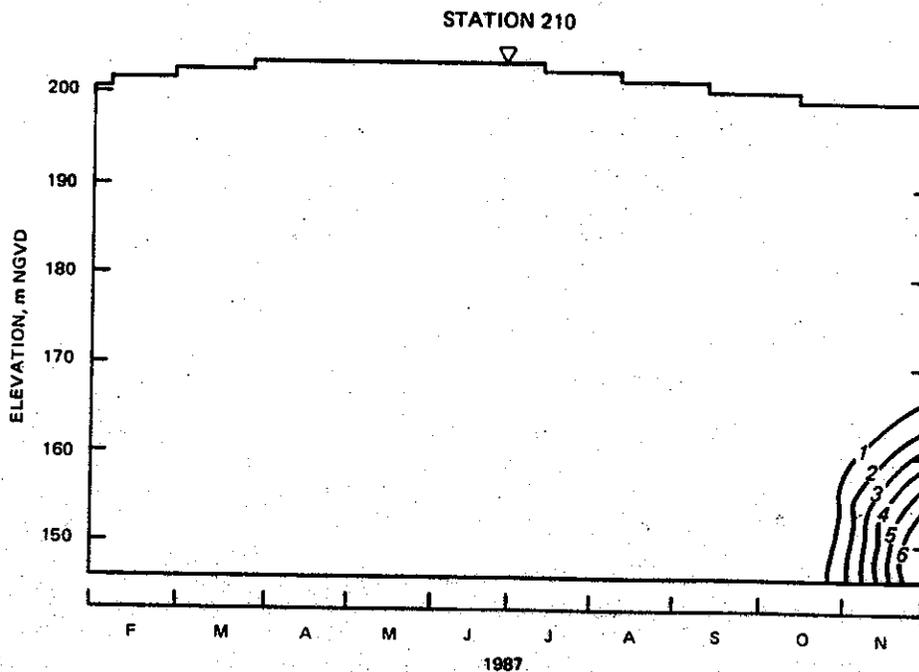
Figure 8. Temporal trends in dissolved manganese concentrations (mg/l) in the Hartwell Lake forebay (Station 210)

July. Values of pH ranged from 5.7 to 7.7 with most values between pH 6 and 7, indicative of circumneutral to mildly acidic waters. Total alkalinity values ranged from 7 to 14 mg/l as CaCO_3 and typify low alkaline conditions of the upper Savannah Basin. Conductivity values ranged from 22 to 73 μS and averaged approximately 30 μS for most depths and times. Minimum and maximum values of selected chemical parameters are presented in Table 4.

22. Temperature and DO concentrations in release waters from Hartwell Dam (i.e., Station 200; Figure 10) displayed seasonal trends and were reflective of conditions in the Hartwell Lake forebay. Temperatures gradually increased from 8° to 10° C (January through March) to 15° to 17° C (September through November). Dissolved oxygen concentrations remained between 11 and 8 mg/l from January through June, but gradually declined to approximately 4 mg/l in mid-September through October, as hypolimnetic oxygen concentrations in the Hartwell Lake forebay declined. Dissolved oxygen concentrations gradually returned to near 10 mg/l during November and December, coincident with fall mixing in Hartwell Lake.



a. Particulate iron, mg/l



b. Dissolved iron, mg/l

Figure 9. Temporal trends in particulate and dissolved iron concentrations in the Hartwell Lake forebay (Station 210)

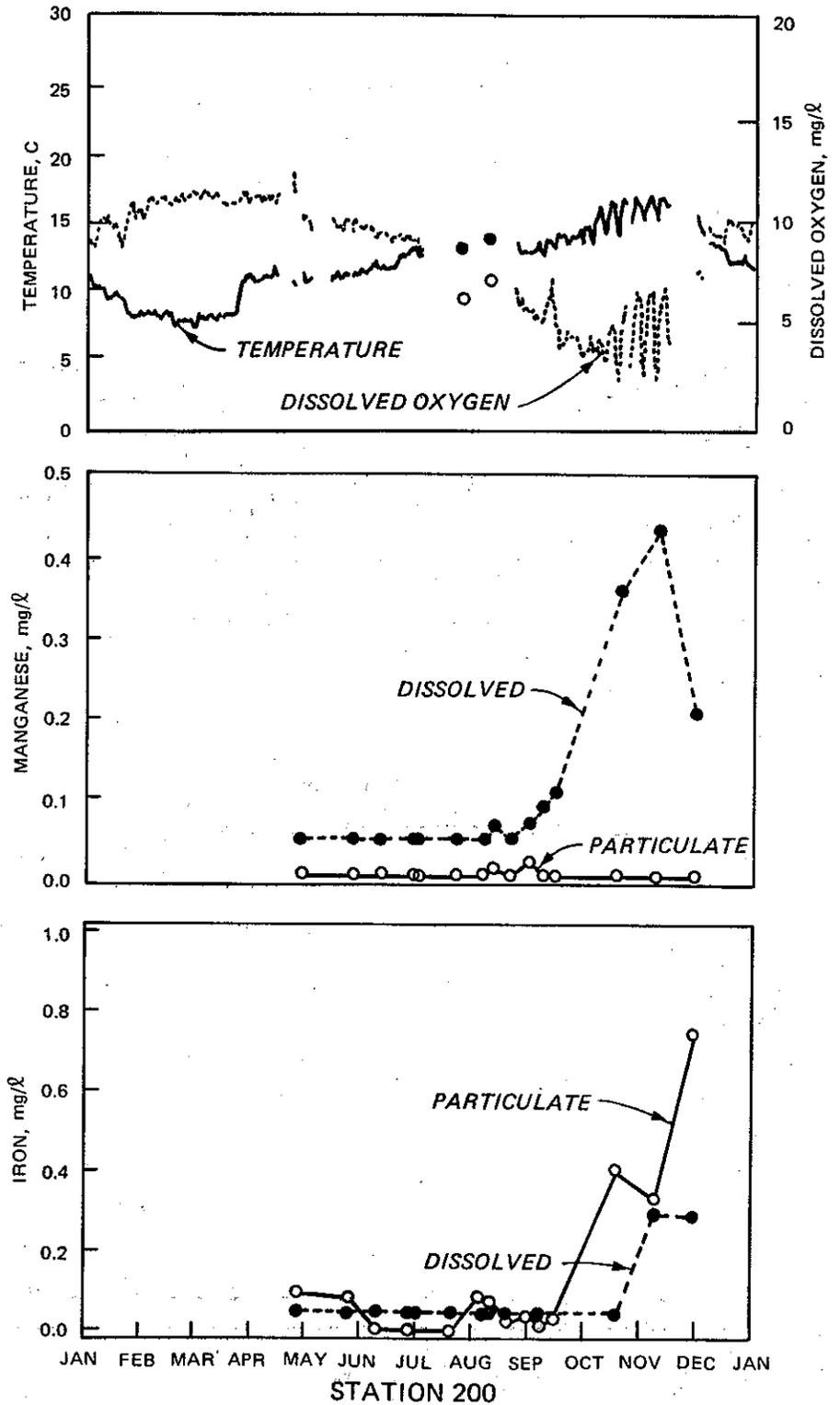


Figure 10. Temperatures, DO concentrations, and particulate and dissolved manganese and iron concentrations in Hartwell Dam releases (Station 200)

23. Moderate seasonal trends in chemical parameter concentrations were observed in release waters and, as with temperature and DO, were reflective of conditions in the Hartwell Lake forebay. Maximum manganese and iron concentrations (0.4 and 0.8 mg/l, respectively) were observed during mid- to late November, prior to complete mixing in the forebay region of the lake and coincident with minimum values of DO (Figure 10). As was observed for the forebay, dissolved manganese and particulate iron comprised the majority of the total manganese and iron pools, respectively, in the release waters.

24. Seasonal trends of other parameters in the release waters were less apparent. Nitrogen concentrations ranged from 0.83 to 0.70 mg/l (April and July, respectively) to 0.27 to 0.39 mg/l (February and October, respectively) and were primarily in dissolved forms. Observed values of conductivity, pH, alkalinity, carbon, and phosphorus were similar to values in the forebay.

Richard B. Russell Lake

25. Pool elevation, precipitation, mean daily inflow, and mean daily outflow for Richard B. Russell Lake during the period 1984-1987 are depicted in Figure 11. Although hydrologic conditions were similar to those of Hartwell Lake, pool elevations in Richard B. Russell Lake were maintained at near-normal levels during 1987, due to the small design drawdown between minimum and maximum conservation pools.

26. Spatial and seasonal patterns in thermal structure were observed along the main stem of Richard B. Russell Lake (Figure 12). Thermal stratification was present from the dam to the headwater region (Stations 060B to 190) from April through September. Changes in monthly temperature at Station 120 exemplify the seasonal pattern of thermal development in the lake (Figure 13). Stratification began in late March, and a well-established thermocline was present by mid-May. The thermocline remained near a depth of 6 to 8 m throughout the season. Temperatures in the epilimnion were between 20° and 28° C, and hypolimnetic temperatures were between 14° and 16° C, during most of the period of stratification. Seasonal cooling in late September and early October reduced surface water temperatures and gradually weakened the thermocline. Continued cooling and wind-induced mixing resulted in complete mixing and near-isothermal conditions by late October.

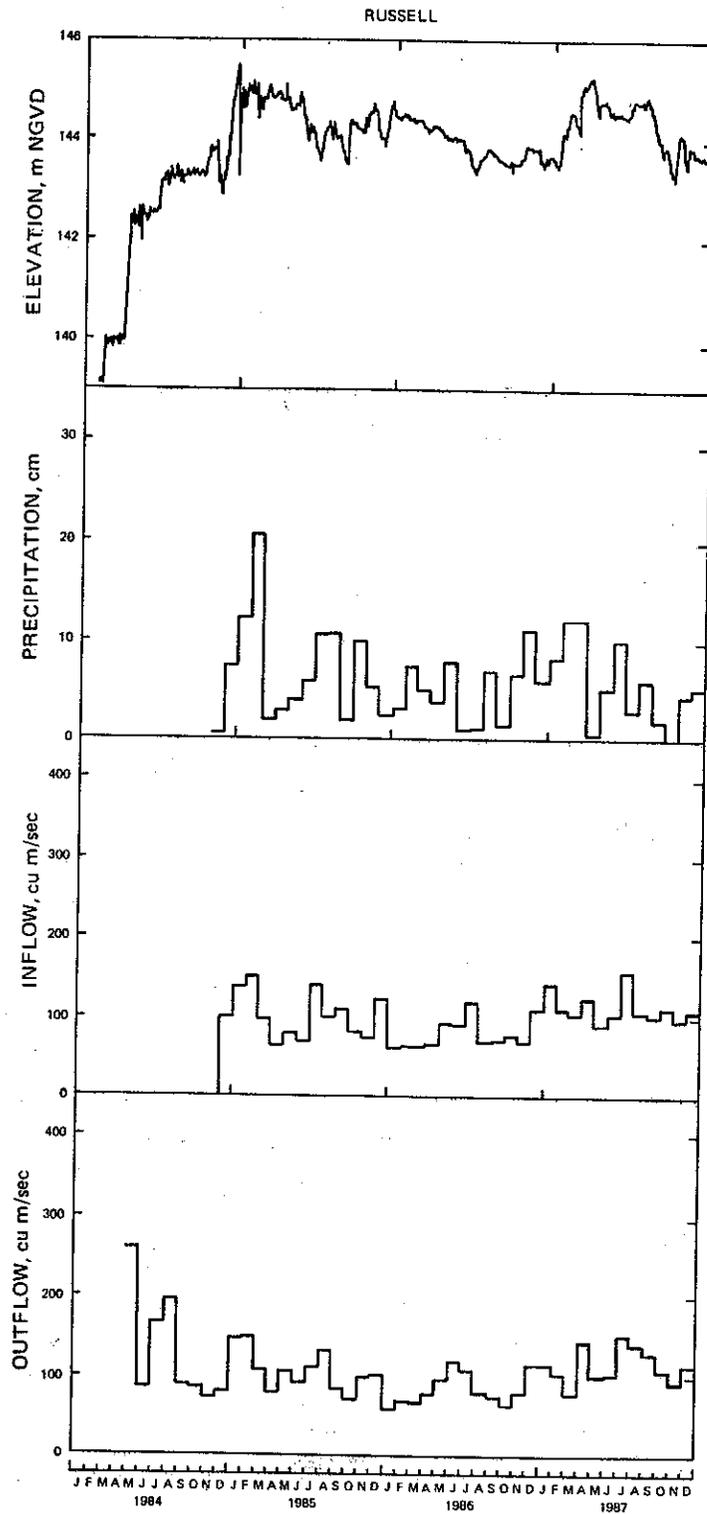


Figure 11. Pool elevation, precipitation, inflows, and outflows for Richard B. Russell Lake, 1984-1987

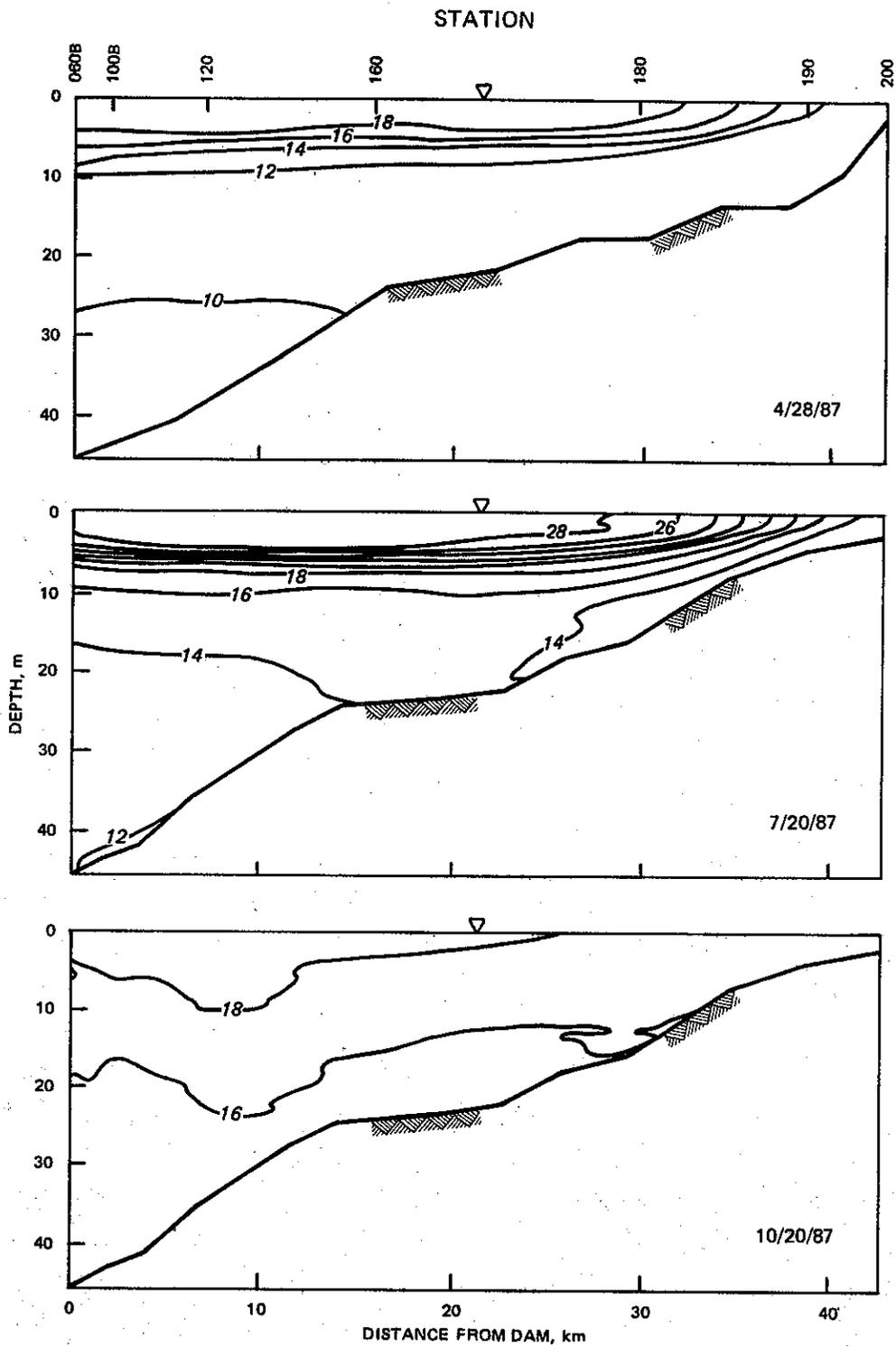


Figure 12. Patterns of spatial distribution of temperatures ($^{\circ}\text{C}$) in the main stem of Richard B. Russell Lake (April, July, and October 1987)

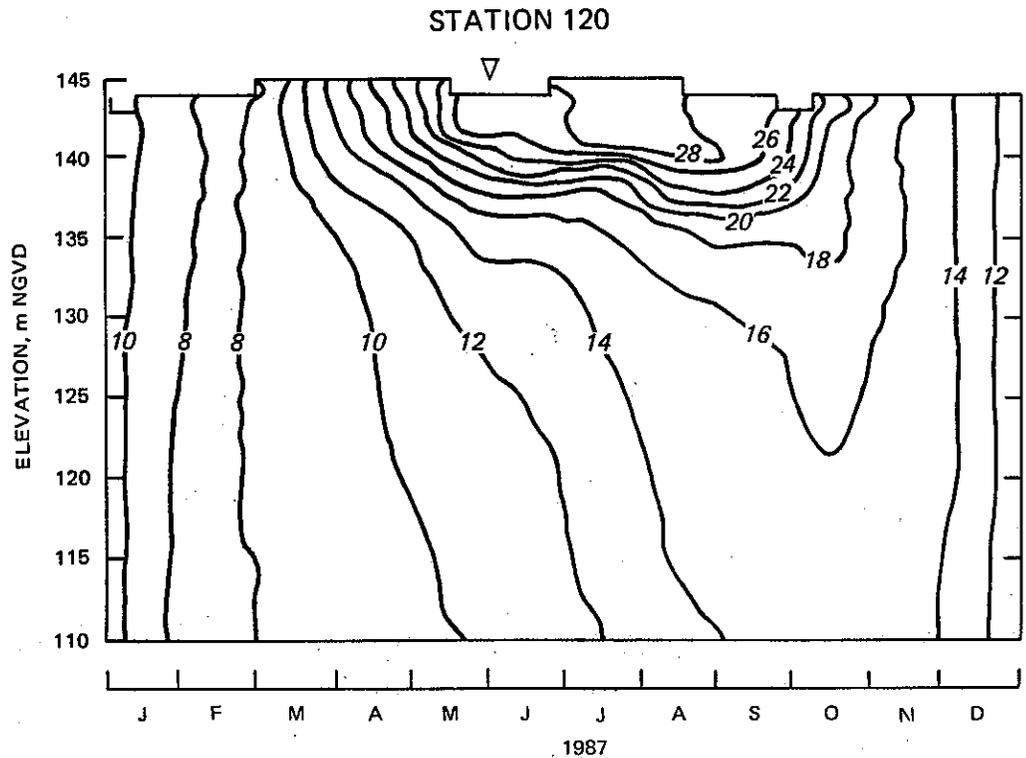


Figure 13. Temporal and vertical changes in temperature ($^{\circ}\text{C}$) in the lower region of Richard B. Russell Lake (Station 120)

27. Temporal and spatial gradients in DO were apparent along the main stem of the lake during the period of stratification (Figure 14). Dissolved oxygen concentrations, while remaining near 8 to 10 mg/l in the epilimnion of the lake, gradually declined in the hypolimnion in areas of the lake unaffected by the oxygenation system (i.e., upstream of Station 100B). Anoxic conditions in the main stem of the lake were confined to bottom waters in the region of the lake from Station 100B to Station 120. Data from Station 120 indicate that anoxic conditions in the hypolimnion were established by mid- to late May and continued until late October (Figure 15).

28. Increases in conductivity values were observed along the main stem of the lake coincident with the development of anoxic conditions (Figure 16). While conductivity levels were between 35 and 40 μS for most of the year, levels in the anoxic waters ranged from 40 to 60 μS due to increased concentrations of dissolved constituents released from the sediments in conjunction with anoxic processes.

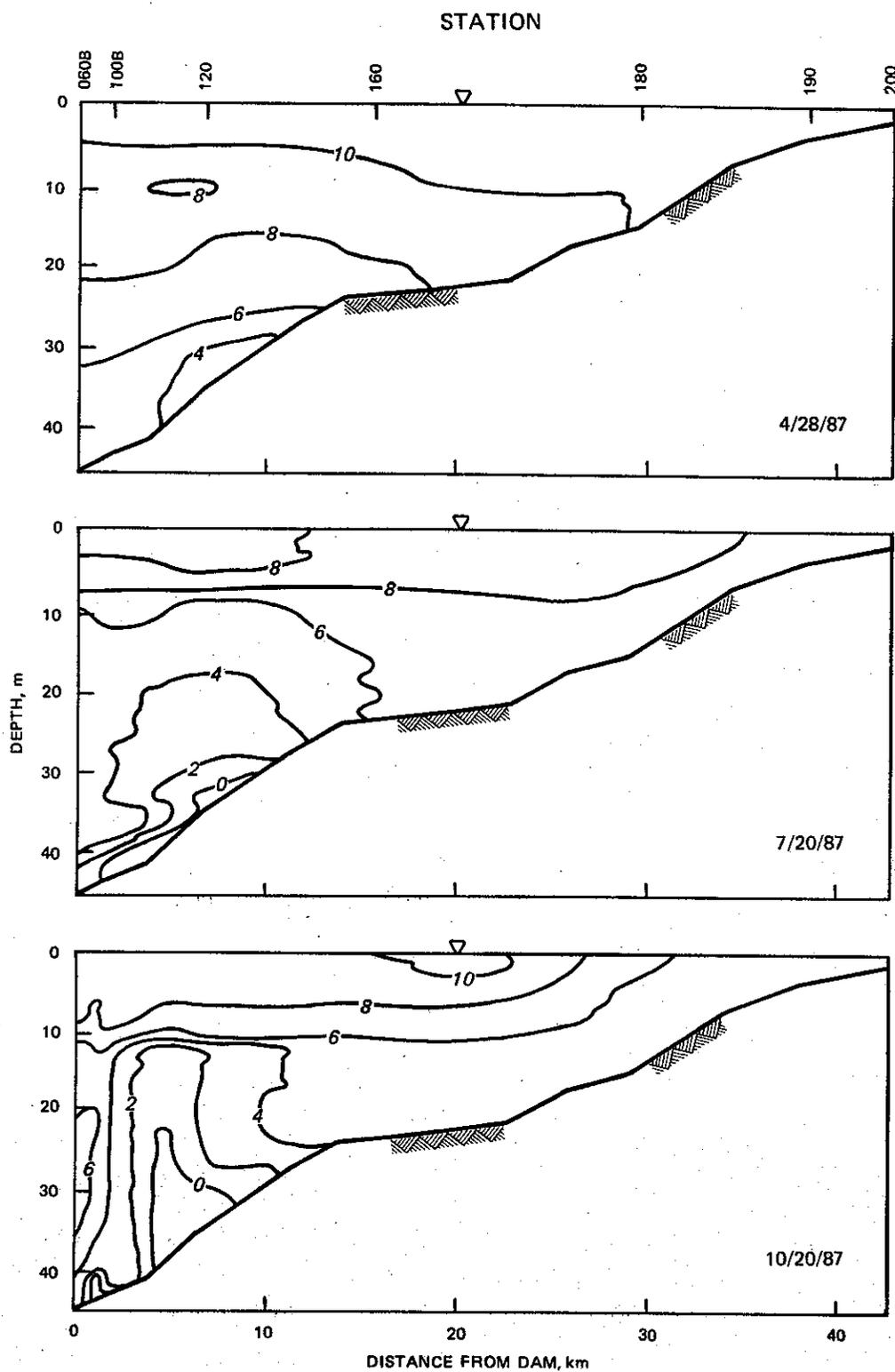


Figure 14. Patterns of spatial distribution of DO concentrations (mg/l) in the main stem of Richard B. Russell Lake (April, July, and October 1987)

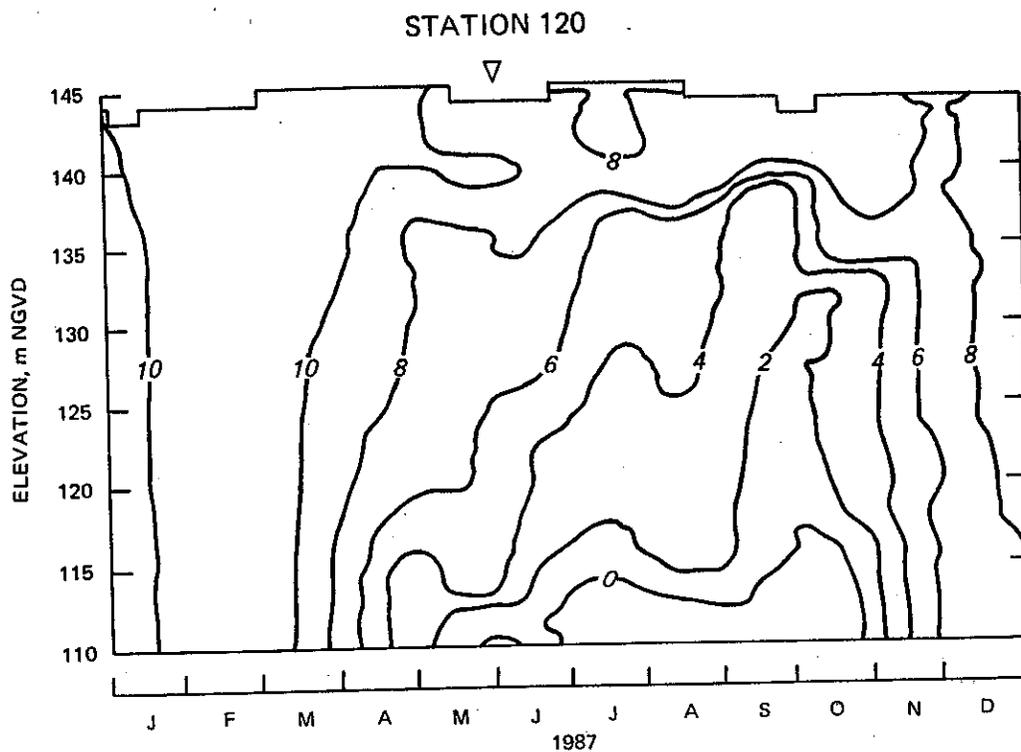


Figure 15. Temporal and vertical changes in DO concentrations (mg/l) in the lower region of Richard B. Russell Lake (Station 120)

29. Seasonal trends in the concentrations of chemical parameters were most pronounced during stratification. Maximum concentrations observed occurred in the bottom waters of the lower region of the lake coincident with anoxic conditions, resulting in both longitudinal and vertical concentration gradients. Total phosphorus and nitrogen concentrations ranged from 0.005 to 0.041 mg/l and from 0.50 to 1.46 mg/l, respectively, and displayed moderate longitudinal and vertical gradients (Figures 17 and 18).

30. Pronounced gradients in manganese concentrations were confined to anoxic regions of the lake. Concentrations of dissolved manganese ranged from the detection limit (0.05 mg/l) to 1.56 mg/l (Figure 19) and comprised the majority of the total manganese pool at all times. Seasonal development of vertical gradients in dissolved manganese concentration in the lower region of Richard B. Russell Lake (i.e., Station 100B) is depicted in Figure 20. Concentrations began to increase in bottom waters in late June, and peak concentrations were observed from July through November. Concentrations returned

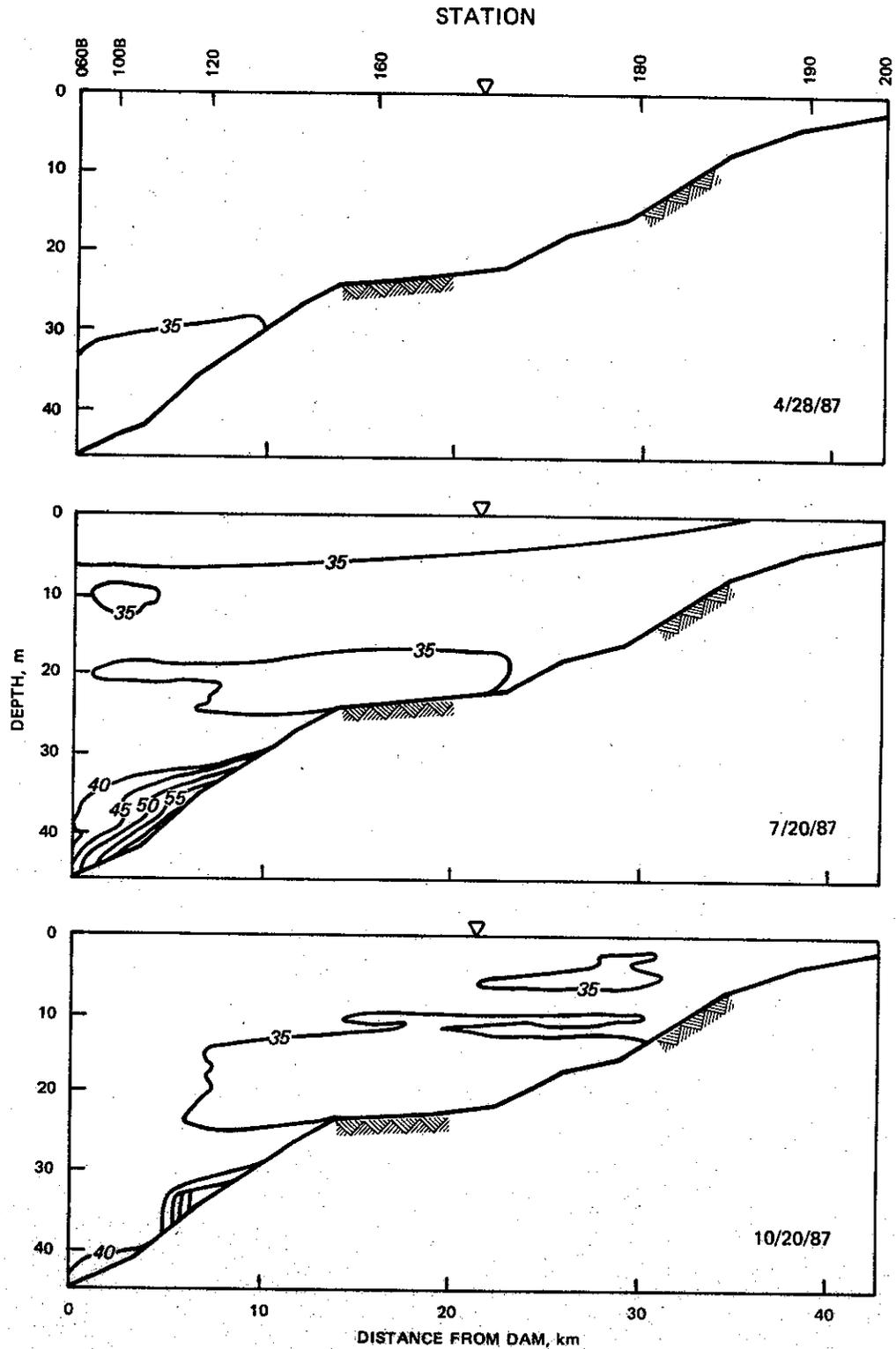


Figure 16. Patterns of spatial distribution of conductivity (μS) in the main stem of Richard B. Russell Lake (April, July, and October 1987)

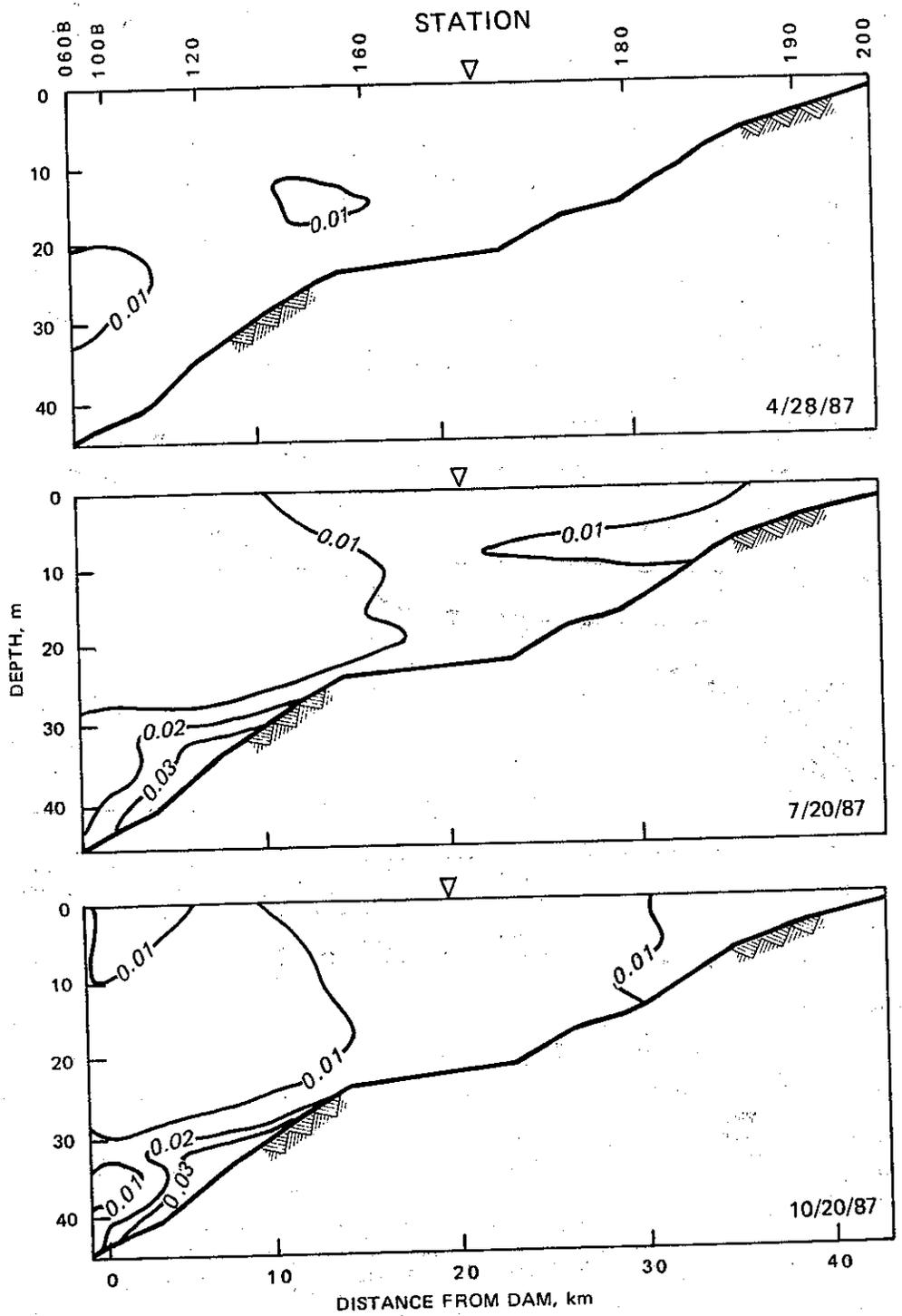


Figure 17. Patterns of spatial distribution of total phosphorus concentrations (mg/l) in the main stem of Richard B. Russell Lake (April, July, and October 1987)

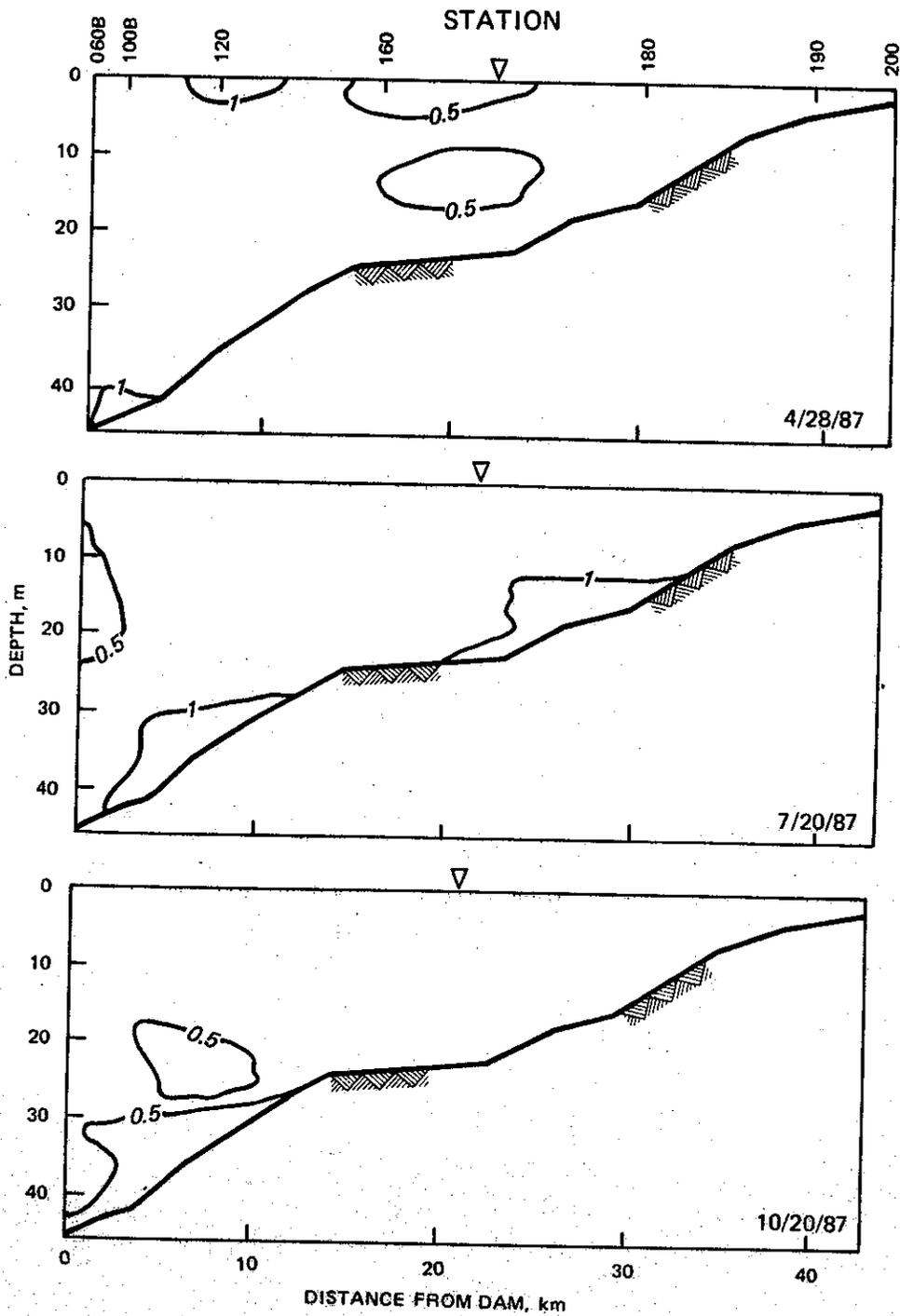


Figure 18. Patterns of spatial distribution of total nitrogen concentrations (mg/l) in the main stem of Richard B. Russell Lake (April, July, and October 1987)

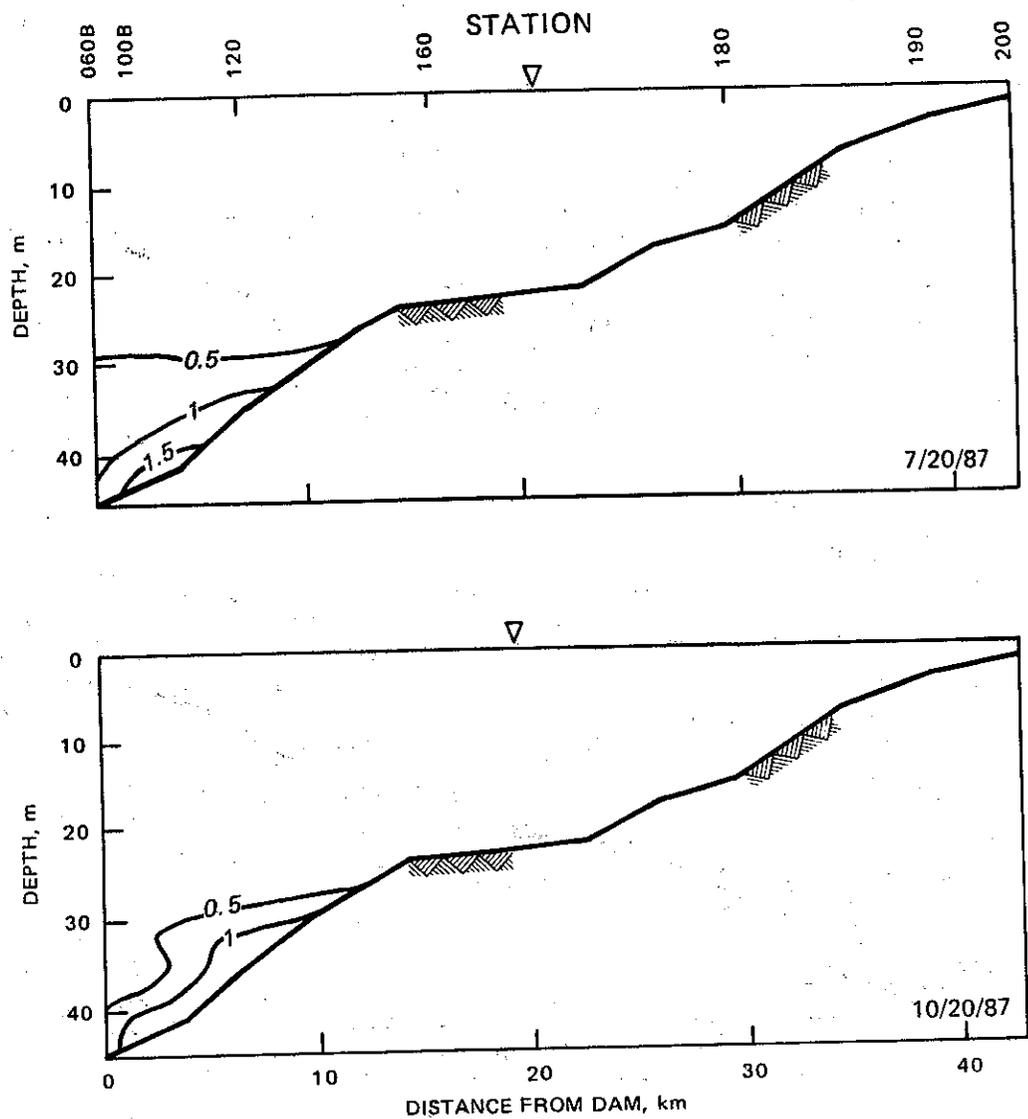


Figure 19. Patterns of spatial distribution of dissolved manganese concentrations (mg/l) in the main stem of Richard B. Russell Lake (July and October 1987)

to near-detection limits following the fall mixing. Concentrations greater than 0.50 mg/l were confined to depths greater than 30 m.

31. Gradients in dissolved iron concentrations coincided with anoxic conditions and were more pronounced than dissolved manganese concentration gradients (Figure 21). Dissolved iron concentrations ranged from the detection limit (0.05 mg/l) to greater than 4.0 mg/l; however, as with manganese concentrations greater than 0.5 mg/l were confined to depths greater than 30 m. Dissolved iron contributed to the majority of the total iron pool;

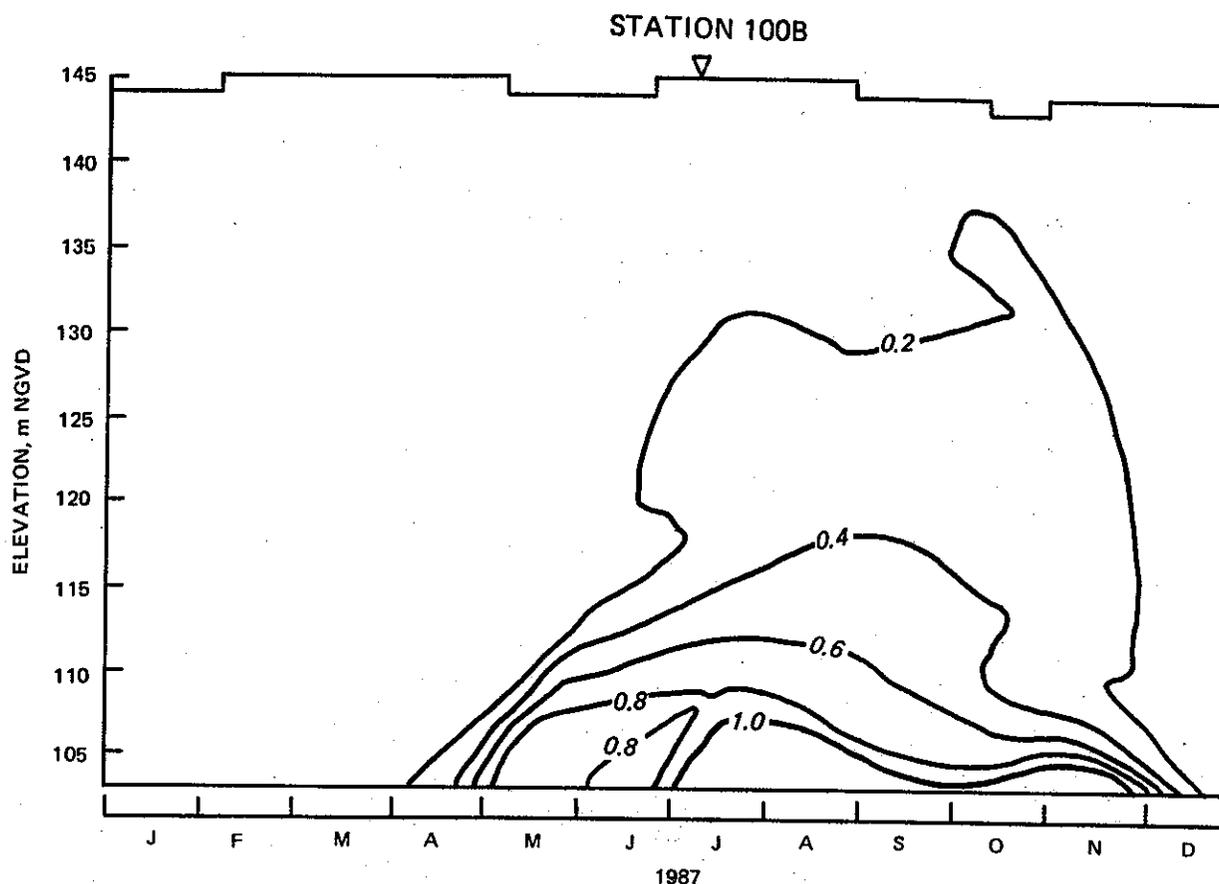


Figure 20. Temporal and vertical changes in dissolved manganese concentrations (mg/l) in the lower region of Richard B. Russell Lake (Station 100B)

however, pronounced concentrations of particulate iron were observed in the lower region of the lake (Figure 22). Additionally, vertical gradients in particulate iron were observed seasonally throughout the lower region of the lake (Figure 23).

32. Water quality conditions in tributary embayments during the period of thermal stratification were more pronounced than those observed in the lower region of the lake. While seasonal development of hypolimnetic anoxia in the tributary embayments was similar to that of the main stem of the lake, the magnitude of anoxic conditions in the embayments was greater (i.e., Station 130; Figure 24). Additionally, maximum observed concentrations of manganese, iron, carbon, nitrogen, and phosphorus occurred at embayment stations (Stations 130, 140, and 150; Table 5).

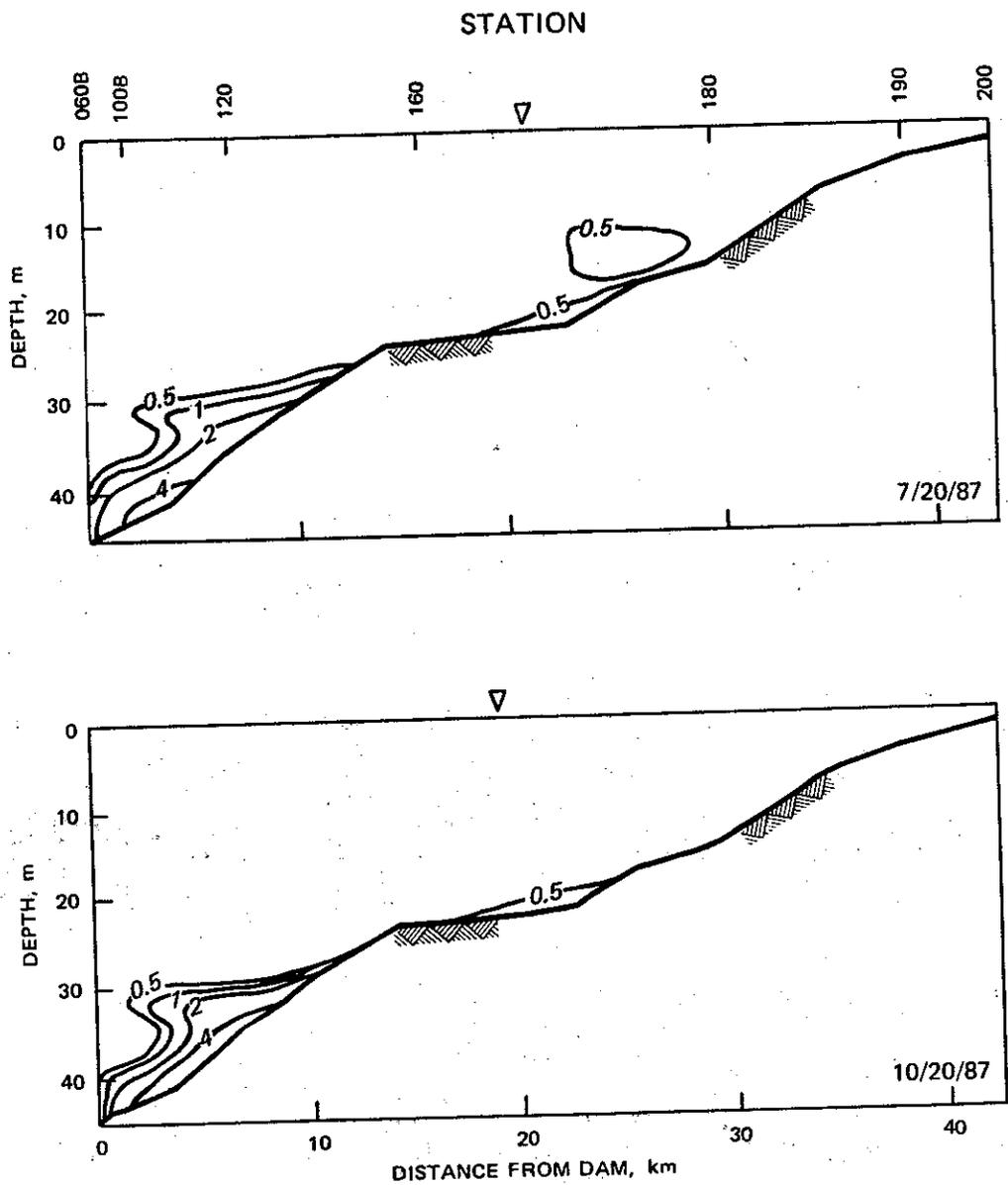


Figure 21. Patterns of spatial distribution of dissolved iron concentrations (mg/l) in the main stem of Richard B. Russell Lake (July and October 1987)

33. Temperature and DO concentrations in release waters from Richard B. Russell Dam (i.e., Station 050; Figure 25) displayed seasonal trends reflective of changing conditions in the Richard B. Russell Lake forebay. Temperatures gradually increased from approximately 8° to 10° C during February through March to 15° to 16° C during September through November. Dissolved oxygen concentrations were between 11 and 8 mg/l from January through April remained near 6 mg/l May through mid-November, due to operation of the

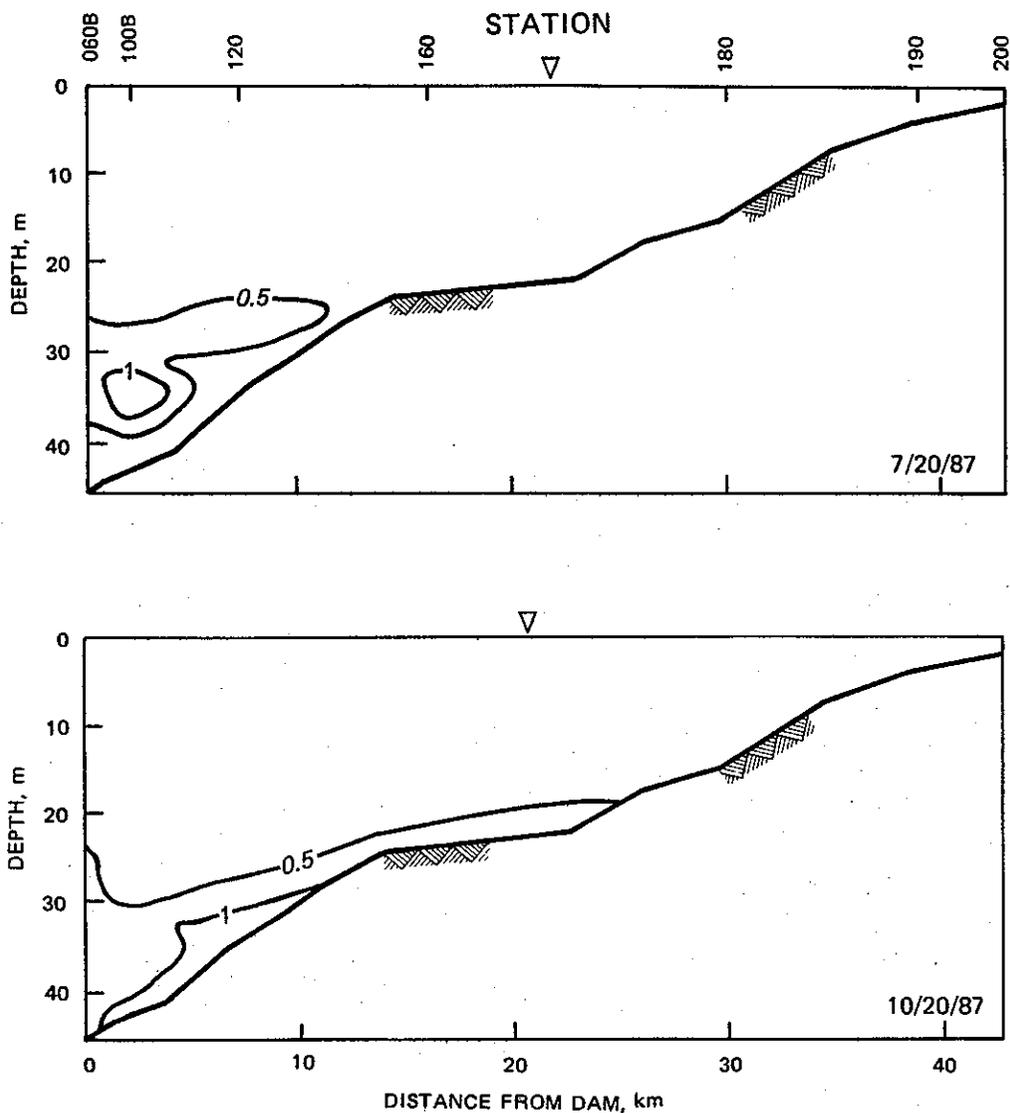


Figure 22. Patterns of spatial distribution of particulate iron concentrations (mg/l) in the main stem of Richard B. Russell Lake (July and October 1987)

oxygenation system, and gradually returned to near 8 to 10 mg/l during November and December, coincident with fall mixing in Richard B. Russell Lake.

34. Moderate seasonal trends in chemical parameter concentrations were observed in release waters and were reflective of conditions in the Richard B. Russell Lake forebay. Manganese and iron concentrations ranged from 0.2 to 0.3 mg/l and from 0.2 to 0.4 mg/l, respectively, from June through November. In general, dissolved manganese and particulate iron comprised the majority of

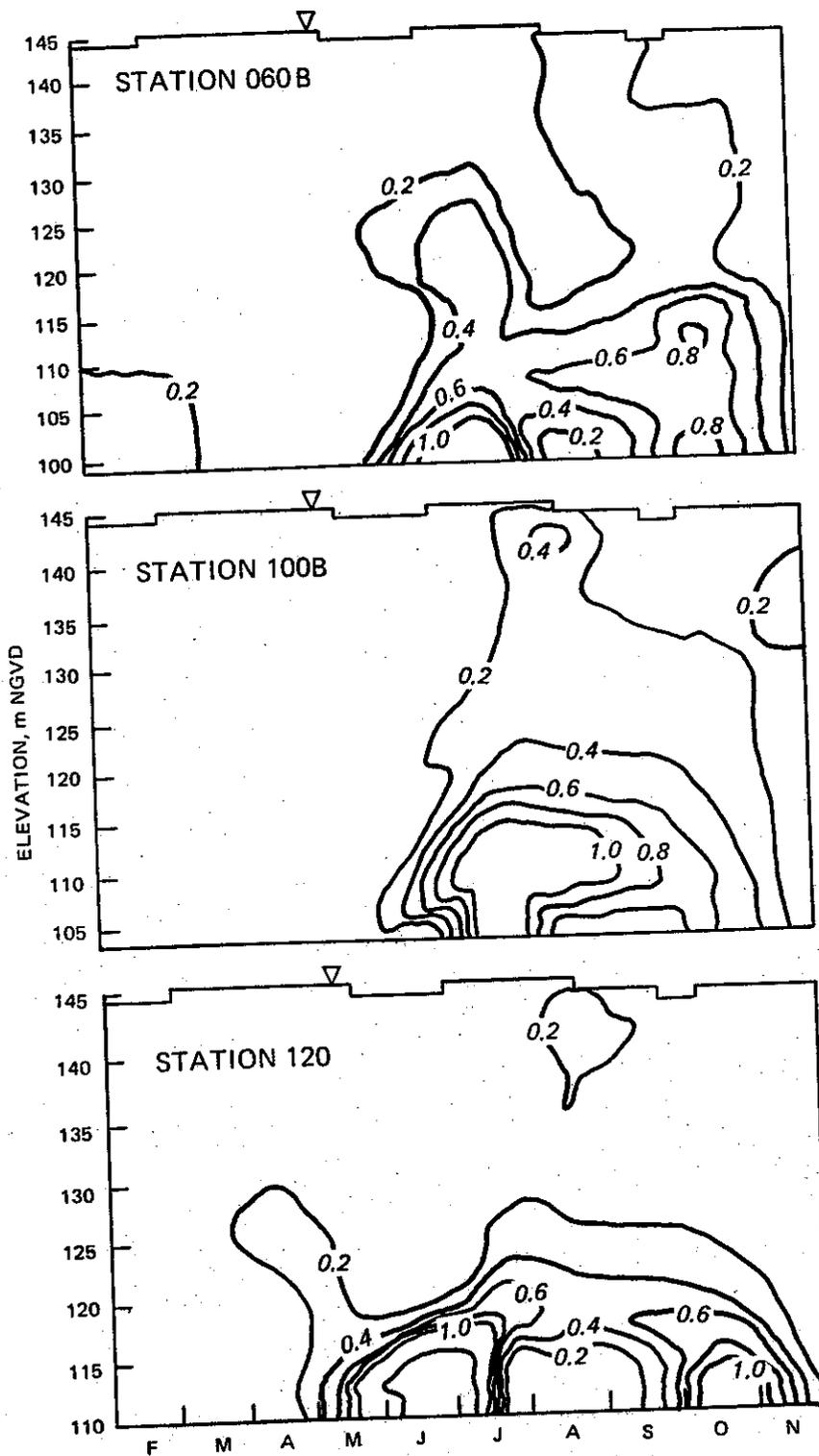


Figure 23. Temporal and vertical changes in particulate iron concentrations (mg/l) in the forebay and lower region of Richard B. Russell Lake

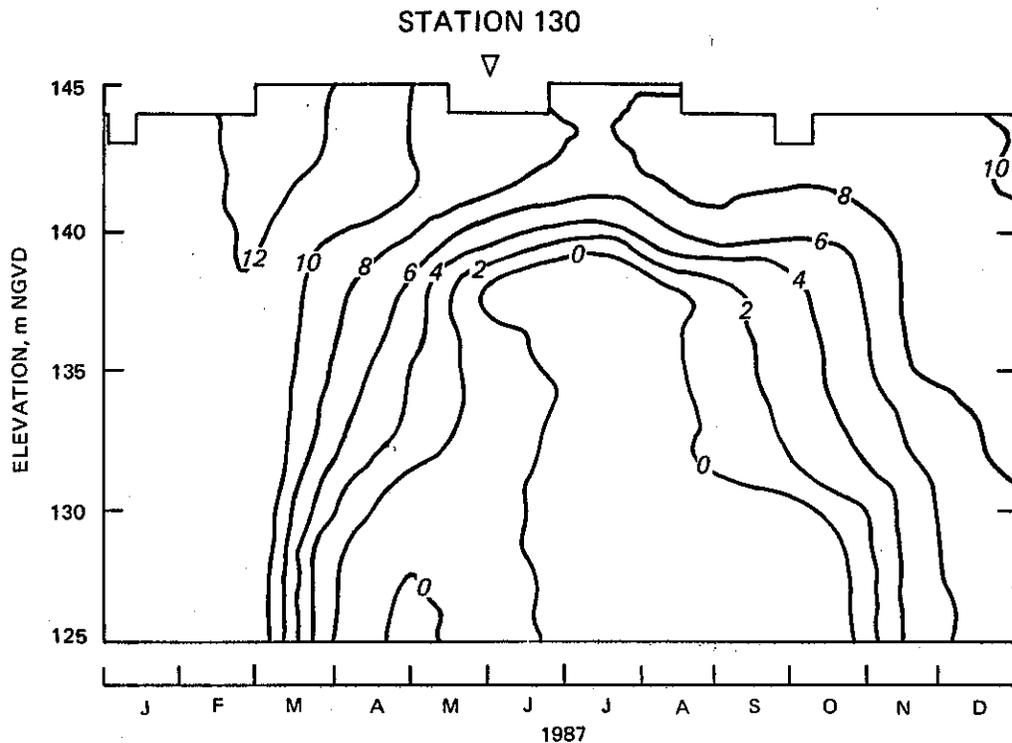


Figure 24. Temporal and vertical changes in DO concentrations (mg/l) in the Beaverdam Creek embayment (Station 130)

the total manganese and iron pools, respectively, in the release waters (Figure 25).

35. Moderate seasonal trends for other parameters in release waters were apparent. Maximum nitrogen concentrations were observed in the spring and summer and ranged from 0.86 to 0.76 mg/l (April and July, respectively). Minimum nitrogen concentrations occurred following the fall mixing and during winter and ranged from 0.46 to 0.29 mg/l (October and February, respectively). Dissolved forms of nitrogen comprised the majority of the total nitrogen pool in release waters at all times. Observed values of conductivity, pH, alkalinity, carbon, and phosphorus were similar to values in the forebay, and seasonal trends were less pronounced.

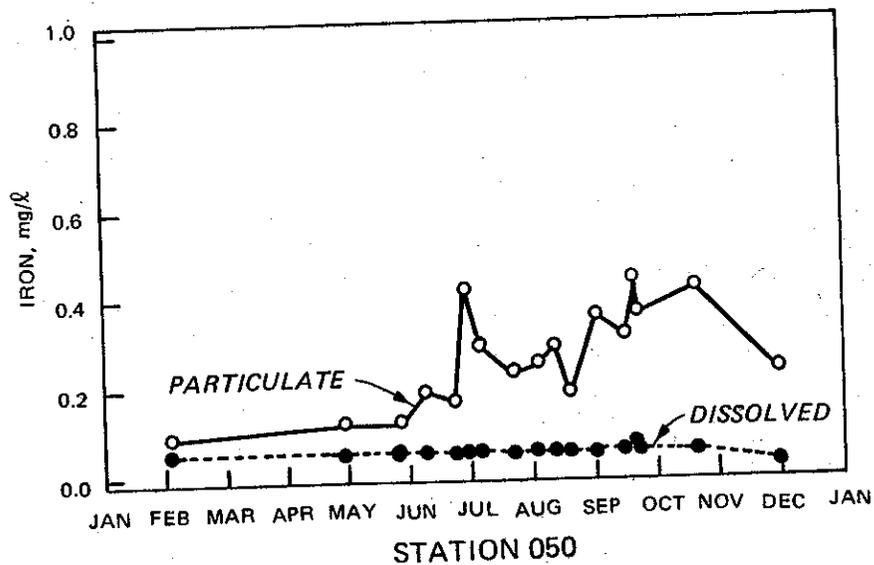
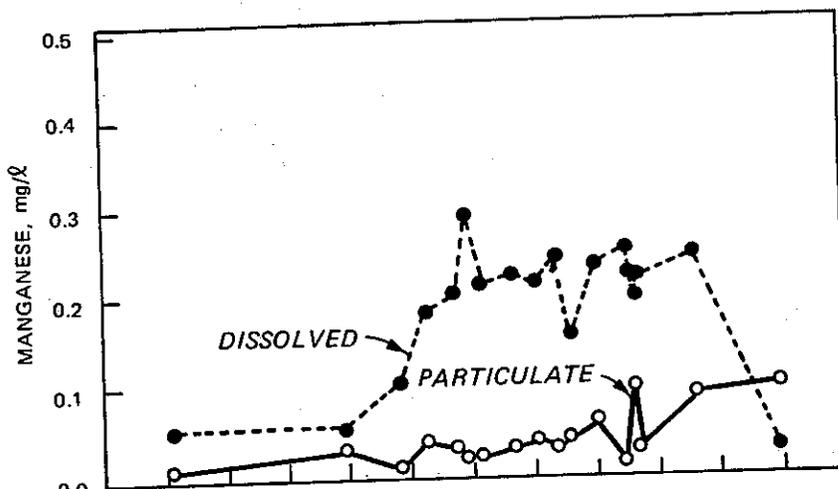
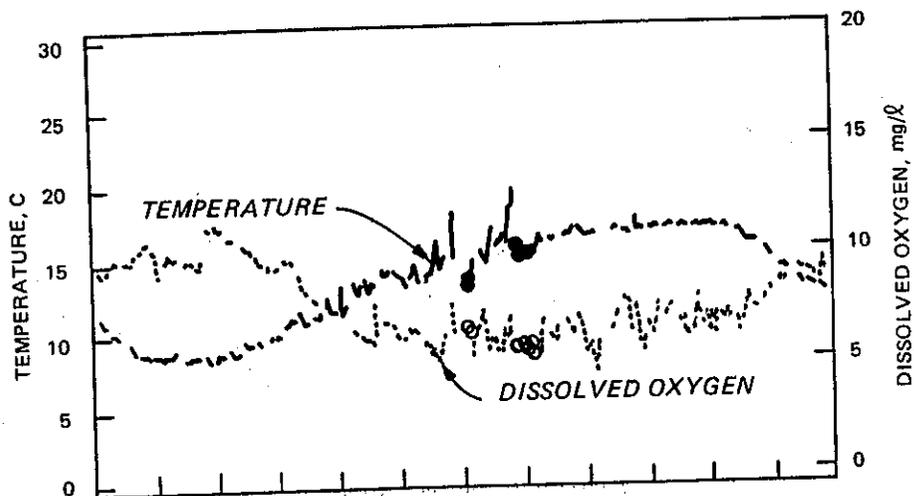


Figure 25. Temperatures and DO, manganese, and iron concentrations in Richard B. Russell Dam releases (Station 050) (1987)

J. Strom Thurmond Lake

36. Pool elevation, monthly precipitation, mean daily inflow, and mean daily outflow for J. Strom Thurmond Lake during the period 1984-1987 are depicted in Figure 26. While pool elevations returned to near-normal levels early in 1987, decreased precipitation and inflow levels and operational requirements resulted in low pool elevations from June through December.

37. Seasonal patterns in thermal structure were observed along the main stem of J. Strom Thurmond Lake (Figure 27). Thermal stratification was present from J. Strom Thurmond Dam to the headwater region (Stations 020 to 050) from April through September. Monthly temperature data from Station 020, located in the lower region of J. Strom Thurmond Lake, depict the seasonal pattern of thermal development in the lake (Figure 28). Thermal stratification began in late April with a well-established thermocline observed by mid-May. The thermocline remained near a depth of 6 to 8 m throughout the season. Temperatures in the epilimnion were between 20° and 30° C, and hypolimnetic temperatures were between 14° and 16° C, during most of the period of stratification. Seasonal cooling in late September and early October reduced surface water temperatures and gradually weakened the thermocline. Continued cooling and wind-induced mixing resulted in complete mixing and near-isothermal conditions by mid-October.

38. Temporal and spatial gradients in DO were apparent along the main stem of the lake during the period of stratification (Figure 29). Dissolved oxygen concentrations, while remaining near 8 mg/l in the epilimnion of the lake, gradually declined in the hypolimnion in the lower region of the lake. Anoxic conditions in the hypolimnion of the lower region of the lake (i.e., Station 020) were established by mid- to late August and continued until late October (Figure 30a). Conversely, DO concentrations in the midregion of the lake did not decline below 2.0 mg/l (Figure 30b).

39. Increases in conductivity were observed along the main stem of the lake coincident with the development of anoxic conditions (Figure 31). While conductivity levels were between 40 and 45 μ S for most of the year, levels in the anoxic waters ranged from 50 to 60 μ S, due to increased concentrations of dissolved constituents.

40. Seasonal trends in manganese distribution were most apparent during stratification. Dissolved manganese concentrations, in the main stem, ranged

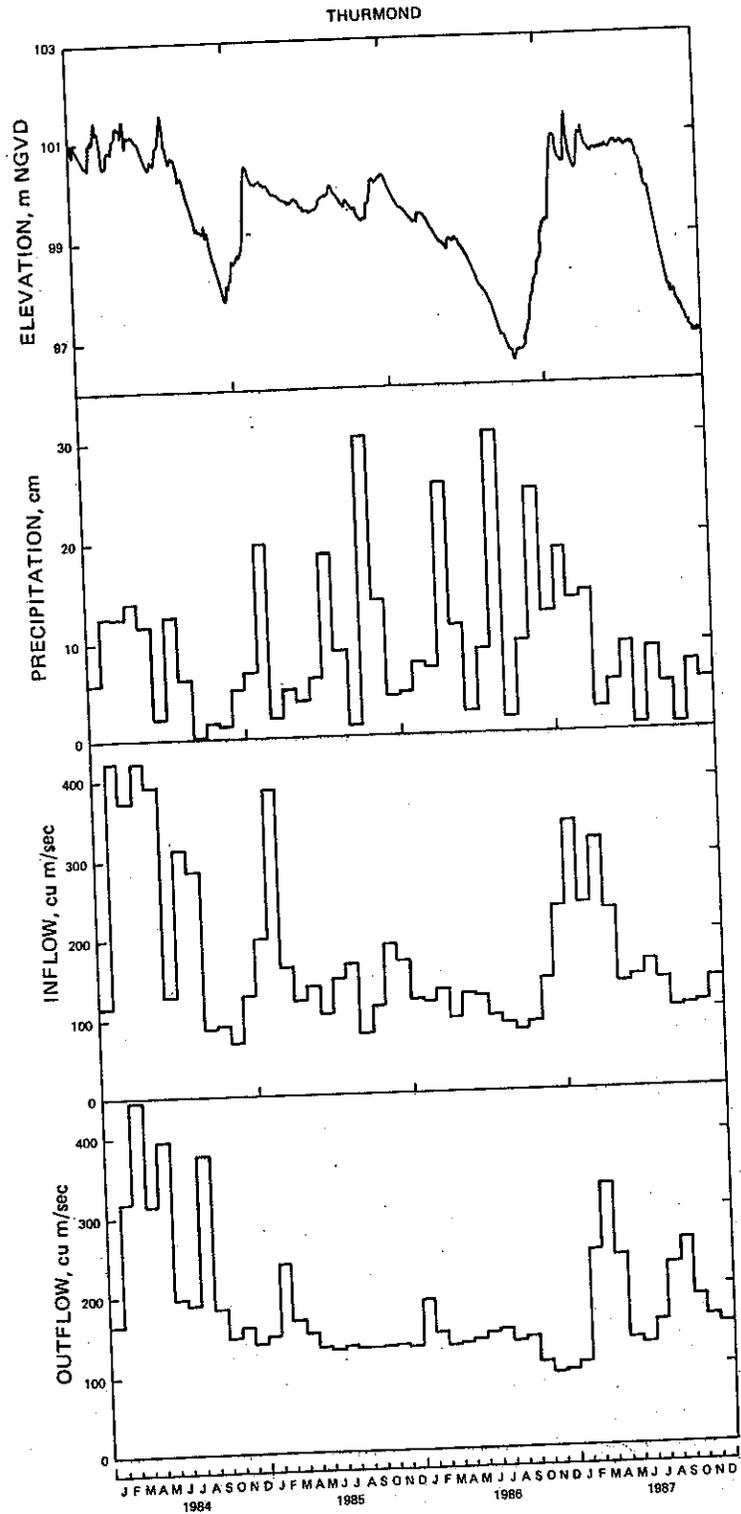


Figure 26. Pool elevation, precipitation, inflows, and outflows for J. Strom Thurmond Lake, 1984-1987

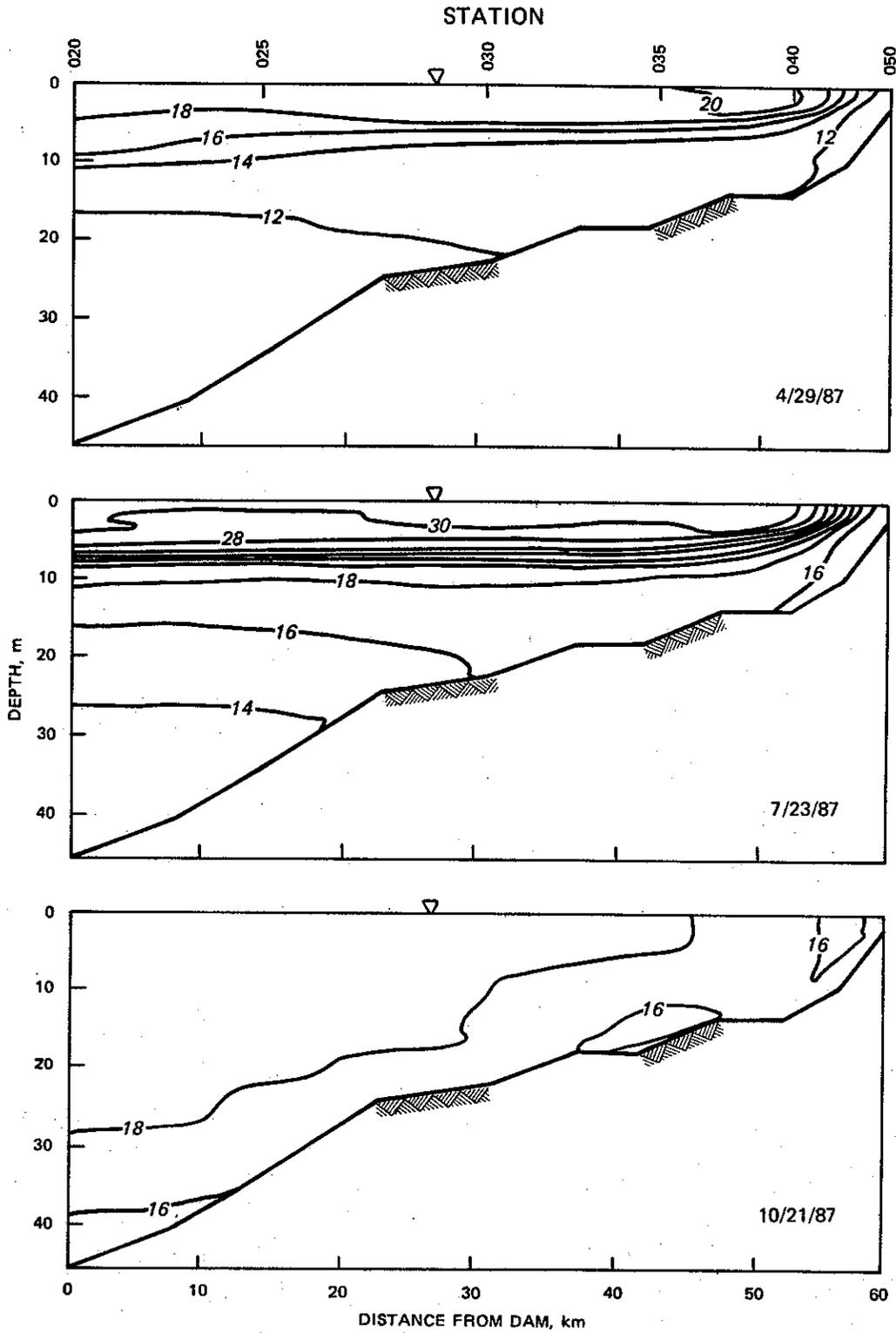


Figure 27. Patterns of spatial distribution of temperatures ($^{\circ}\text{C}$) in the main stem of J. Strom Thurmond Lake (April, July, and October 1987)

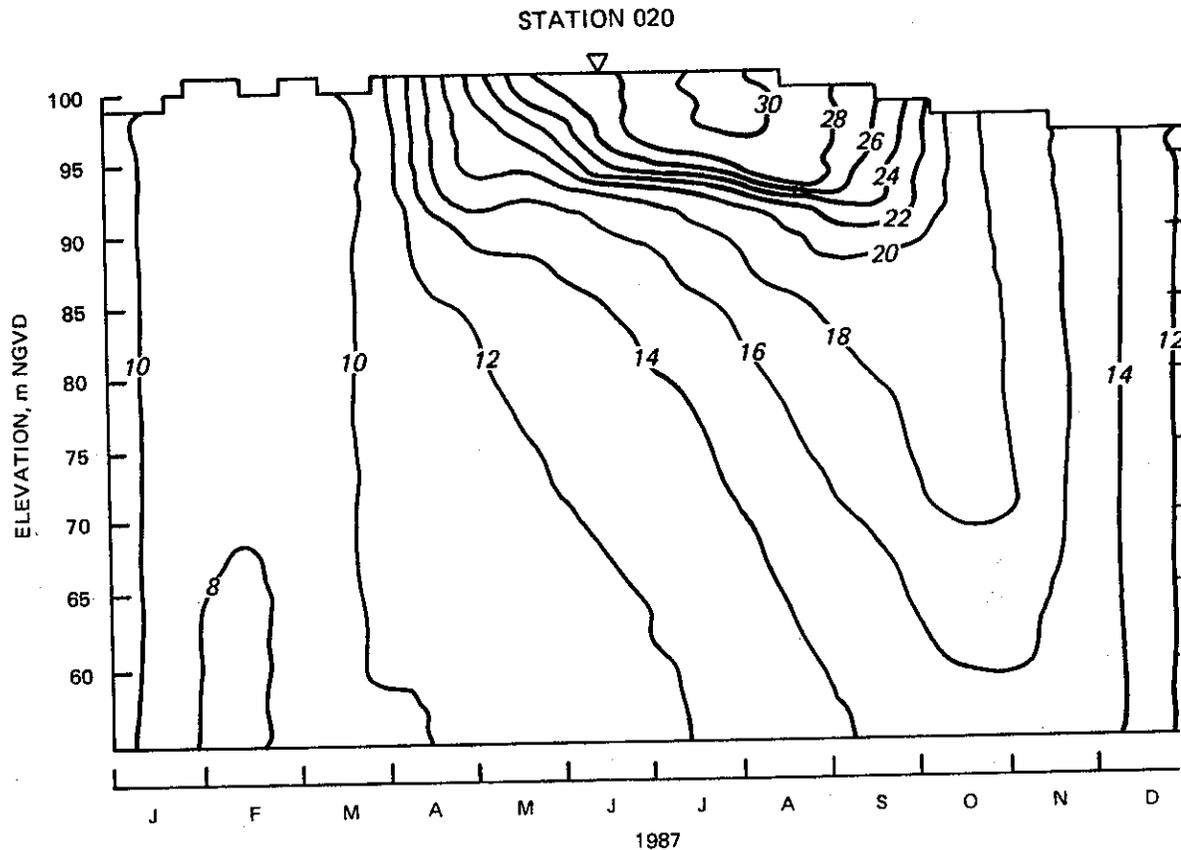


Figure 28. Temporal and vertical changes in temperature ($^{\circ}\text{C}$) in the forebay of J. Strom Thurmond Lake (Station 020)

from the detection limit (0.05 mg/l) to 4.57 mg/l and comprised the majority of the total manganese pool at all times (Figure 32). While pronounced concentration gradients were confined to depths greater than 30 m, concentrations between 0.5 and 1.0 mg/l were observed at depths up to 15 m in the midregion of the lake during July. Seasonal development of vertical gradients in manganese concentrations in J. Strom Thurmond Lake is depicted in Figure 33. Concentrations of dissolved manganese began to increase in bottom waters in June, were at peak concentrations from July through early October, and returned to levels near the detection limit (0.05 mg/l) following fall mixing. Additionally, concentrations of particulate manganese were observed in the upper region of the lake during the same period (Figure 33).

41. Gradients in dissolved iron concentrations (Figure 34a) coincided with anoxic conditions and were less pronounced than dissolved manganese

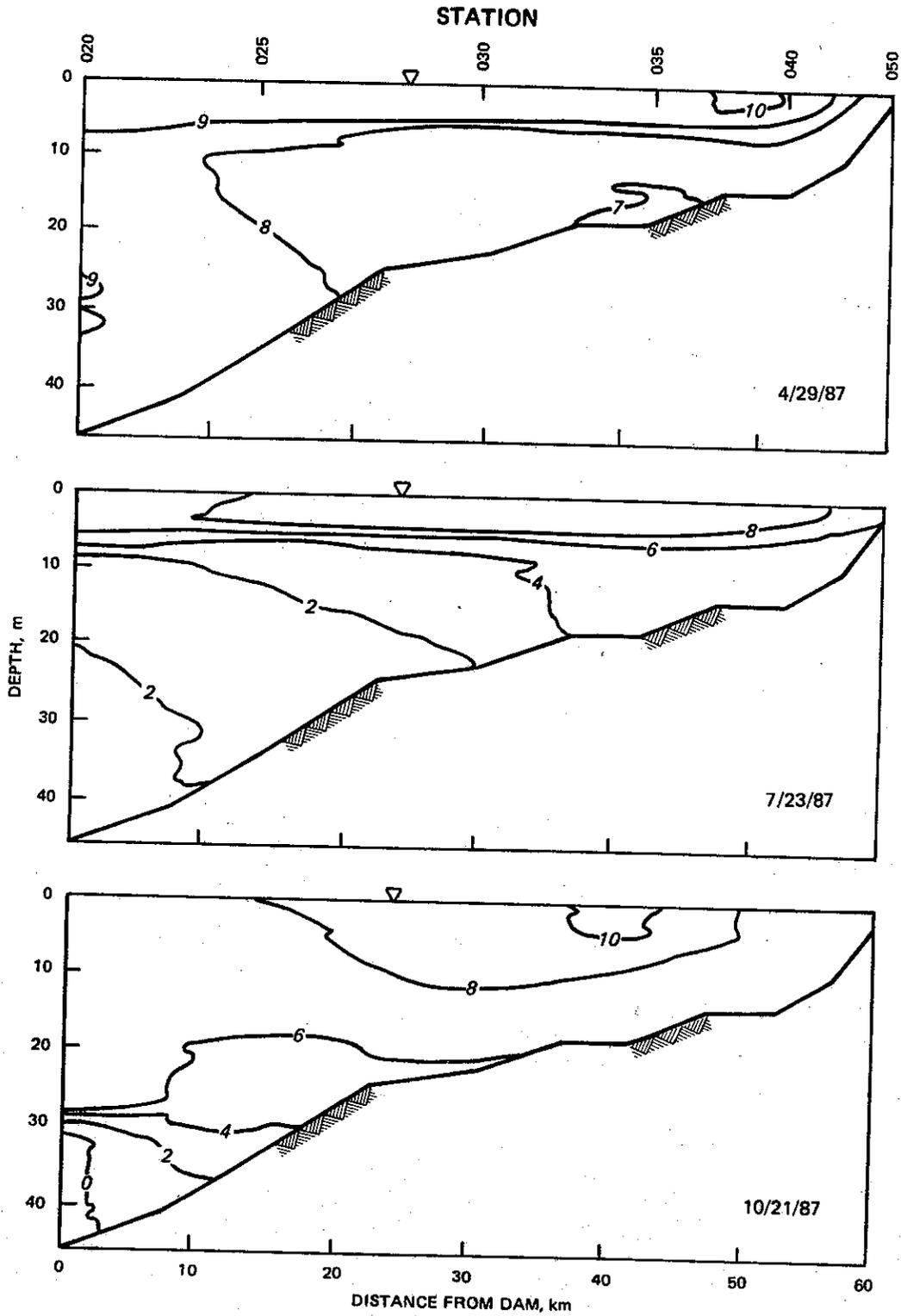
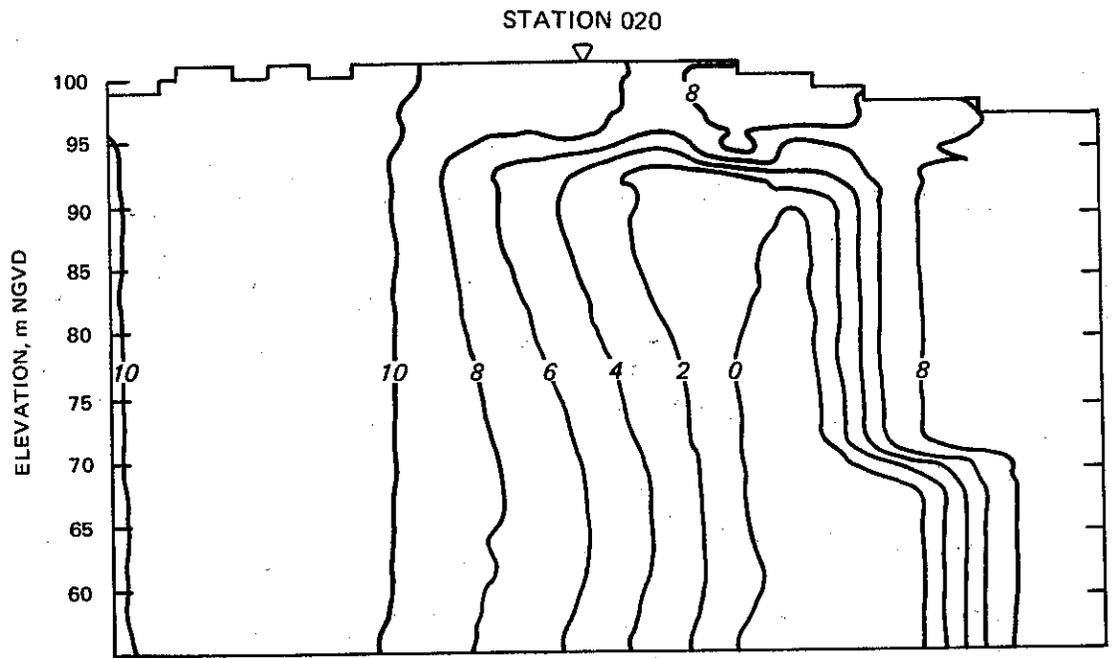
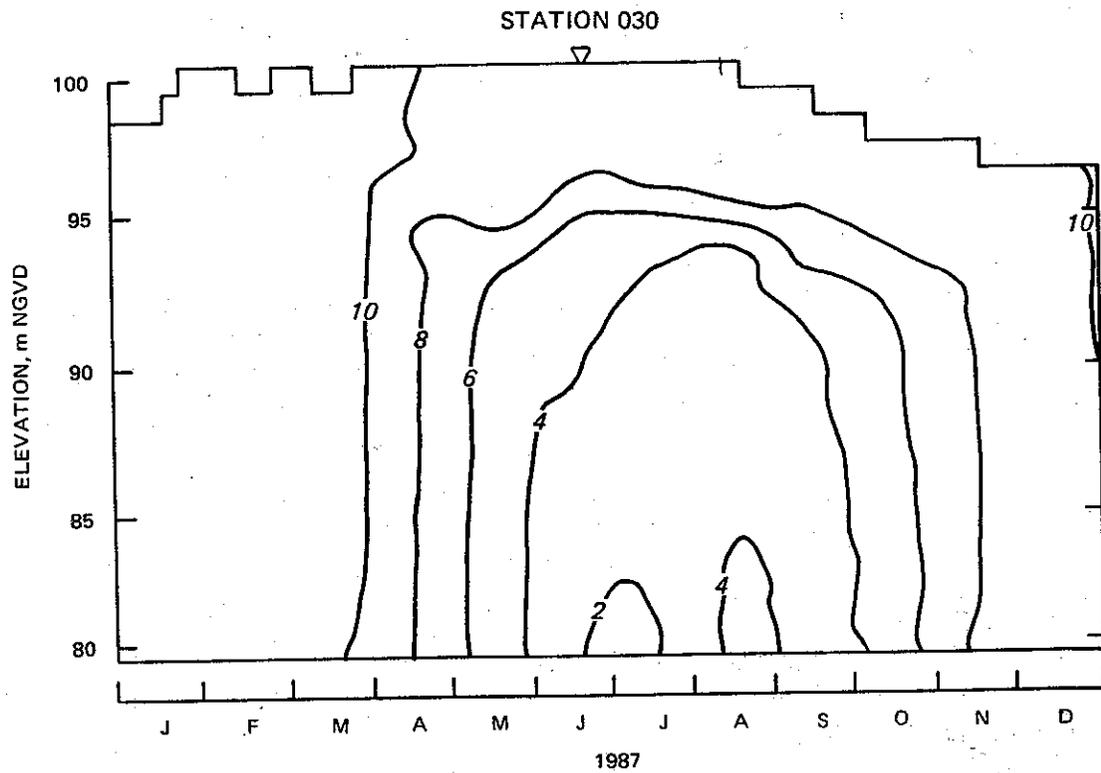


Figure 29. Patterns of spatial distribution of DO concentrations (mg/l) in the main stem of J. Strom Thurmond Lake (April, July, and October 1987)



a. Forebay



b. Midlake region

Figure 30. Temporal and vertical changes in DO concentrations (mg/l) in the forebay (Station 020) and midlake region (Station 030) of J. Strom Thurmond Lake

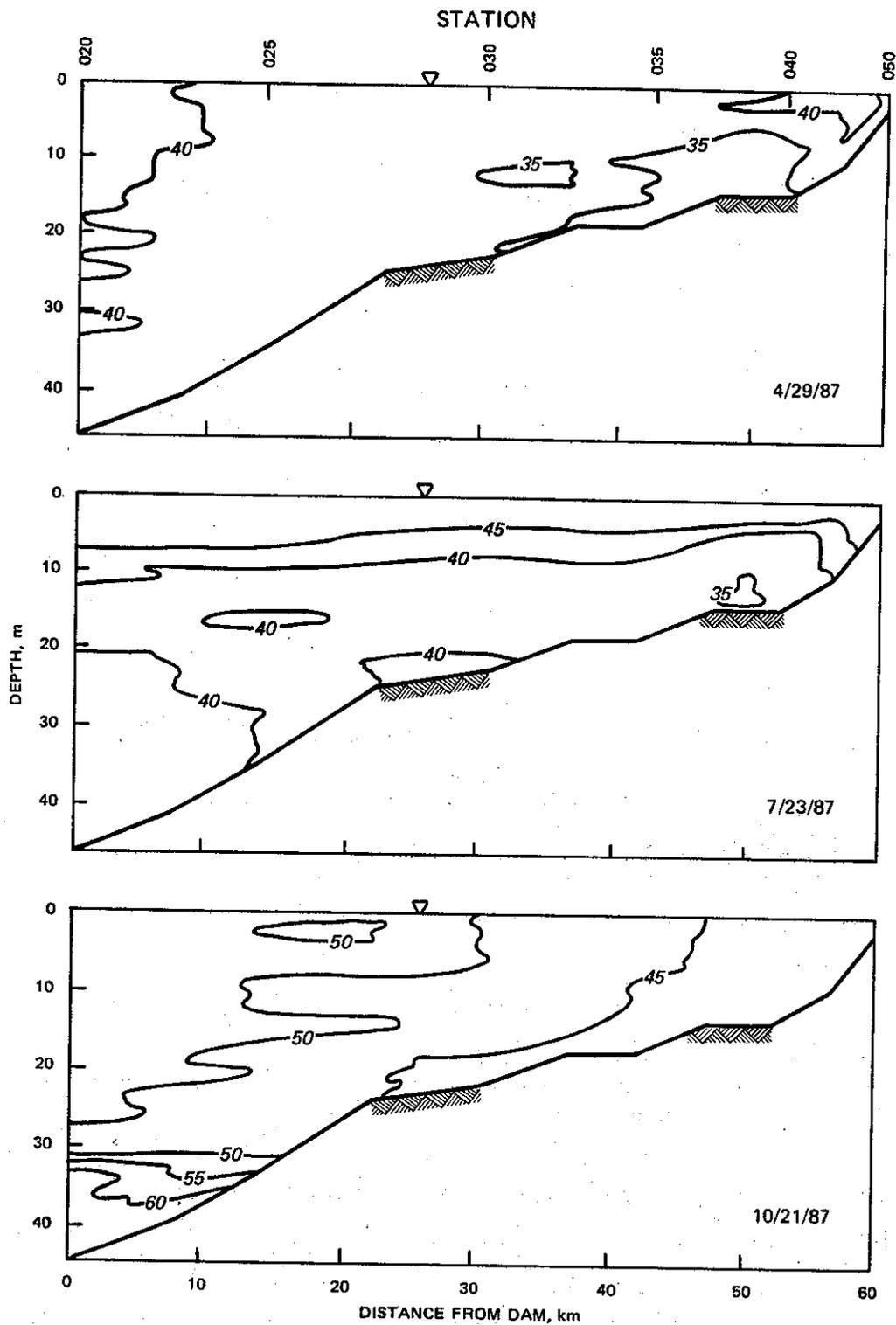


Figure 31. Patterns of spatial distribution of specific conductance (μS) in the main stem of J. Strom Thurmond Lake (April, July, and October 1987)

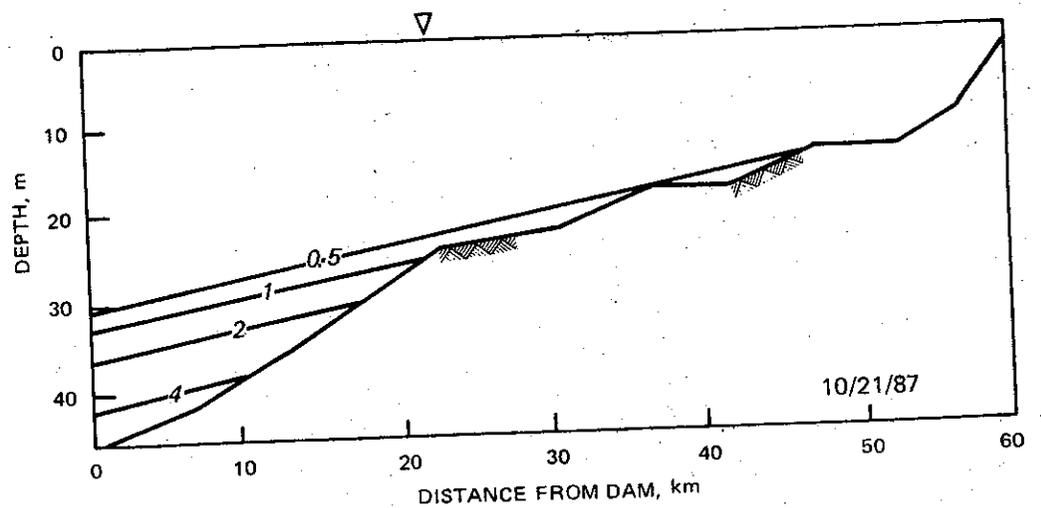
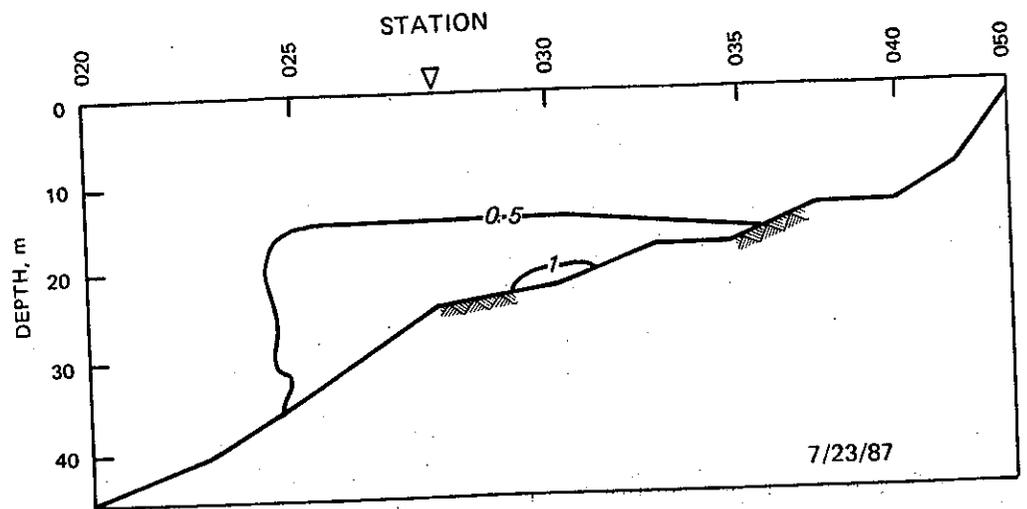


Figure 32. Patterns of spatial distribution of dissolved manganese concentrations (mg/l) in the main stem of J. Strom Thurmond Lake (July and October 1987)

concentration gradients. Dissolved iron concentrations, ranging from the detection limit (0.05 mg/l) to 1.13 mg/l, comprised the majority of the iron pool in the anoxic region of the main stem of the lake. Conversely, particulate iron ranged from 0.5 to 1.09 mg/l (Figure 34b) and comprised the majority of the total iron pool in the mid to upper region of the lake, which was not anoxic.

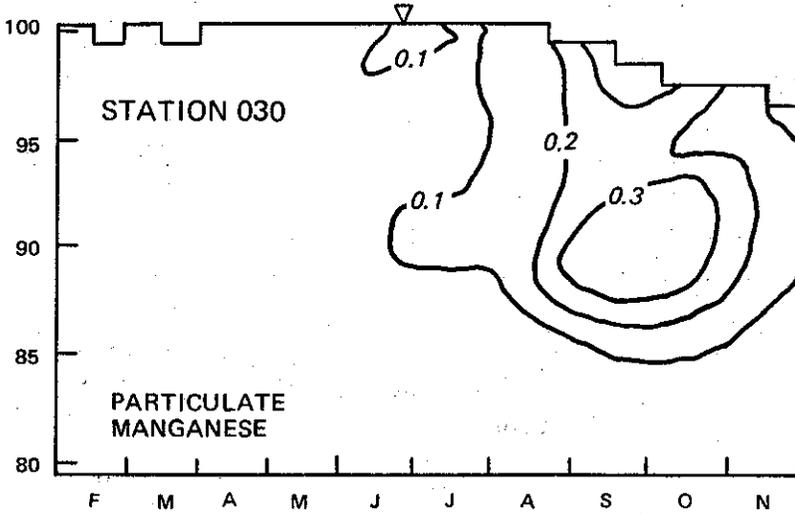
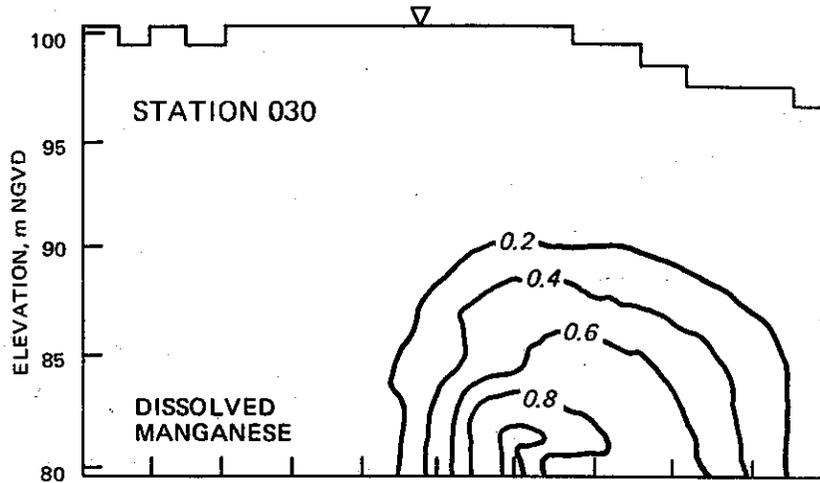
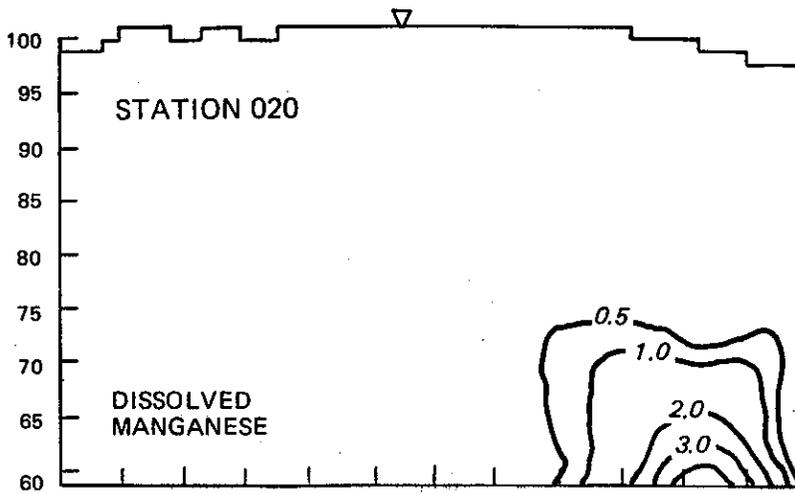
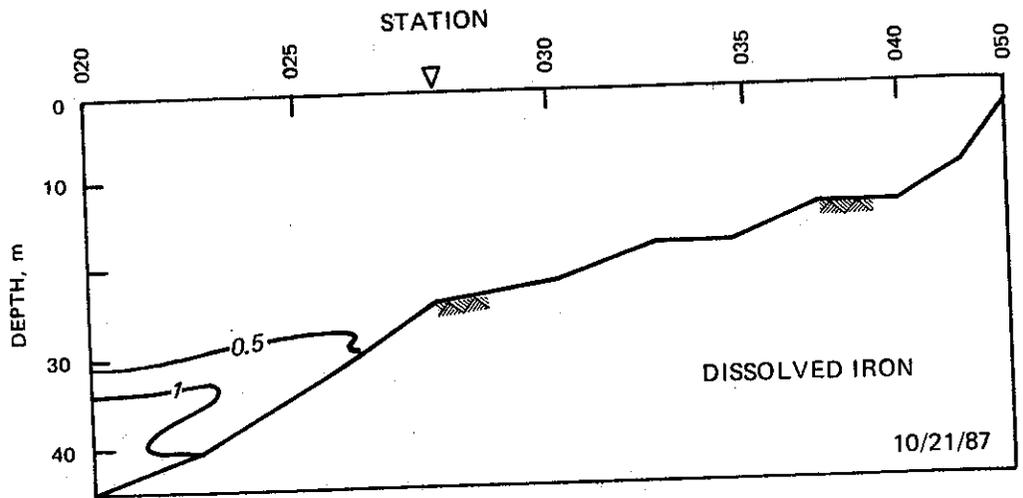
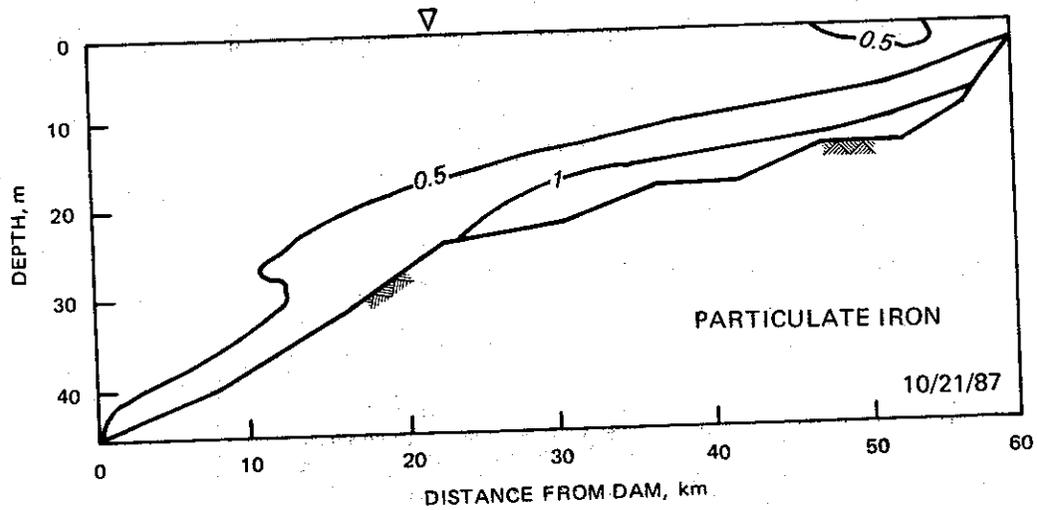


Figure 33. Temporal and vertical changes in manganese concentrations (mg/l) in the forebay (Station 020) and midlake region (Station 030) of J. Strom Thurmond Lake

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a. Dissolved iron, mg/l



b. Particulate iron, mg/l

Figure 34. Patterns of spatial distribution of dissolved and particulate iron concentrations in the main stem of J. Strom Thurmond Lake (October 1987)

42. Concentrations of total phosphorus, nitrogen, and organic carbon ranged from 0.005 mg/l to 0.044 mg/l, from 0.32 to 1.25 mg/l, and from 1.4 to 3.8 mg/l, respectively, and pronounced gradients were not observed in the main stem of the lake. Seasonal variation was most pronounced for nitrogen concentrations, with maximum values observed in April and July; minimum values occurred in February and October.

43. As was observed in Richard B. Russell Lake, water quality conditions in tributary embayments, during the period of thermal stratification, were more pronounced than those observed in the lower region of the lake. Maximum observed concentrations of total iron (6.2 mg/l), organic carbon (6.6 mg/l), nitrogen (1.4 mg/l), and phosphorus (0.125 mg/l) occurred at embayment stations. Additionally, increased concentrations of manganese (3.5 mg/l) and iron (1.9 mg/l) were observed at Station 036 in the Broad River embayment, which contributes approximately 30 percent of the inflow to J. Strom Thurmond Lake.

44. Temperature and DO concentrations in release waters from J. Strom Thurmond Dam (i.e., Station 010; Figure 35) displayed seasonal trends and were reflective of conditions in the J. Strom Thurmond Lake forebay. Temperatures gradually increased from 9° to 10° C (February through March) to 18° to 20° C (September through November). Dissolved oxygen concentrations remained between 11 and 8 mg/l from January through May, declined to less than 2 mg/l July through September, and gradually returned to near 8 to 10 mg/l during October, November, and December, coincident with fall mixing in J. Strom Thurmond Lake.

45. Moderate seasonal trends in chemical concentrations were observed in release waters and were reflective of conditions in the J. Strom Thurmond Lake forebay. Maximum total manganese concentrations (0.3 mg/l) were observed during September, and dissolved manganese comprised the majority of the total manganese pool in the release waters (Figure 35). Alternately, maximum concentrations of total iron (0.4 to 0.6 mg/l) were observed February through July, and particulate iron comprised the majority of the total iron pool (Figure 35). Nitrogen concentrations ranged from 1.14 to 1.09 mg/l (April and July, respectively) to 0.41 to 0.36 mg/l (February and October, respectively) and were primarily in dissolved forms. Values of conductivity, pH, alkalinity, organic carbon, and phosphorus were similar to values observed in the forebay.

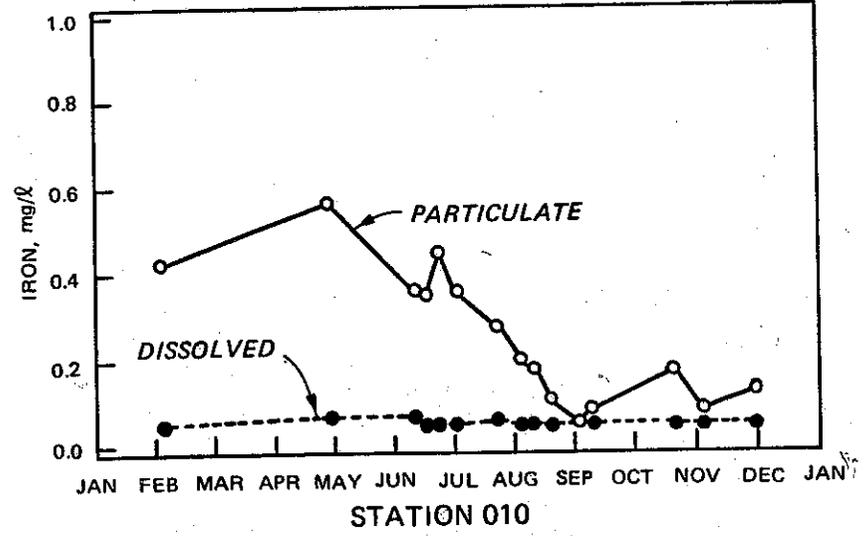
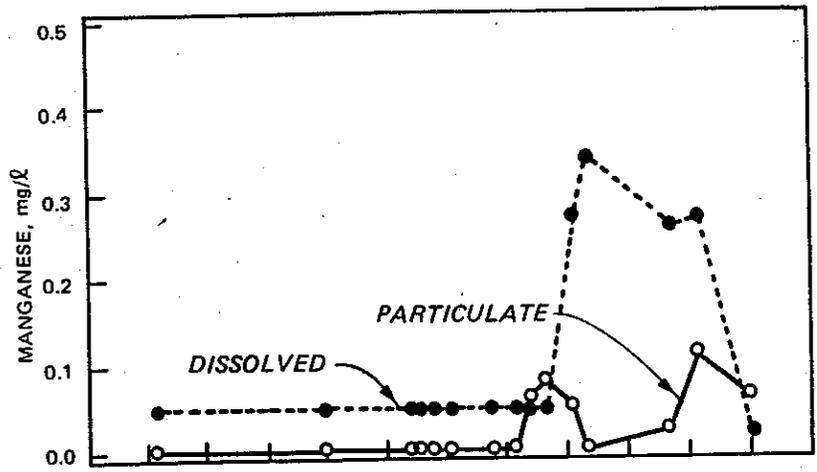
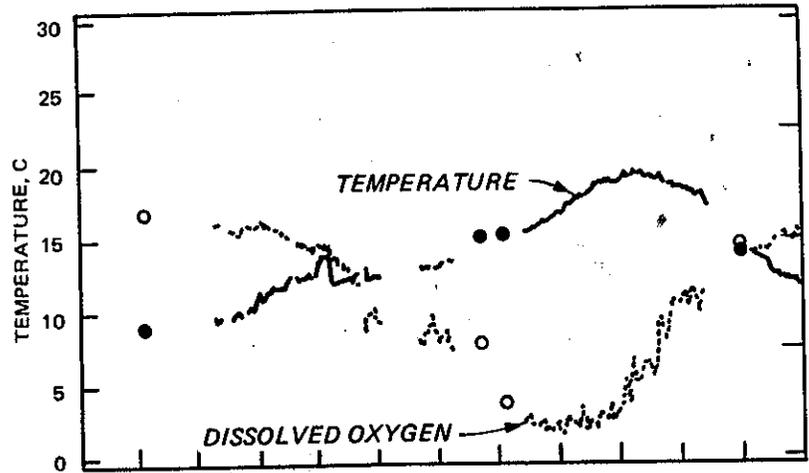


Figure 35. Temperatures, dissolved oxygen, manganese, and iron concentrations in J. Strom Thurmond Dam releases (Station 010) (1987)

Oxygenation System Operation

46. Operation of the oxygenation system was initiated on May 22, 1987, with a delivery rate of 10 tons* of oxygen per day through the pulse injection system located at the Richard B. Russell Dam face. A rate of 10 to 30 tons of oxygen per day was maintained through the pulse injection system until July 13, at which time operation of the continuous injection system (located 1 mile (1.6 km) upstream of the dam) was initiated. At this time, the continuous injection system delivered a rate of 32 tons of oxygen per day, and the rate at the pulse injection system was reduced to 14 tons of oxygen per day. Both systems were operated throughout the remainder of the period of stratification (until November 28) at a combined capacity of 70 to 100 tons of oxygen per day.

47. Operation of the oxygenation system maintained the concentration of DO near 6 mg/l, at most depths, in the area affected by the system (Figure 36). Dissolved oxygen concentrations below 6 mg/l were observed in the Richard B. Russell forebay (i.e., Station 060B) only at depths below 35 m with the exception of occasional concentrations near 4 mg/l occurring in the metalimnion during September and October. Additionally, concentrations of DO in the releases from Richard B. Russell Dam were maintained near 6 mg/l with operation of the oxygenation system (Figure 37). The permanent liquid oxygen storage facility began initial operation in 1987. Several problems were discovered which caused large fluctuations in the gas outflow into the lake (Figure 37, solid line). Modifications were made during the off-season to provide a constant, consistent oxygen flow rate from this facility.

48. The water quality model SELECT (Davis et al. 1987) was employed to predict outflow oxygen concentrations based on lake data from Stations 060B and 120 in the presence and absence, respectively, of oxygen system operation. A comparison of the SELECT predictions and the observed outflow concentrations is shown as Figure 38. Results from SELECT indicate that the oxygenation system adds approximately 2 to 4 mg/l DO to Richard B. Russell Dam releases.

* To convert tons (2,000 lb, mass) to kilograms, multiply by 907.1847.

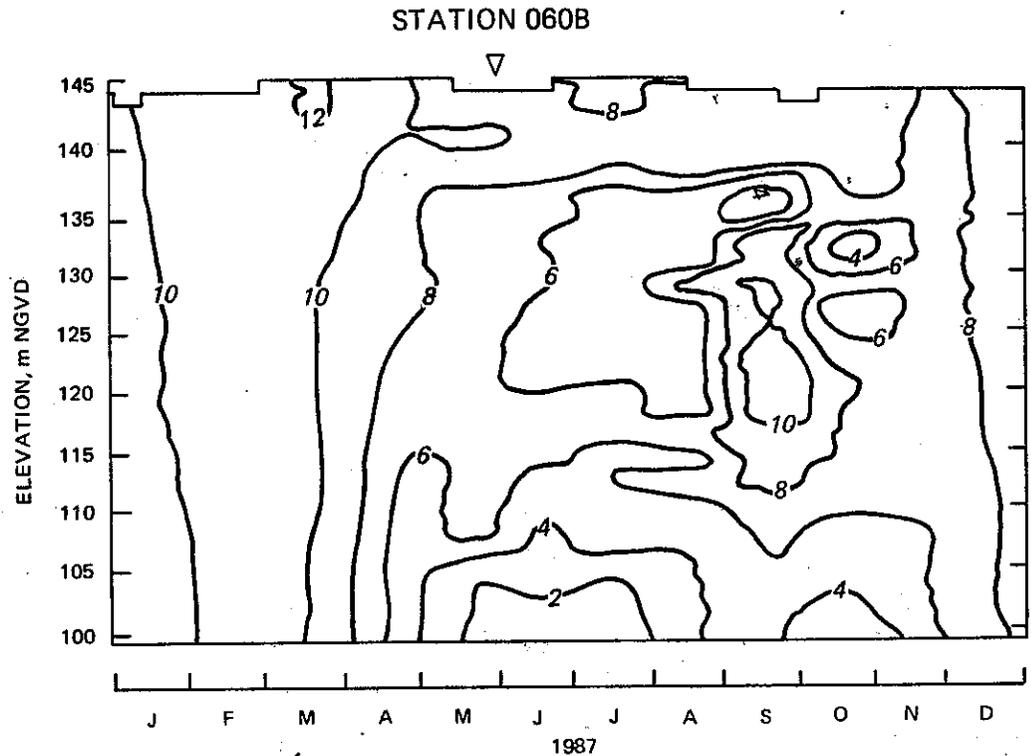


Figure 36. Temporal and vertical changes in DO concentrations (mg/l) in the lower region of Richard B. Russell Lake (Station 060B)

Phytopigment Distributions

49. Chlorophyll a concentrations in Richard B. Russell and J. Strom Thurmond Lakes displayed seasonal and spatial trends similar to those observed in previous years of the study (Hains et al. 1988) (Figure 39). In January concentrations were low (mostly <10 $\mu\text{g}/\text{l}$) at all locations, but minor spatial trends were apparent in each lake with concentrations increasing in a downstream direction. In April, concentrations were still low, and spatial trends were less pronounced. Concentrations in July were similar to those in April with slightly higher concentrations occurring in J. Strom Thurmond Lake. In October, maximum concentrations of approximately 20 $\mu\text{g}/\text{l}$ were observed in each lake, and spatial trends within each lake were most pronounced. Concentrations peaked in the mid to upper region of each lake and decreased in a downstream direction.

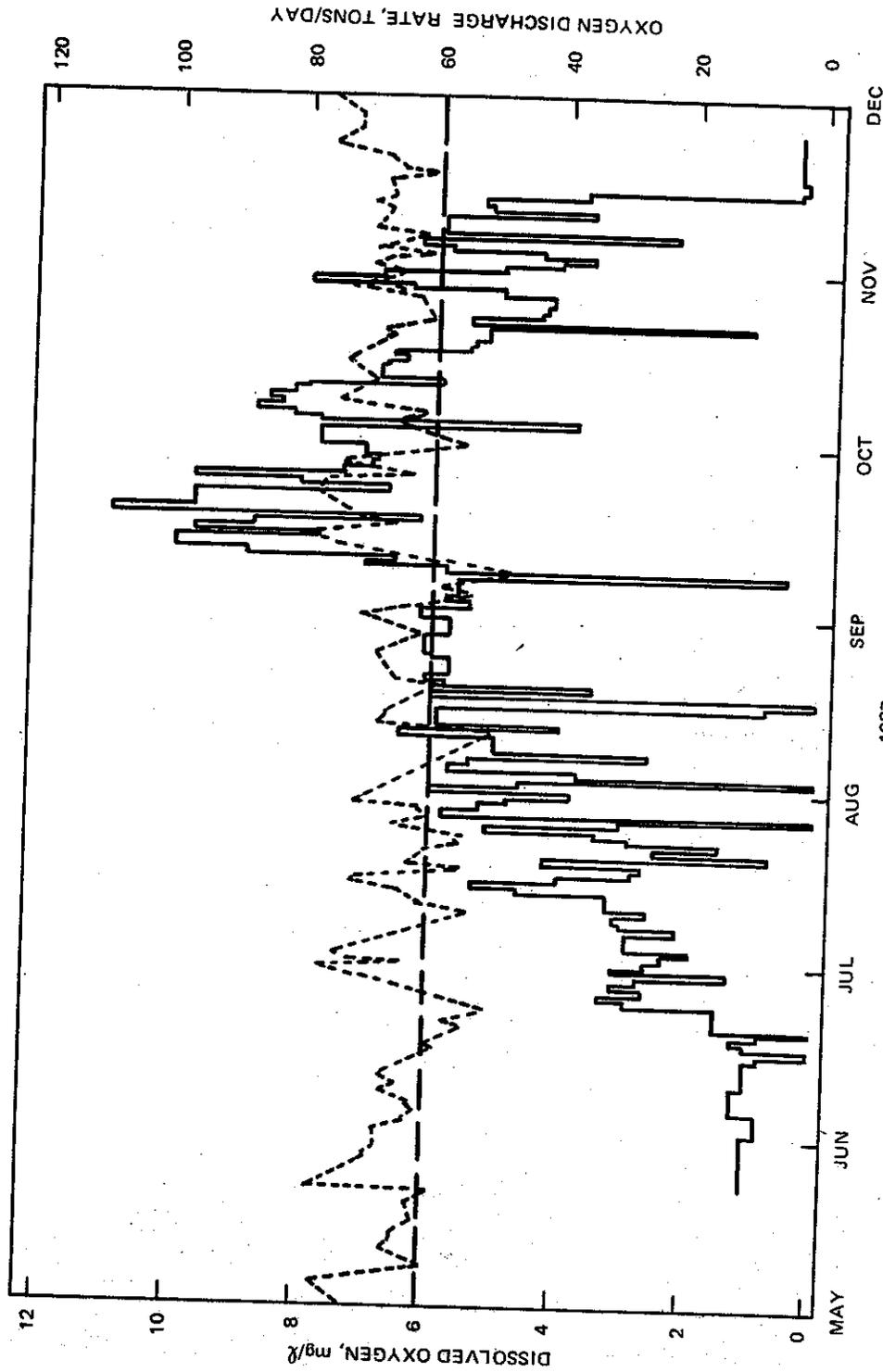


Figure 37. Dissolved oxygen concentrations (dashed line) in the Richard B. Russell Dam releases and the oxygen delivery rate from the oxygenation system (solid line). (Horizontal bold dashed line indicates the 6-mg/l target DO concentration)

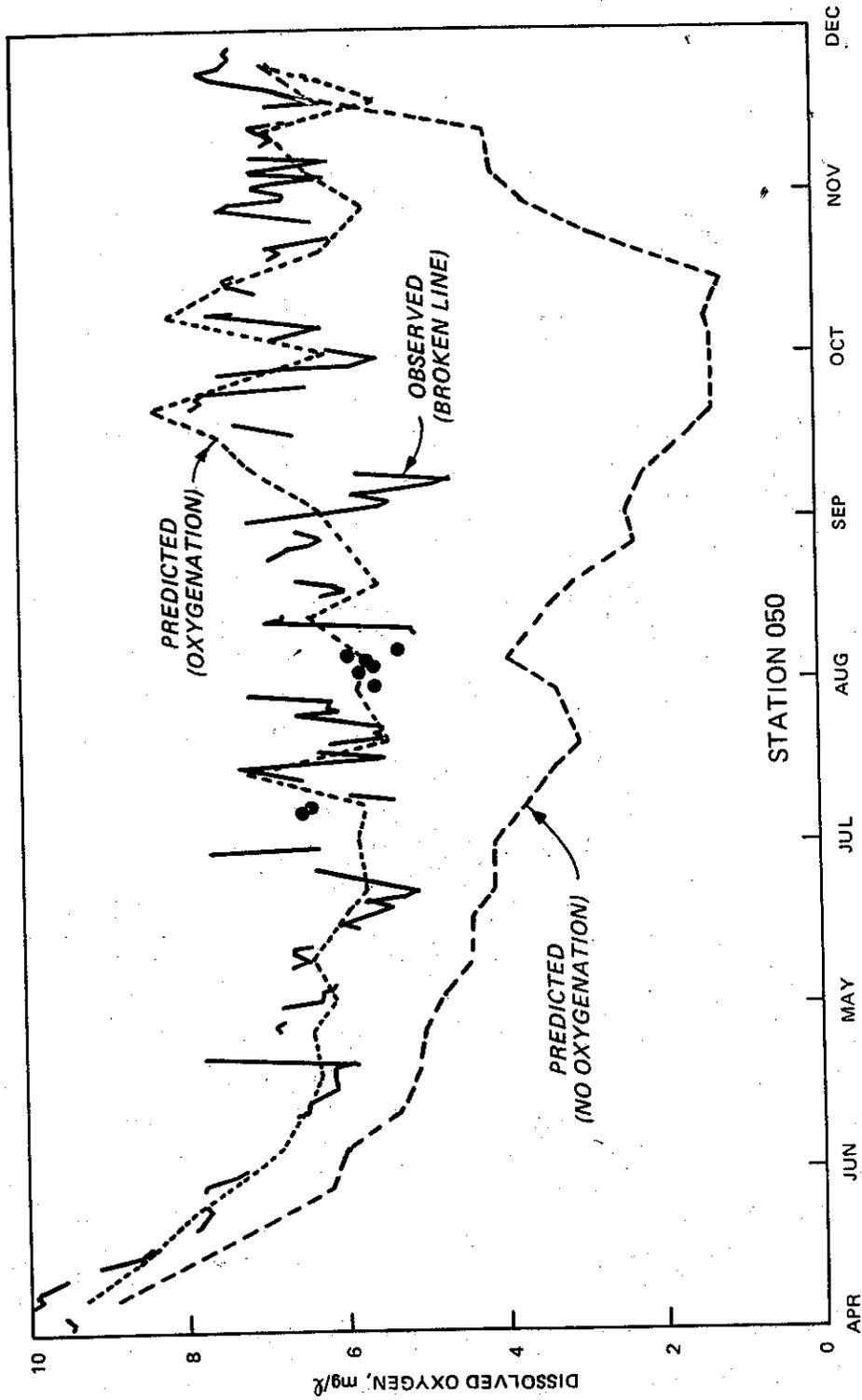


Figure 38. SELECT predictions of DO concentrations versus observed concentrations in the Richard B. Russell Dam releases

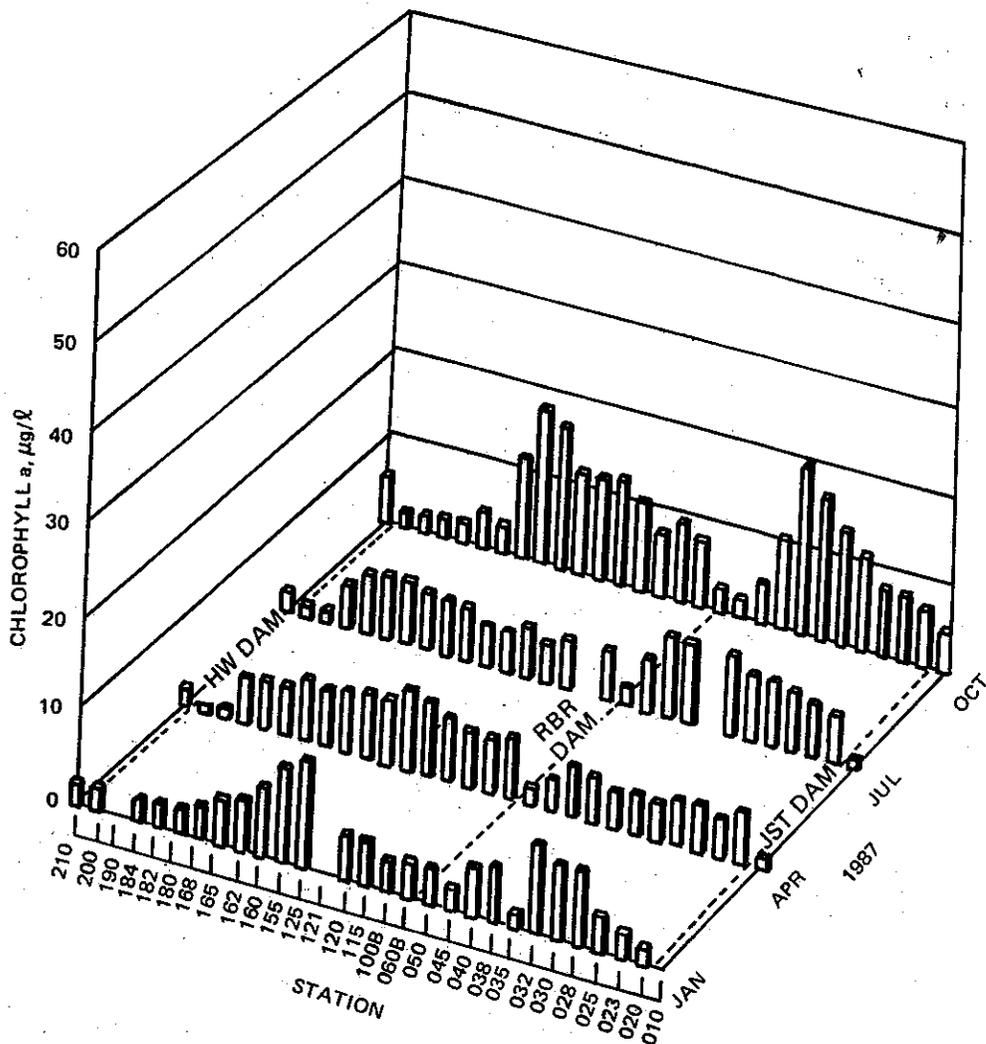


Figure 39. Patterns of distribution of chlorophyll a concentrations ($\mu\text{g}/\ell$) in Hartwell, Richard B. Russell, and J. Strom Thurmond Lakes (January, April, July, and October 1987)

Diel Study

50. Diel variations in water quality of the headwaters of J. Strom Thurmond Lake resulting from Richard B. Russell Dam releases were evaluated during the period September 20 to 22, 1987. This study involved repeated in situ sampling of several stations in the upstream reach of J. Strom Thurmond Lake. Pool elevations during the study were between 98.9 and 99.2 m NGVD. The six stations sampled during the study were located from 0.2 to 7 km

downstream of Richard B. Russell Dam in J. Strom Thurmond Lake (Figure 40). Vertical profiles of DO, temperature, pH, and specific conductance were obtained at the stations and time intervals indicated in Table 6. Nine sampling rounds were conducted at six stations, starting at 1750 hr on September 20 and ending at 1225 hr on September 22. In addition, samples for iron and manganese analyses were collected from multiple depths at each station during rounds 2, 6, and 9.

51. The sampling times were selected to bracket the daily generation cycle of Monday, September 21. In accordance with normal operating schedules the releases from Richard B. Russell Dam had been suspended over the weekend of September 19-20. Releases on Monday, September 21, were in accordance with normal operational procedures to meet peak demands for hydropower generation. Releases for the day started in early afternoon and ended shortly before midnight, with maximum releases of 625 cu m/sec occurring at 1700 hr (Figure 41). During the generation period, release water temperature ranged from 15.9° to 17.4° C, with a mean of 16.3° C; dissolved oxygen concentrations ranged from 7.4 to 8.9 mg/l, with a mean of 8.0 mg/l.

52. Contour plots of temperature (Figure 42) and dissolved oxygen (Figure 43) distribution in J. Strom Thurmond Lake are shown for three of the nine sampling rounds. These three rounds were found to be representative of pre-generation (round 3), generation (round 5), and postgeneration (round 9) periods of the study. Prior to generation, on the morning of September 21, thermal stratification patterns in the study area were typical of lake stratification patterns, with warm, 25° C surface waters extending upstream to Richard B. Russell Dam (round 3, Figure 42). Within 4 hr of the start of generation, a well-developed plunge point was present 3 km downstream of the dam between Stations 045 and 047 (round 5, Figure 42). All of the water upstream of this point was well mixed, with a temperature of 15° to 16° C. Round 9 (Figure 42), which occurred about 12 hr after generation ceased, again showed near-normal lake stratification patterns with relatively warm surface water extending upstream to the dam.

53. Dissolved oxygen contours (Figure 43) depict trends similar to those for temperature. During generation, data from round 5 (Figure 43) indicate well-mixed release water with about 8.7 mg/l dissolved oxygen from the surface to bottom extending down to about the location of the plunge point, as defined by the temperature profiles. At this point, the surface-water DO

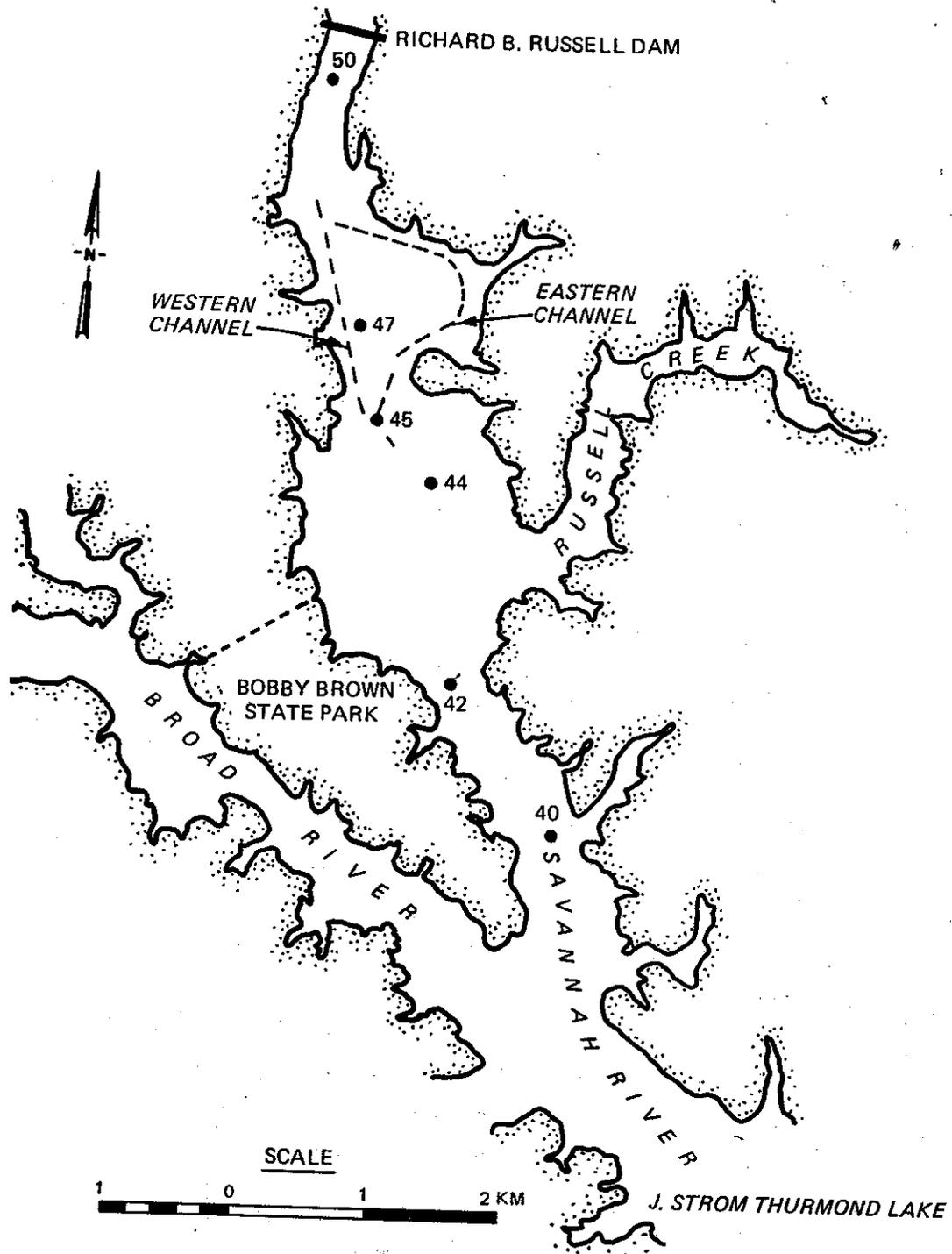


Figure 40. Location of diel study sampling stations in the headwater region of J. Strom Thurmond Lake

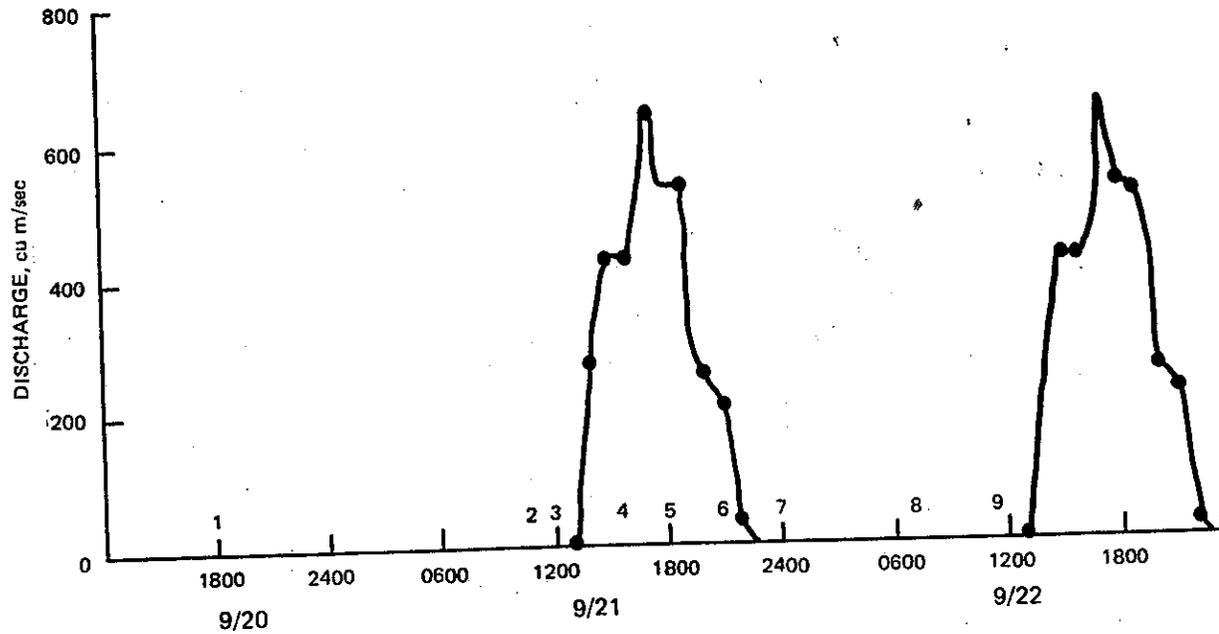


Figure 41. Discharge from Richard B. Russell Dam from September 20-22, 1987

concentrations increased to around 10 mg/l, and bottom water concentrations from Station 042 downstream, decreased to below 7 mg/l, indicating an interflow between Stations 044 and 042. The two rounds during nongeneration, 3 and 9 (Figure 43), depict DO profiles with vertical gradients occurring throughout the study area.

54. Contour plots of total manganese (Figure 44) and total iron (Figure 45) are shown for pregeneration (round 2), during generation (round 6) and postgeneration (round 9). The range for iron (0.1 to 1.0 mg/l) and manganese (0.05 to 0.4 mg/l) during nongenerating periods was the same as during release. However, during the release period, higher concentrations of metals were present higher in the water column throughout the study area and reflected release water concentrations (0.6 mg/l Fe and 0.3 mg/l Mn). The contour plots for the metals, again, show very similar patterns to those for temperature and dissolved oxygen, with a plunge point between Stations 044 and 047 and an interflow starting downstream of Station 044.

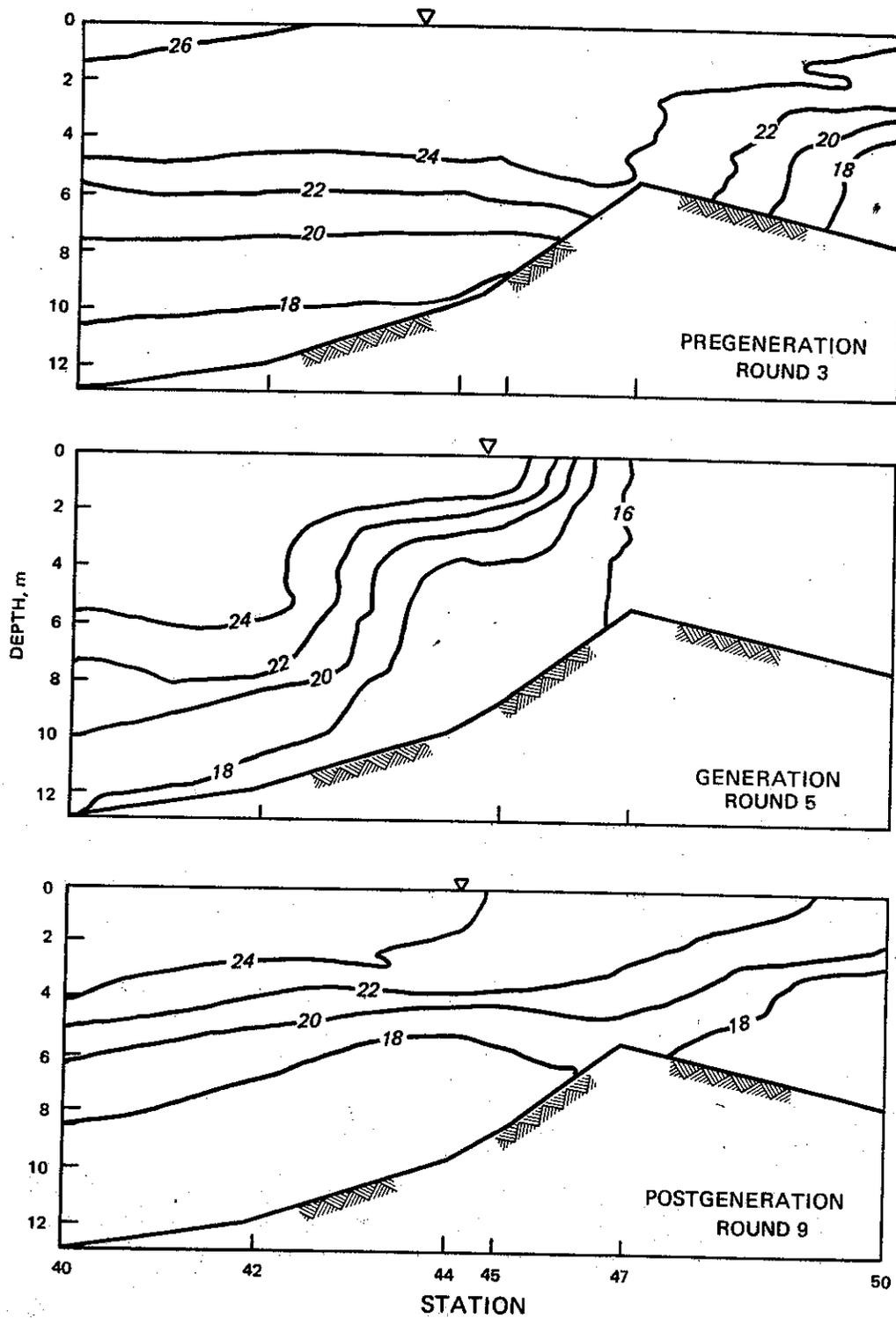


Figure 42. Longitudinal and vertical distribution in temperature ($^{\circ}\text{C}$) in the headwater region of J. Strom Thurmond Lake (Rounds 3, 5, and 9 of the diel study)

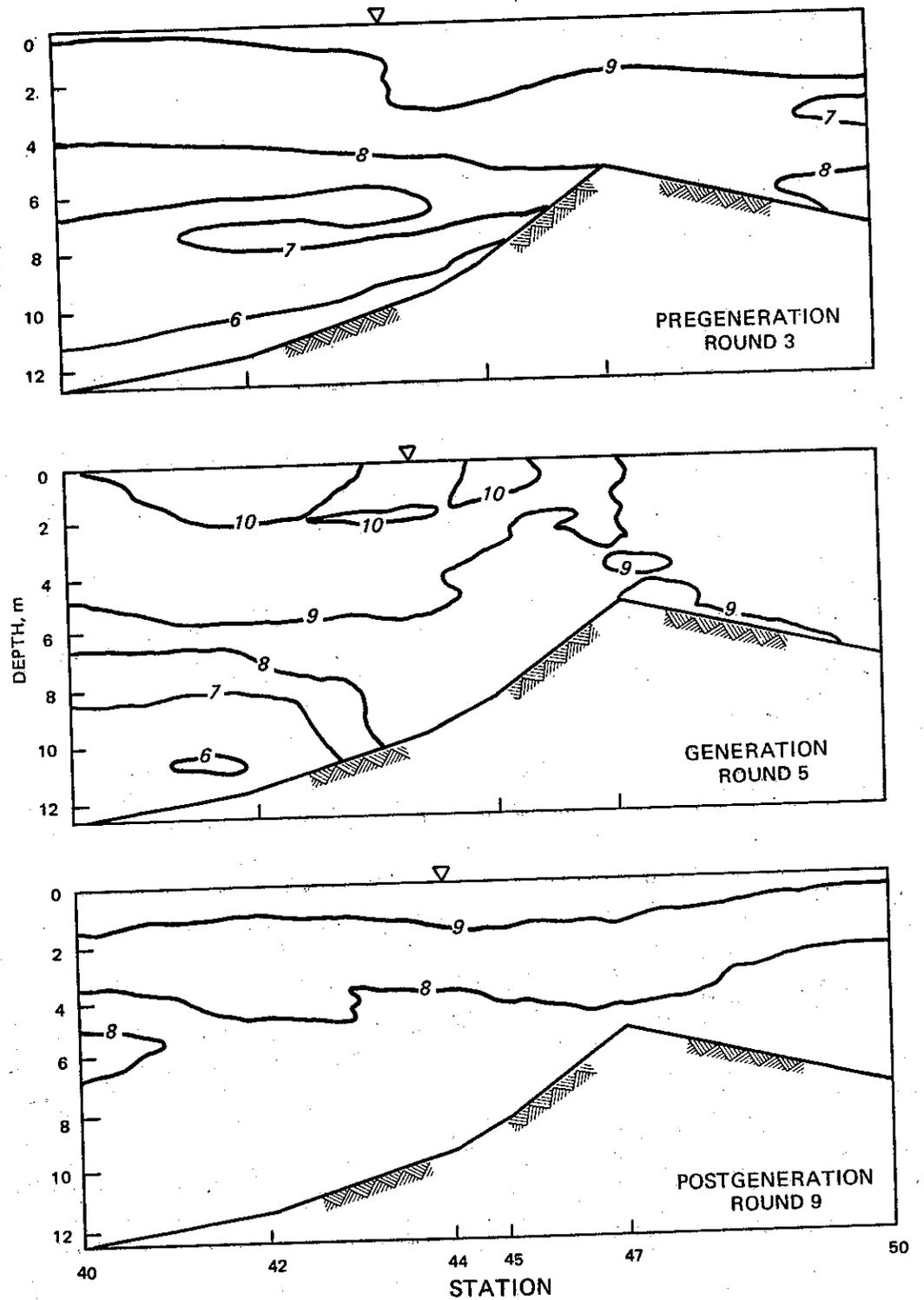


Figure 43. Longitudinal and vertical distribution in DO concentrations (mg/l) in the headwater region of J. Strom Thurmond Lake (Rounds 3, 5, and 9 of the diel study)

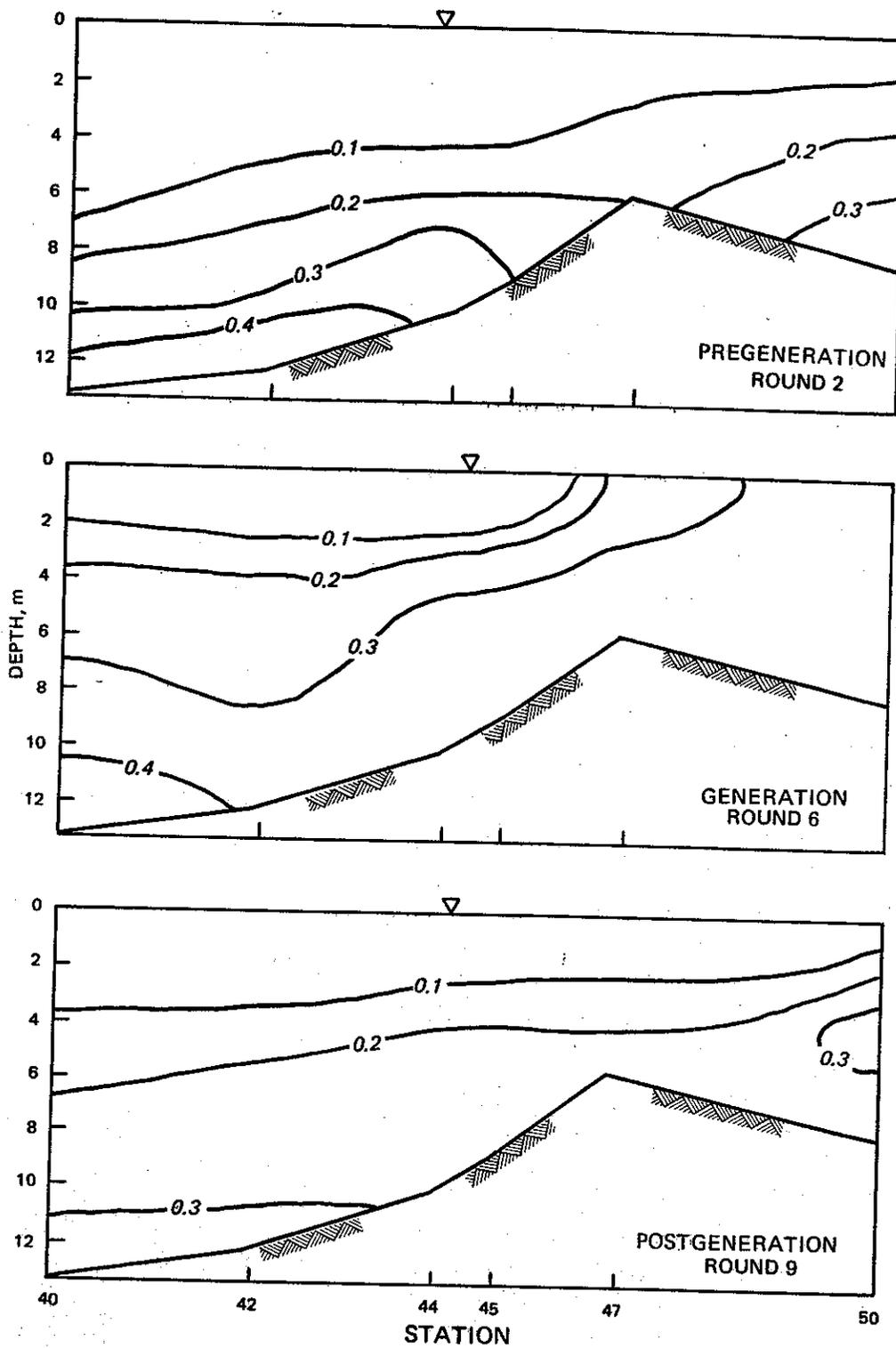


Figure 44. Longitudinal and vertical distribution in total manganese concentrations (mg/l) in the headwater region of J. Strom Thurmond Lake (Rounds 2, 6, and 9 of the diel study)

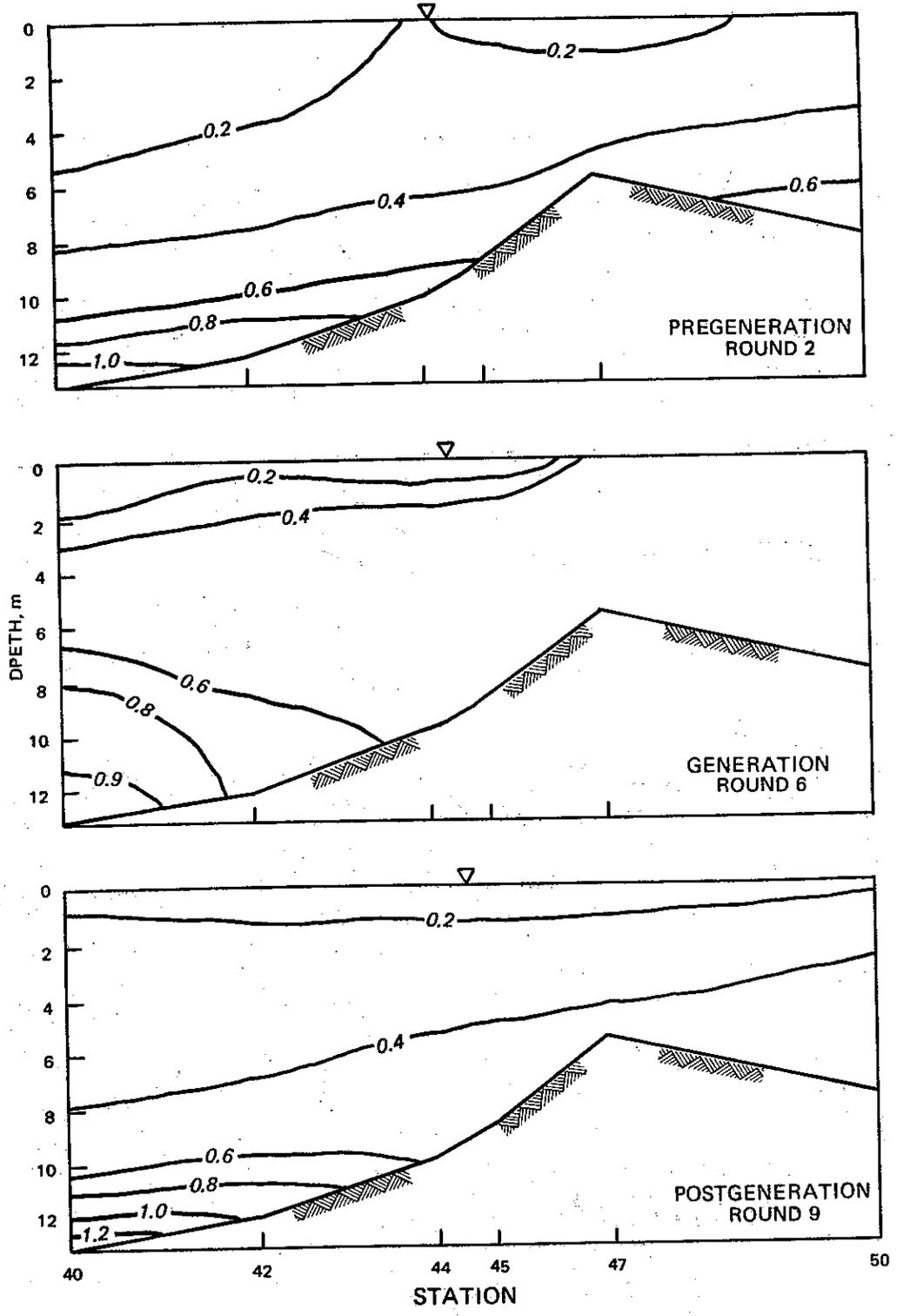


Figure 45. Longitudinal and vertical distribution in total iron concentrations (mg/l) in the headwater region of J. Strom Thurmond Lake (Rounds 2, 6, and 9 of the diel study)

Dye Injection Study

55. Approximately 25 gal (94.6 l) of Rhodamine WT dye (Crompton and Knowles Company, Reading, PA), a fluorescent compound commonly used for water movement studies (Johnson 1984), was injected in surface waters (0.5 to 1 m) immediately downstream from Station 050 in an attempt to elucidate flow patterns of release waters in upstream reaches of J. Strom Thurmond Lake (see Figure 40). Time of travel and flow patterns were determined based on comparison of relative dye concentrations at individual stations. Dye concentrations in the following discussion and related figures are relative concentrations expressed as a percentage of maximum observed concentration at individual stations and do not reflect water volume.

56. Injection of the dye, which required approximately 1 min using a siphon attached to the dye container, occurred at 1435 hr on September 22, 1987. Mixing of the dye was accomplished by turbulence as two boats repeatedly traversed the injection area. Penstock releases had begun at approximately 1330 hr, and the discharge rate at the time of injection was approximately 425 cu m/sec. Discharge reached a maximum of 625 cu m/sec at 1700 hr before ceasing at approximately 2200 hr (see Figure 41).

57. The location of the dye was immediately apparent as an area of red, discolored water. The dye mass, as observed from the surface, moved rapidly downstream and somewhat to the east, and appeared to follow the old river channel or thalweg. Approximately 1.8 km downstream, the dye mass had increased greatly in lateral extent, and a well-defined plunge line was apparent.

58. Monitoring of dye concentrations was conducted using a hose and pump system and a Turner Designs fluorometer (Turner Designs, Inc., Mountain View, CA). A weighted and depth-calibrated plastic hose was lowered to selected depths, after which water samples were pumped to the surface and through the sample compartment of the fluorometer. Care was taken to ensure sufficient time for flushing of water through the hose to prevent contamination by water from the previous sample depth. Results were read directly from the instrument, which had previously been standardized using dye solutions of known concentration.

59. Since initial attempts to quantify the spatial characteristics of the dye mass were made difficult by the rate of movement of dyed water,

stationary monitoring was conducted at two locations near Station 047 (see Figure 40). At this point, two distinct channels occur--an eastern channel along the South Carolina shore, which is the inundated main channel of the Savannah River, and a western channel of somewhat shallower depth along the Georgia shore. Dye was first detected in the western channel approximately 1.25 hr following injection (Figure 46). The arrival of dye at the monitoring site over the eastern channel was delayed by approximately 0.5 hr, due presumably to the longer travel distance associated with the easterly meander of this branch of the channel.

60. A marked difference between sites was the vertical distribution of dye (Figure 46). While concentrations were highest near bottom and little dye was detected in surface waters (0 to 2 m) in the west channel, peak concentrations in the east channel were observed at midwater column. Maximum concentration in the east channel was also higher than in the west channel. Due to mixing, which increased its longitudinal extent, the dye mass required approximately 1 hr to pass both the eastern and western sampling sites.

61. Upon completion of sampling activities at Station 047, both sampling crews moved downstream in an attempt to delineate the spatial extent of the dye mass in an area of increased lake width and depth. Unexpectedly, relatively high dye concentrations were observed in surface waters along the reach from Station 044 to Station 042. While a detailed assessment of the extent of the dye mass was not possible due to the continued rapid movement of water in this area of the lake, it did appear that bottom waters had mixed to some degree with surface waters. This conclusion is based on the observation that relative dye concentrations in surface waters at several sites downstream were higher than maximum relative concentrations in surface waters at the two stations located upstream near Station 047. This would suggest that dye had mixed upward in the water column. While the data are not conclusive, possible explanations for this occurrence would be the upwelling of bottom waters due to the effects of bottom morphometry or mixing due to the turbulent interaction between release flows and stratified waters in this deeper area of the lake.

62. Subsequent sampling rounds involved vertical profiles of dye concentration at stations located along the thalweg. The locations of these stations were determined for each sampling round by first estimating the probable location of the dye mass and then successively increasing the number of

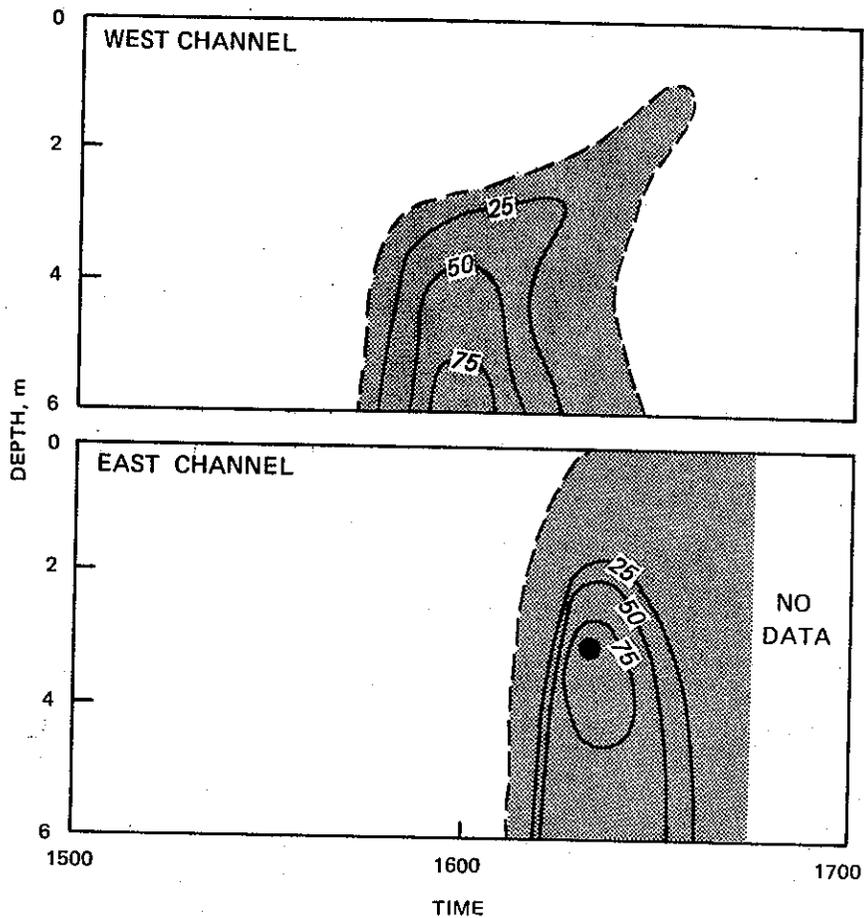


Figure 46. Vertical distribution of relative dye concentrations (expressed as a percentage of maximum observed concentration) observed during successive sampling rounds at stations located over the eastern and western channel in the vicinity of Station 047 on September 22

sampled stations until the upstream and downstream extent of the dye mass was defined. Additional stations were added based on review of initial concentration data. Since flow rate slowed considerably with distance downstream, samples collected during each round provide a relatively accurate description of the location of the dye mass at one point in time. Movements of the dye mass can then be inferred from a review of data collected during successive sampling rounds.

63. Vertical and longitudinal profiles of dye concentration were obtained on September 23, 24, 25, and 28. As presented in Figure 47, the distribution and movement of dye indicate that release waters plunged approximately 5 km downstream from Richard B. Russell Dam and progressed through the upper reaches of J. Strom Thurmond Lake as an underflow. Dye was detectable only in bottom waters at locations greater than approximately 15 km downstream from Richard B. Russell Dam, and maximum concentrations were observed near bottom. The separation of flows from the bottom, as inferred previously from water quality data (James et al. 1985), was not observed during the course of this study. Whether this occurred in the 20-km downstream reach of J. Strom Thurmond Lake could not be determined during this study since greatly diminished dye concentrations precluded sampling in this reach of the lake.

64. The average flow velocity of release waters in the upper reach of J. Strom Thurmond Lake was determined by a plot of the location of the center of the dye mass at successive times, the slope of which estimates average velocity (Figure 48). The average velocity thus obtained was 0.11 m/sec. At this velocity, the average time of travel of waters released from Richard B. Russell Dam to reach J. Strom Thurmond Dam would be 6.3 days. Of additional interest is the fact that flows were unaffected by the presence of a plunge line. This differs from results of studies conducted at other stratified reservoirs (Kennedy, Gunkel, and Carlisle 1984). In these studies, velocity was observed to be initially high, reduced in the vicinity of the plunge line and then increased or further reduced beyond the plunge line. The reduction of velocity in the vicinity of the plunge line is expected due to complex interactions between momentum and buoyancy forces (Ford and Johnson 1983). The fact that this phenomenon was not observed during this study may reflect the lack of detailed data describing dye distribution in the area of the plunge line. Additionally, effects of generation cycles on downstream velocities are not known.

65. Additional samples were collected in portions of the Russell Creek and Broad River embayment to determine the influence of release flows on the off-channel areas of the lake. Analyses of data collected in a 1.6-km reach of Russell Creek embayment indicated the presence of a wedge of release water on September 23 (Figure 49). This wedge occurred at depths greater than 4 to 5 m; however, detectable concentrations of dye were observed in surface waters, indicating a degree of mixing of bottom waters into surface layers.

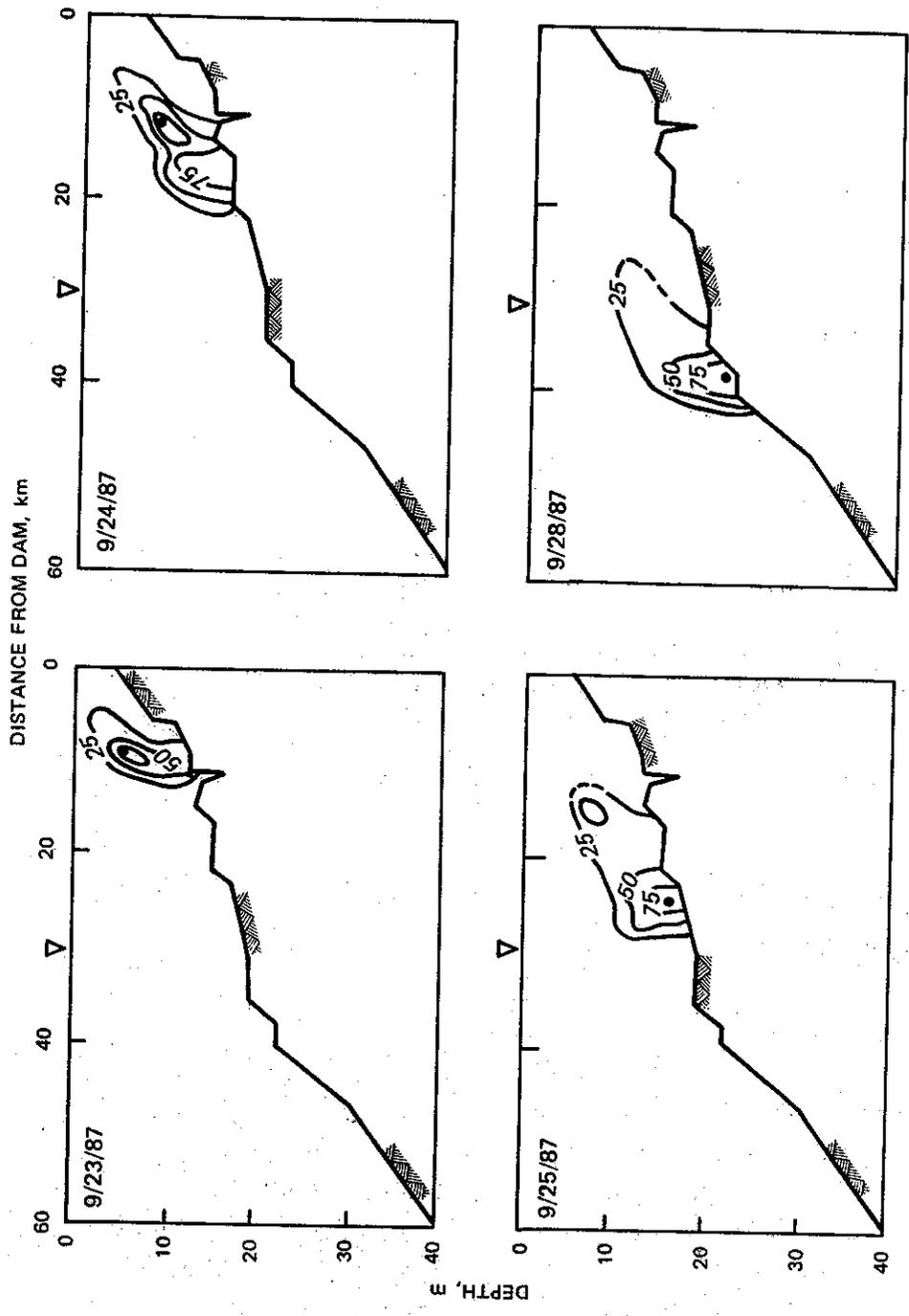


Figure 47. Vertical and longitudinal distribution of relative dye concentration (expressed as a percentage of maximum observed concentration) in J. Strom Thurmond Lake during successive sampling rounds. Distance is measured from point of injection

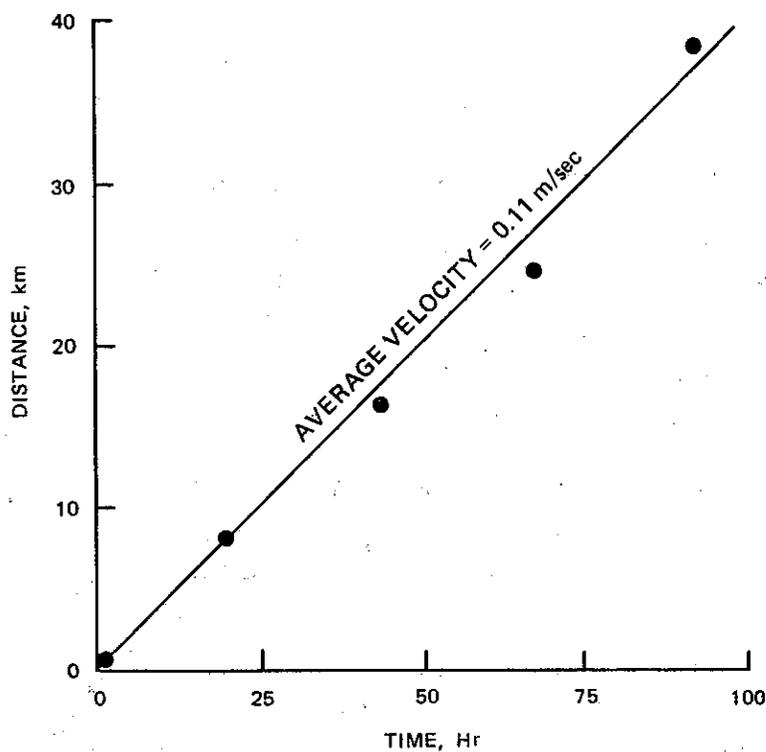


Figure 48. Location of the center of the dye mass in relation to distance from the point of injection and time since injection. (The slope of the relationship approximates average flow velocity)

The mechanisms by which this mixing occurred cannot be elucidated with these data. Detectable, but considerably lower, dye concentrations were also observed in the Broad River embayment, but no clear description of the distribution of dye was possible.

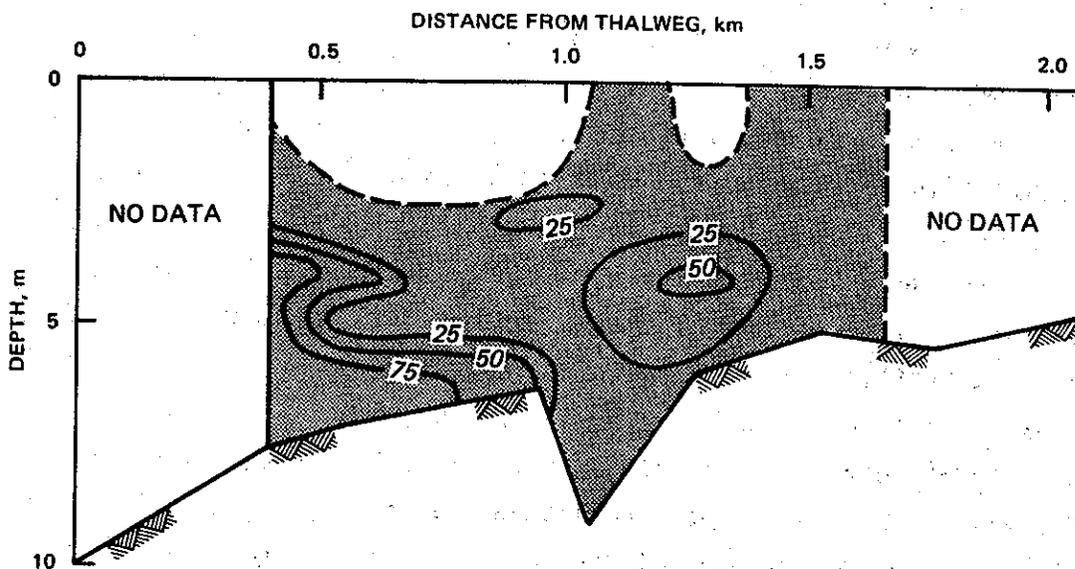


Figure 49. Vertical and longitudinal distribution of relative dye concentration (expressed as a percentage of maximum observed concentration) in Russell Creek embayment during the period 1300 to 1410 hr on September 23. (Distance is measured from the thalweg in J. Strom Thurmond Lake)

PART V: DISCUSSION

Water Quality Conditions During 1987

66. Temporal and spatial trends in thermal structure observed in 1987 in Hartwell, Richard B. Russell, and J. Strom Thurmond Lakes were similar to those observed in previous studies (James et al. 1985, 1986; Hains et al. 1988). In each lake the onset of stratification occurred in March and April, and a well-developed thermocline was established by May to June. Although temporal trends were similar for each lake, the vertical development of stratification in Hartwell Lake differed from that of Richard B. Russell and J. Strom Thurmond Lakes.

67. While the thermoclines in Richard B. Russell and J. Strom Thurmond Lakes remained near a depth of 6 to 8 m throughout the stratified period, the thermocline in Hartwell Lake deepened throughout the summer to a maximum depth of 18 m. Hypolimnetic temperatures were approximately 2° C cooler in Hartwell Lake, as well. Additionally, the fall mixing varied somewhat in each lake. Richard B. Russell and J. Strom Thurmond Lakes were completely mixed by November, while Hartwell Lake did not completely mix until late December.

68. Several morphometric and operational features of Hartwell Lake, as well as operationally dependent interactions between the three lakes, may account for the above-mentioned differences. Of the three lakes (at maximum conservation pool elevations), Hartwell Lake is deeper, has the greatest volume and mean depth, highest residence time, and lowest discharge. And, unlike Richard B. Russell and J. Strom Thurmond Lakes which receive cool inflows from upstream projects, Hartwell Lake receives relatively warm inflows. As a result of these features, Hartwell Lake would tend to lose cooler hypolimnetic water as a result of hydropower releases. This, in turn, would result in a gradual deepening of the thermocline throughout the summer. While similar losses of cool hypolimnetic waters occur at Richard B. Russell and J. Strom Thurmond Lakes, such losses are partially offset by the continual inflow of cool water from upstream releases. This leads to stability in the thermal budgets of those lakes and the observed stability in thermocline depth. The fact that Hartwell Lake mixes later in the fall is apparently related to the lake's greater depth.

69. Anoxic conditions developed initially in the major embayments of Richard B. Russell and J. Strom Thurmond Lakes, where thermal stratification and subsequent isolation of bottom waters first occurred. Additionally, concentrations of organic carbon and reduced metals (which contribute to oxygen depletion) were higher in embayments than at main stem locations. As the hypolimnia of the main stems of each lake became isolated, due to thermal stratification, oxygen depletion occurred. Anoxic conditions were well established in the forebay of Hartwell and J. Strom Thurmond Lakes by late September. In contrast, DO concentrations in the forebay of Richard B. Russell Lake were maintained near 6 mg/l due to operation of the oxygenation system. However, anoxic conditions developed upstream of the oxygenation system.

70. Operation of the oxygenation system in the hypolimnion of the lower region of Richard B. Russell Lake markedly impacts water quality in the vicinity of the system, in release waters, and in J. Strom Thurmond Lake. Operation of the oxygenation system maintained concentrations of dissolved oxygen near 6 mg/l in the releases from Richard B. Russell Dam during stratification. Without operation of the oxygenation system, outflow concentrations (based on predictions from SELECT) would have been approximately 2 mg/l lower.

71. Additional effects of the oxygenation system include effects on the dynamics of manganese and iron in the area influenced by the system. Oxidation and resultant precipitation of reduced iron is enhanced in the presence of the oxygenation system, as indicated by concentrations of dissolved and particulate iron in the area affected by the system. Additionally, sediment data from the Richard B. Russell forebay indicate that precipitation of particulate iron is greater downstream of the continuous system.* Observed changes in the concentration of dissolved and particulate manganese downstream of the system indicate that the effects of the oxygenation system on the oxidation of reduced manganese are less pronounced.

72. Oxygen depletion in sediments and hypolimnia results in solubilization and increased mobility of nutrients and metals, and the establishment of concentration gradients. Vertical gradients in chemical concentrations became apparent as anoxic conditions developed in the hypolimnia of tributary

* US Army Engineer Waterways Experiment Station, 1987, "Richard B. Russell Lake Water Quality Studies; Quarterly Summary of Field Activities; Summary No. 27," Vicksburg, MS.

embayments and in bottom waters in the lower regions of the lakes. Most pronounced were the vertical gradients in manganese and iron in each lake.

73. Dissolved manganese comprised the majority of the total manganese pool in each lake, and maximum observed concentrations occurred in anoxic bottom waters. Additionally, manganese in the outflow of each lake was primarily in dissolved forms, suggesting minimal oxidation, even under aerobic conditions. However, increased concentrations of particulate manganese occurred in the surface waters of the midlake region of J. Strom Thurmond Lake (see Figure 33, Station 030). Several possible sources for the formation of particulate manganese (due to oxidation of reduced manganese) are depicted in Figure 50. Dissolved (i.e., reduced) manganese concentrations were highest in the bottom waters of Broad River (Station 036) and in the midlake region of J. Strom Thurmond Lake (Station 030). Additionally, dissolved manganese was present in the release waters from Richard B. Russell Dam. Dissolved oxygen concentrations in the surface waters in the vicinity of Station 030 and upstream were greater than 4 mg/l and were sufficient for oxidation of reduced manganese. Transport of reduced manganese via diffusion, advection, and inflow mixing into oxic environments would allow oxidation and particulate formation. The occurrence of particulate manganese in the vicinity of Station 030 and the absence of particulate manganese elsewhere in J. Strom Thurmond Lake indicate that this region may be a zone of deposition of particulate manganese.

74. Increased concentrations of manganese in the midlake region may contribute to concentration increases observed downstream. Seasonal increases in dissolved manganese concentrations in the bottom waters at Station 030 increase availability of reduced manganese for transport downstream via diffusion and advection. The magnitude of dissolved manganese concentrations was greater in the J. Strom Thurmond Lake main stem (4.6 mg/l) than in the main stems of Richard B. Russell and Hartwell Lakes (1.6 mg/l). This trend has been apparent for previous years of study, with the exception of the first year of impoundment of Richard B. Russell Lake (James et al. 1985, 1986; Hains et al. 1988).

75. While temporal trends in iron concentrations were similar to those of manganese, spatial trends were not. As has been observed in previous years, particulate iron comprised the majority of the total iron pool except during peak anoxic conditions. The rate of oxidation of reduced iron is

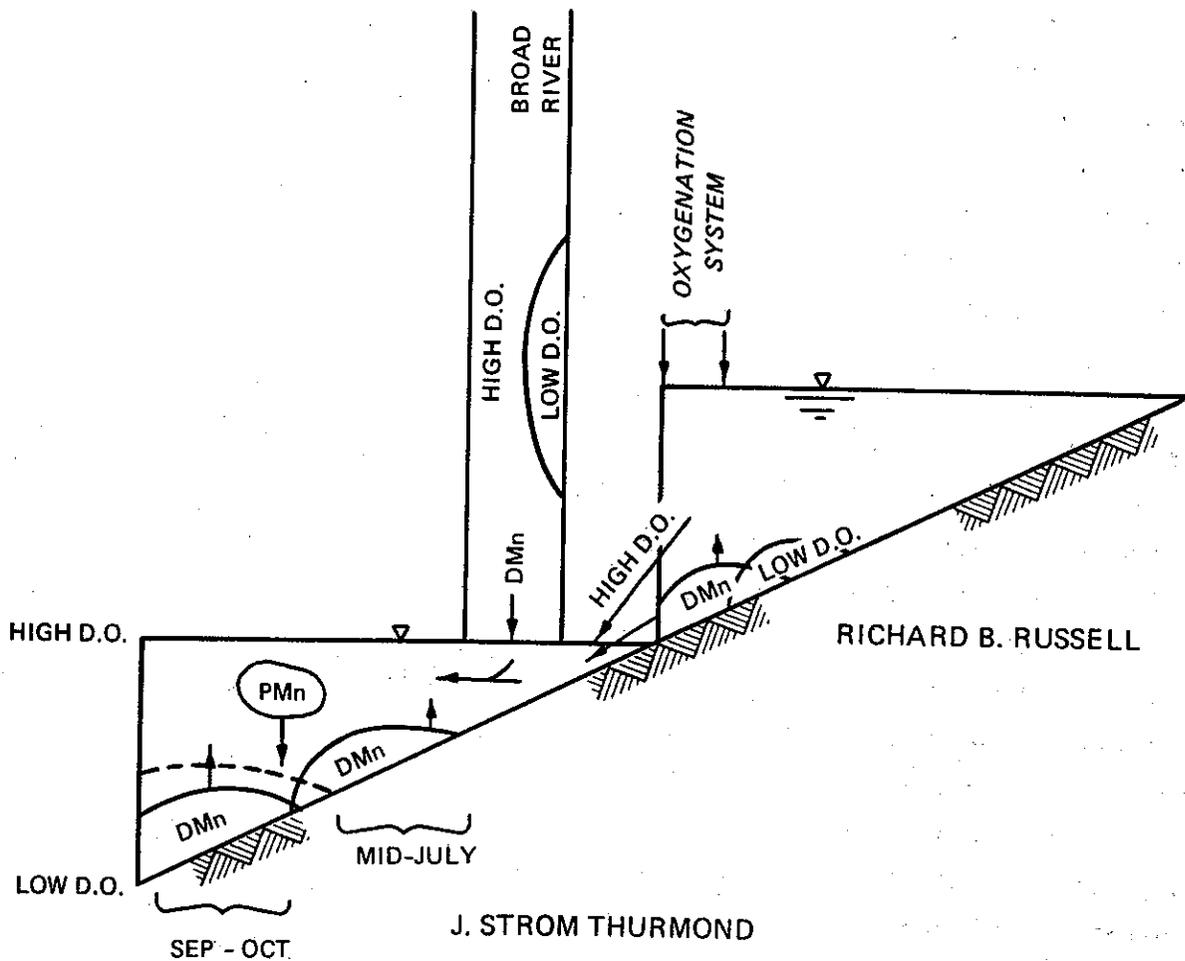


Figure 50. Suggested scenario for manganese cycling in Richard B. Russell and J. Strom Thurmond Lakes

higher than the rate of oxidation of reduced manganese (Cole 1983) and may account for particulate iron concentrations observed in the lakes. Reduced iron, mobilized from anoxic regions in each lake, is subjected to rapid oxidation (and formation of particulates) as it comes in contact (via diffusive and advective transport) with oxic waters. Consequently, increases in particulate concentrations would be expected in systems with anoxic and oxic regions, which occur during stratification.

76. In the main stem of Richard B. Russell Lake, iron was primarily in dissolved forms upstream of the oxygenation system, while particulate iron was the major form downstream of the system. Consequently, iron in the releases from Richard B. Russell Dam was primarily in particulate forms. Additionally,

iron in the Broad River was primarily in particulate forms until September when increased dissolved iron concentrations occurred coincident with anoxia. However, dissolved iron concentrations were near the detection limit in the mid and upper regions of J. Strom Thurmond Lake, suggesting that oxidation of reduced iron from Broad River occurred downstream from Station 036. Consequently, particulate iron comprised the majority of the total iron pool in the mid and upper regions of J. Strom Thurmond Lake. It follows that the Broad River and the releases from Richard B. Russell Dam are important sources of particulate iron in the mid and upper regions of J. Strom Thurmond Lake. Anoxic conditions necessary for iron reduction and mobilization in the main stem of J. Strom Thurmond Lake occurred only in the bottom waters of the forebay where dissolved iron comprised the majority of the total iron pool. A suggested scenario for the transport of iron in Richard B. Russell and J. Strom Thurmond Lakes is depicted in Figure 51.

77. Differences between lakes were also observed for iron concentrations. Maximum iron concentrations were observed in the forebay of Hartwell Lake (7.6 mg/l), while main stem concentration maxima in Richard B. Russell and J. Strom Thurmond Lakes were 4.0 and 1.1 mg/l, respectively, indicating a decrease in the downstream direction. Additionally, iron concentrations for 1987 were markedly different from those observed in 1986, except for J. Strom Thurmond. Iron concentrations in the main stem of Richard B. Russell Lake in 1987 displayed a maximum value 50 percent less than that observed in 1986. In contrast, maximum observed concentrations in Hartwell Lake were three times higher in 1987 than in 1986. Annual differences in concentrations may, however, be a function of year-to-year variability and temporal differences not addressed by current sampling intervals.

78. Nitrogen concentrations, although slightly lower in Hartwell Lake than in Richard B. Russell and J. Strom Thurmond Lakes, displayed moderate seasonal and spatial trends similar to those observed in previous years (James et al. 1985, 1986; Hains et al. 1988). While total nitrogen concentrations remained relatively constant (0.5 to 1.0 mg/l), concentrations of dissolved forms were seasonally variable. Maximum nitrogen concentrations were observed in spring following the high-flow period and in summer prior to peak phytoplankton productivity. Dissolved organic forms comprised the majority of the total nitrogen pool at this time. As phytoplankton productivity increased (as suggested by increases in chlorophyll a concentrations), dissolved organic

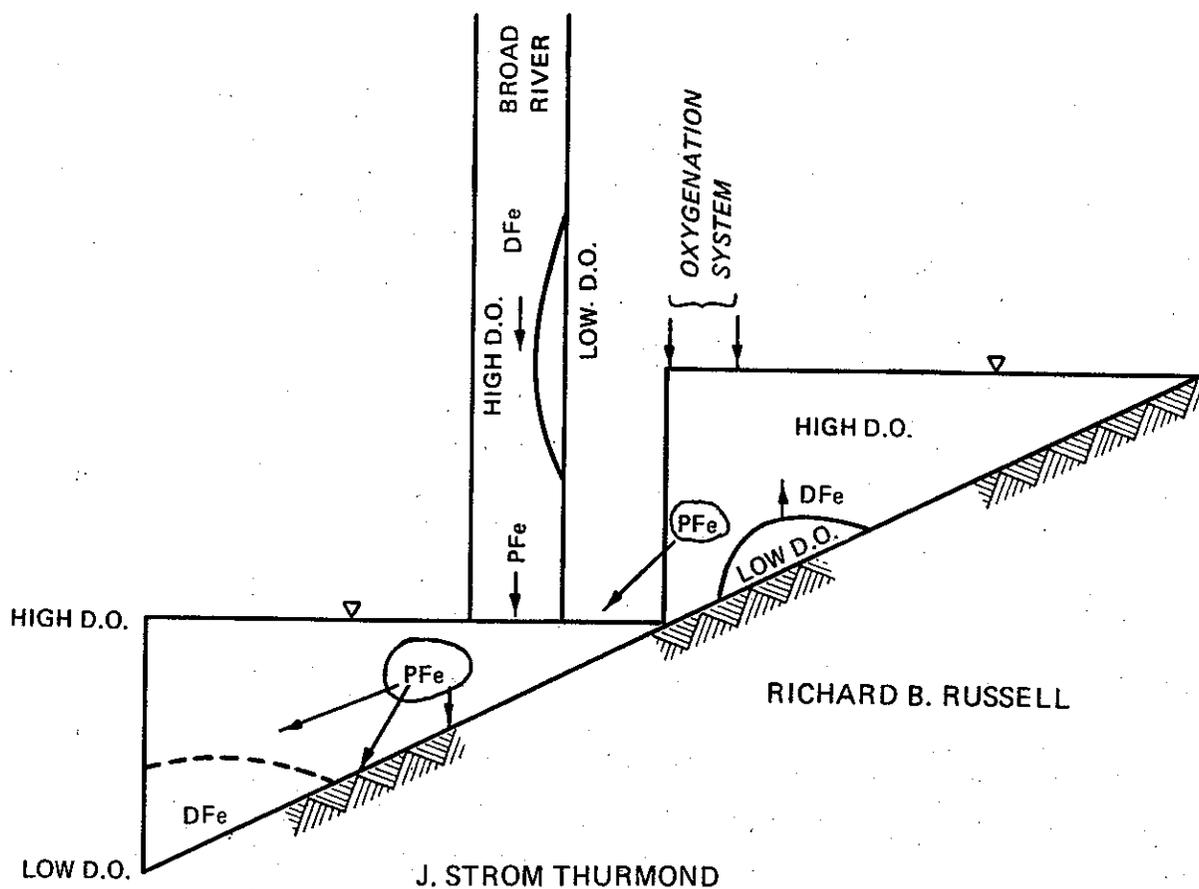


Figure 51. Suggested scenario for iron cycling in Richard B. Russell and J. Strom Thurmond Lakes

nitrogen concentrations decreased in the surface waters while the concentrations of inorganic forms increased in bottom waters. Oxidized forms of nitrogen, primarily nitrate, were predominant in bottom waters prior to the onset of anoxic conditions. As hypolimnia became anoxic, nitrate concentrations decreased to near the detection limit, due to reduction, and concentrations of ammonia increased. However, oxidized forms of nitrogen comprised the majority of the total nitrogen in the bottom waters of Richard B. Russell Lake, downstream of the oxygenation system, at all times, due to operation of the system during stratification. Following fall mixing, oxidized forms of dissolved nitrogen again comprised the majority of the total nitrogen pool.

79. Unlike interlake differences observed in 1986, chlorophyll a concentrations in each lake were similar in 1987, suggesting that phytoplankton

productivity in Richard B. Russell Lake is becoming similar to that of Hartwell and J. Strom Thurmond Lakes. However, chlorophyll a concentrations were mostly lower than 20 $\mu\text{g}/\ell$, suggesting that phytoplankton productivity is low in each lake.

80. Water quality conditions were more pronounced in the embayments than in the main stems of Richard B. Russell and J. Strom Thurmond Lakes. Anoxic zones were more pronounced, and maximum observed concentrations of metals and nutrients occurred at tributary embayment stations. The influence of these embayments on main stem water quality appears to be minimal, however, due to mixing between the main stem and the embayments and subsequent dilution.

81. The outflow from Hartwell Dam provides over 80 percent of the total inflow to Richard B. Russell Lake and has a marked influence in water quality in the mid and upper regions of the lake. Water quality conditions of the lower region of the lake, although subject to anoxic conditions, are less severe due to operation of the oxygenation system. The outflow from Richard B. Russell Dam contributes nearly 60 percent of the total inflow to J. Strom Thurmond Lake; however, its effects on water quality are less discernible due to the contributions of Broad River.

82. Data from diel and dye studies provide insight into flow patterns that exist in the release waters from Richard B. Russell Dam. Diel effects on temperature and dissolved oxygen are apparent, and generation has a pronounced effect on flow patterns in the headwater and upper region of J. Strom Thurmond Lake. Furthermore, data from the dye study suggest that release water moves through the lake as a well-defined underflow, at least as far down as Station 030 in the midlake region.

83. Water quality data from the diel study support observations of previous studies (James et al. 1985, Hains et al. 1988), indicating that generation cycles have a strong influence on water quality in the Richard B. Russell Dam tailrace. Release waters first displace lake water downstream to the plunge line (approximately 5 km downstream from the dam). After plunging, release water travels through the lake below surface waters as an underflow. Following cessation of generation, lake surface waters downstream of the plunge point flow upstream and mix with the released water upstream of the plunge point. The cycle is repeated with each subsequent generation.

84. The current morphometry of the headwater region of J. Strom Thurmond Lake may influence diel and mixing patterns as well. Temperature measurements

from the diel study (see Figure 42) indicate that a less than 2° C change in bottom water temperature occurs in the deep pool immediately downstream from Richard B. Russell Dam between periods of generation and nongeneration (Figure 52).

Long-Term Trends in Water Quality

85. Temperatures observed in the forebay (Station 020) and midlake region (Station 030) of J. Strom Thurmond Lake during the 4-year study are depicted in Figures 53 and 54, respectively. A comparison of mean hypolimnetic temperature, calculated for the stratification period (May through October) for each year at depths greater than 12 m at Station 020, indicates cooler temperatures since 1984 (Table 7). Mean hypolimnetic temperatures in 1985 and 1987 were not statistically different at the 5-percent confidence interval but were less than the mean value for 1986 ($p > 0.001$) indicating annual variability. Although less pronounced, thermal stratification appears to be more defined as a result of cooler hypolimnetic temperatures.

86. Dissolved oxygen concentrations at the forebay station of each lake in 1987 were similar to those observed in previous years (Figures 55-57). While comparisons between lakes are difficult, due to operation of the oxygenation system in Richard B. Russell, annual comparisons of each lake can be made. Most apparent is an increase in the extent of the anoxic zone in the forebay of J. Strom Thurmond Lake (Figure 55), particularly between 1984 and 1985. However, while anoxic conditions were observed in the hypolimnion at Station 030 in 1984, DO levels have remained above 2 mg/l since 1985 (Figure 58).

87. Dissolved oxygen conditions in the tributary embayments of Richard B. Russell have remained similar during the 4-year study period (Figures 59 and 60). In contrast, DO conditions in the main stem of Richard B. Russell improved from 1984 to 1987 (Figure 61). Additionally, the anoxic region of the main stem was confined to the lower region of the main stem between Station 100 and just upstream from Station 120 during 1987. Prior to 1987, anoxic conditions had been observed as far upstream as Station 160 (James et al. 1985, 1986; Hains et al. 1988).

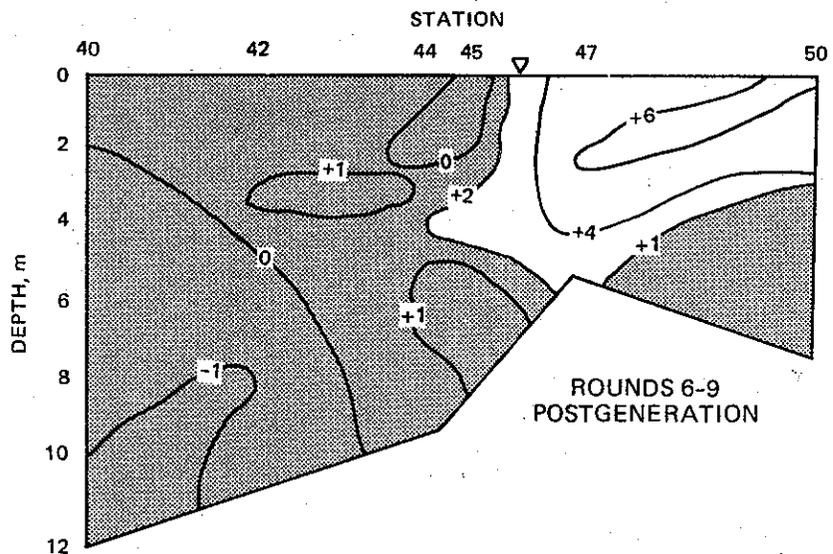
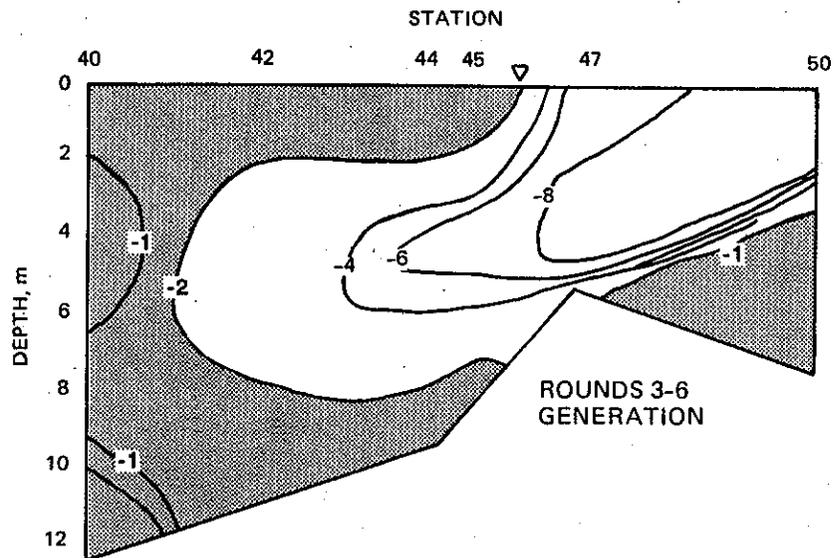


Figure 52. Spatial changes in water temperature (expressed as change per °C) during generation and postgeneration periods in the headwater region of J. Strom Thurmond Lake

88. The computer program PROFILE was used to calculate volumetric depletion rates at selected stations in Richard B. Russell and J. Strom Thurmond Lakes for 1987 (Table 8). Since selection of dates and depths necessary for calculations is subjective, a range of values is reported for most of the

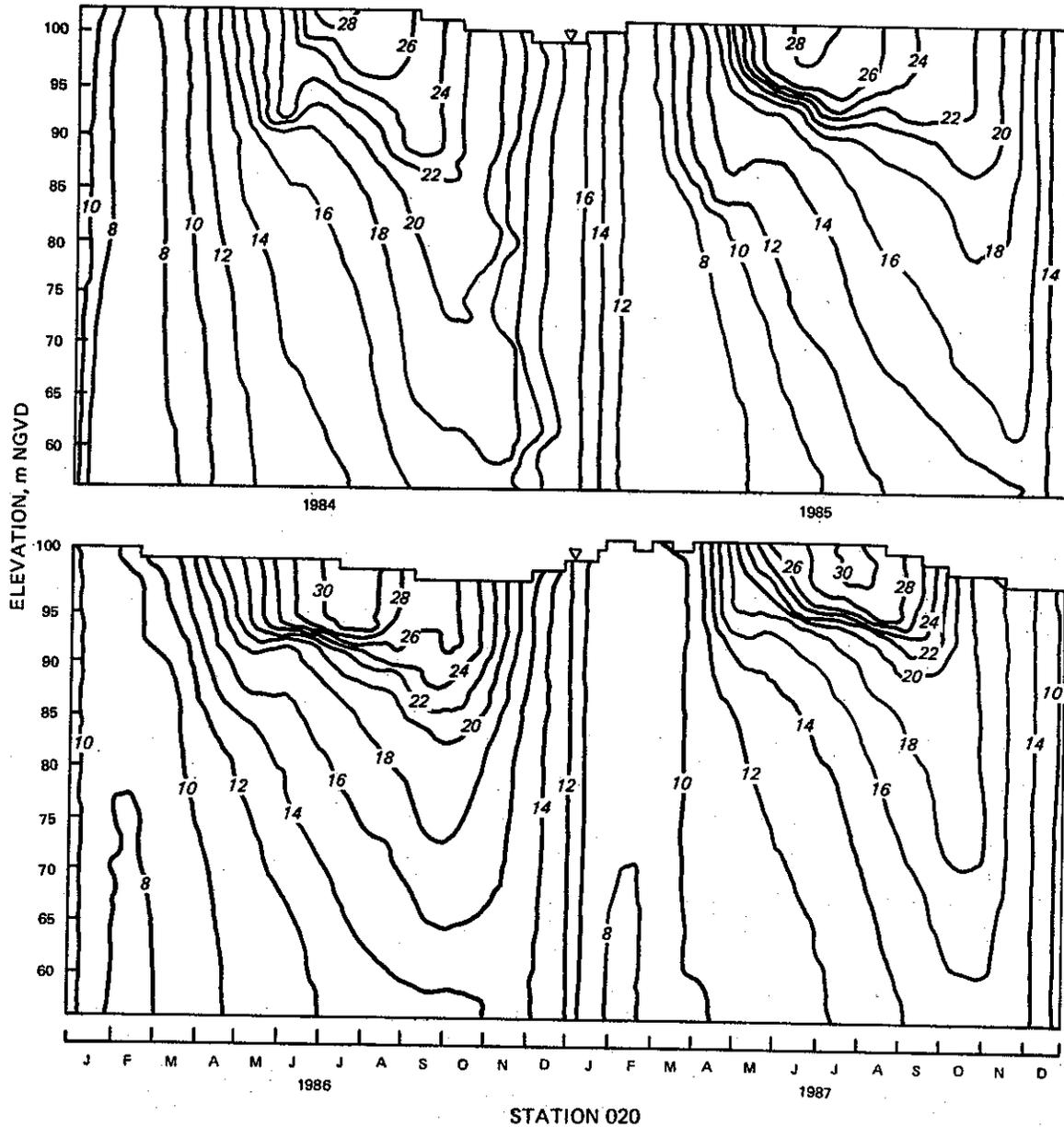


Figure 53. Temporal and vertical patterns in temperature ($^{\circ}\text{C}$) for Station 020, J. Strom Thurmond Lake, 1984-1987

stations, and rigorous annual comparisons of rates are inappropriate. In general, volumetric depletion rates in the hypolimnion are greater than those for the metalimnion, especially in the tributary embayments of Richard B. Russell Lake. Depletion rates in the main stem of each lake are similar and relatively lower than rates in the tributary embayments, indicating differences in water quality between the main stems and embayments.

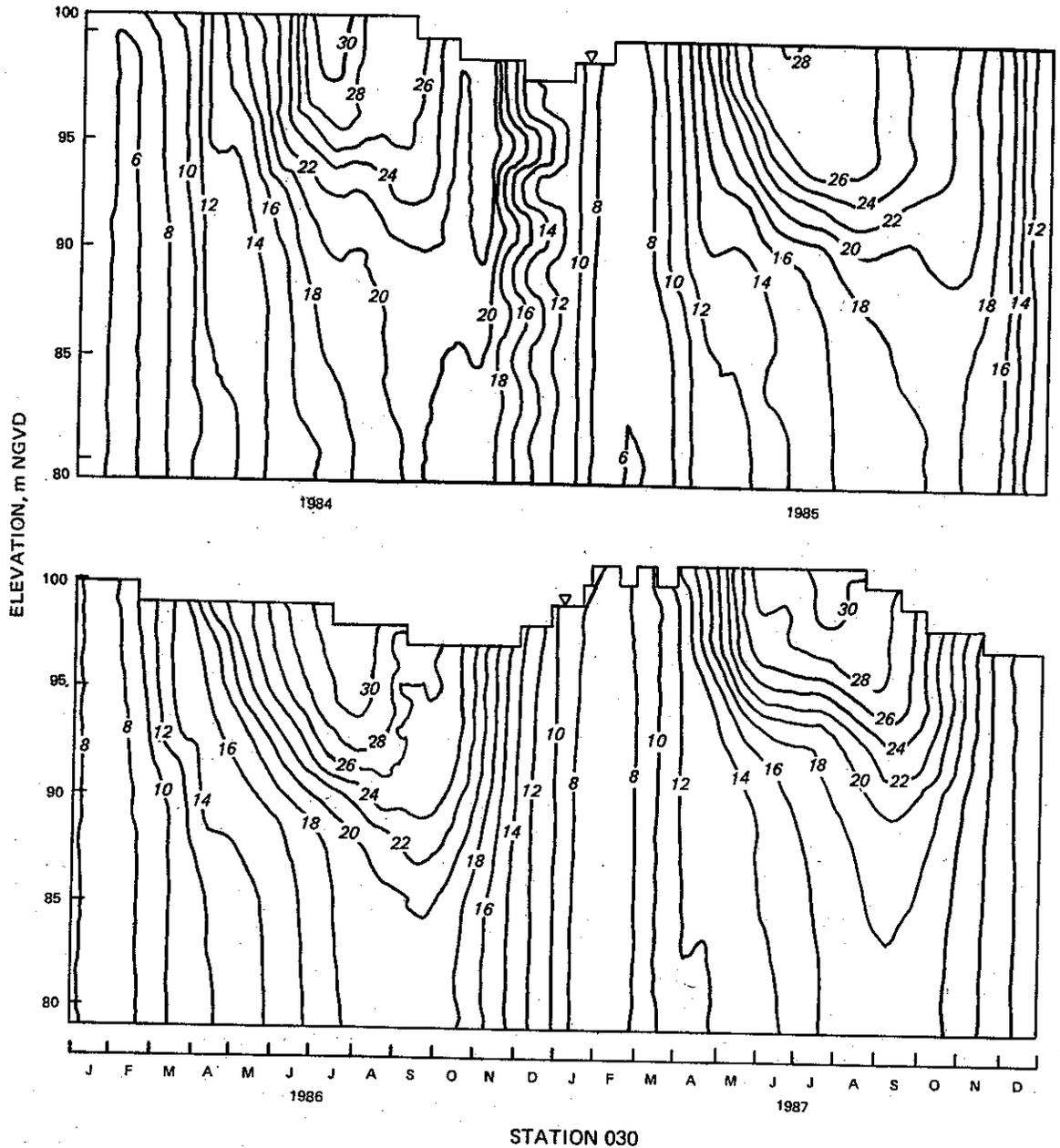


Figure 54. Temporal and vertical patterns in temperature ($^{\circ}\text{C}$) for Station 030, J. Strom Thurmond Lake, 1984-1987

89. Water quality conditions in releases from Hartwell, Richard B. Russell, and J. Strom Thurmond Dams for the 4-year period reflect conditions in each lake and provide an additional viewpoint in evaluating long-term trends in water quality in the three-lake system. However, limited data for 1984 and 1985 restrict detailed annual comparisons at this time. Seasonal and

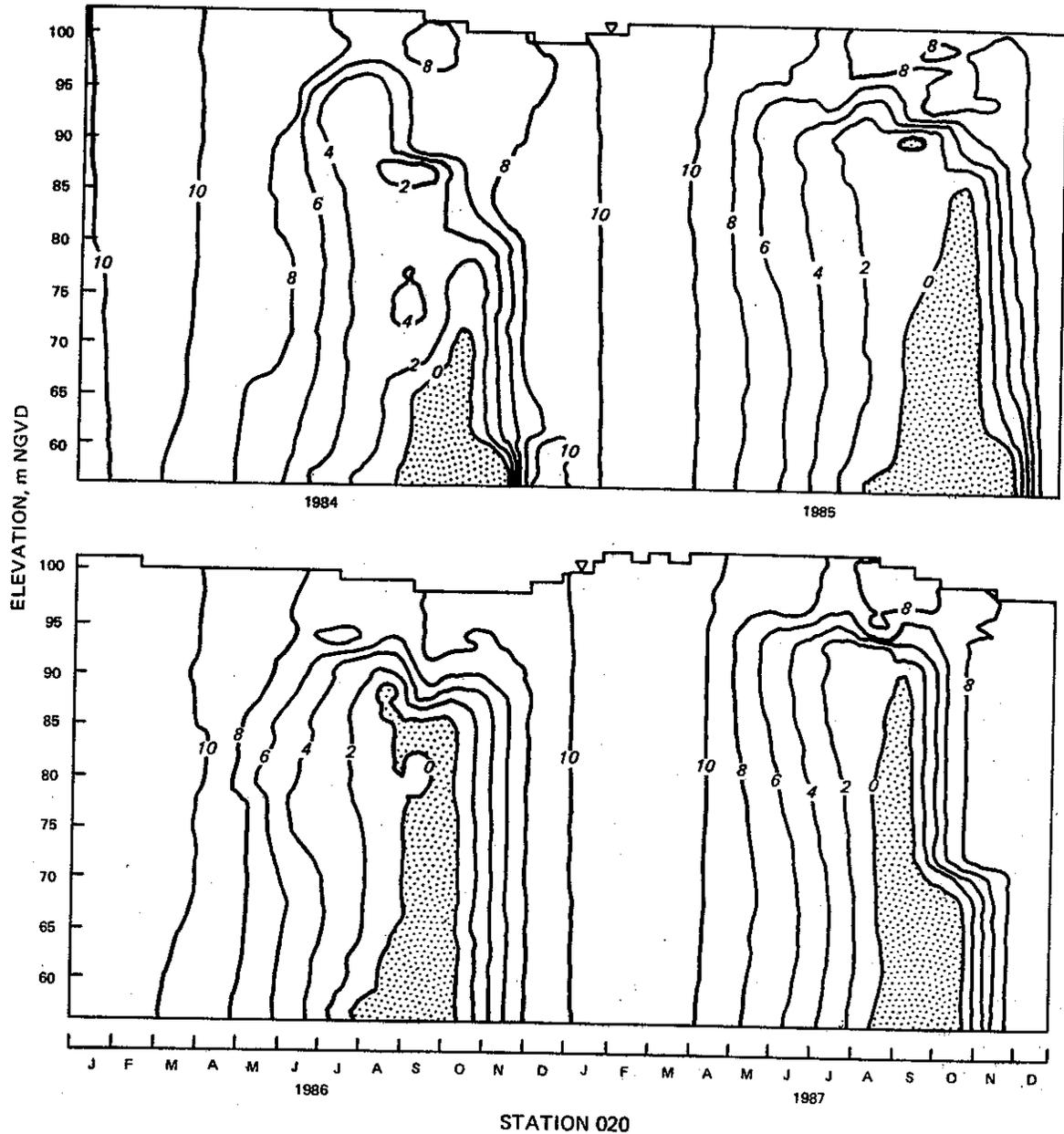


Figure 55. Temporal and vertical patterns in DO (mg/l) for Station 020, J. Strom Thurmond Lake, 1984-1987

spatial trends in release water concentrations of dissolved oxygen, manganese, and iron were most apparent.

90. Spatial trends in DO concentrations are apparent in the outflows of each lake (Figure 62). Concentrations of DO in the releases from Richard B. Russell Dam during thermal stratification each year remained near 6.0 mg/l. Conversely, DO concentrations in the releases from Hartwell and J. Strom

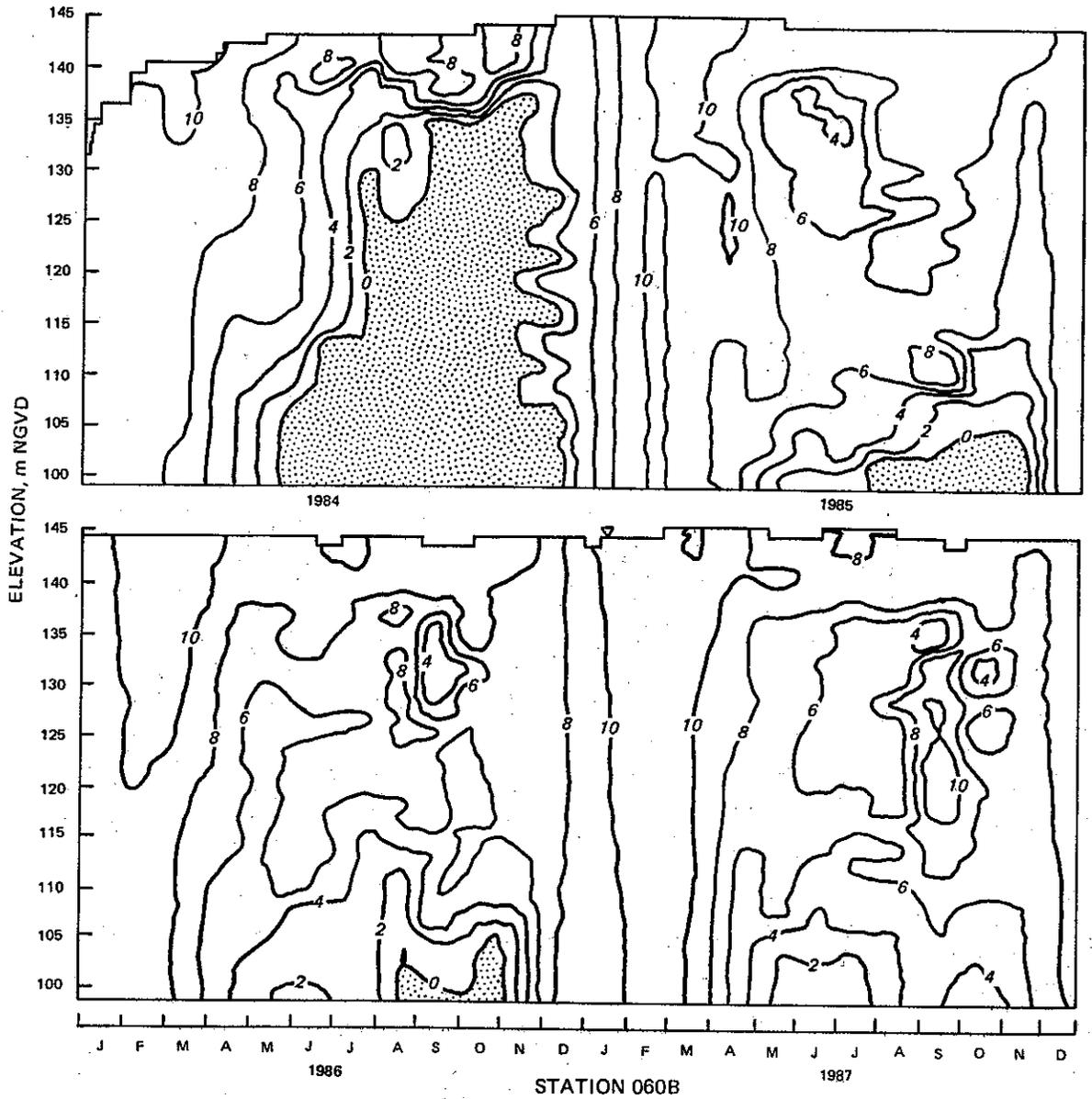


Figure 56. Temporal and vertical patterns in DO (mg/l) for Station 060B, Richard B. Russell Lake, 1984-1987

Thurmond Dams for similar periods each year have been consistently lower and more variable (1.0 to 5.0 mg/l). Additionally, minimum DO concentrations in the releases from J. Strom Thurmond Dam appear to be lower in 1986 and 1987 than in 1984 and 1985.

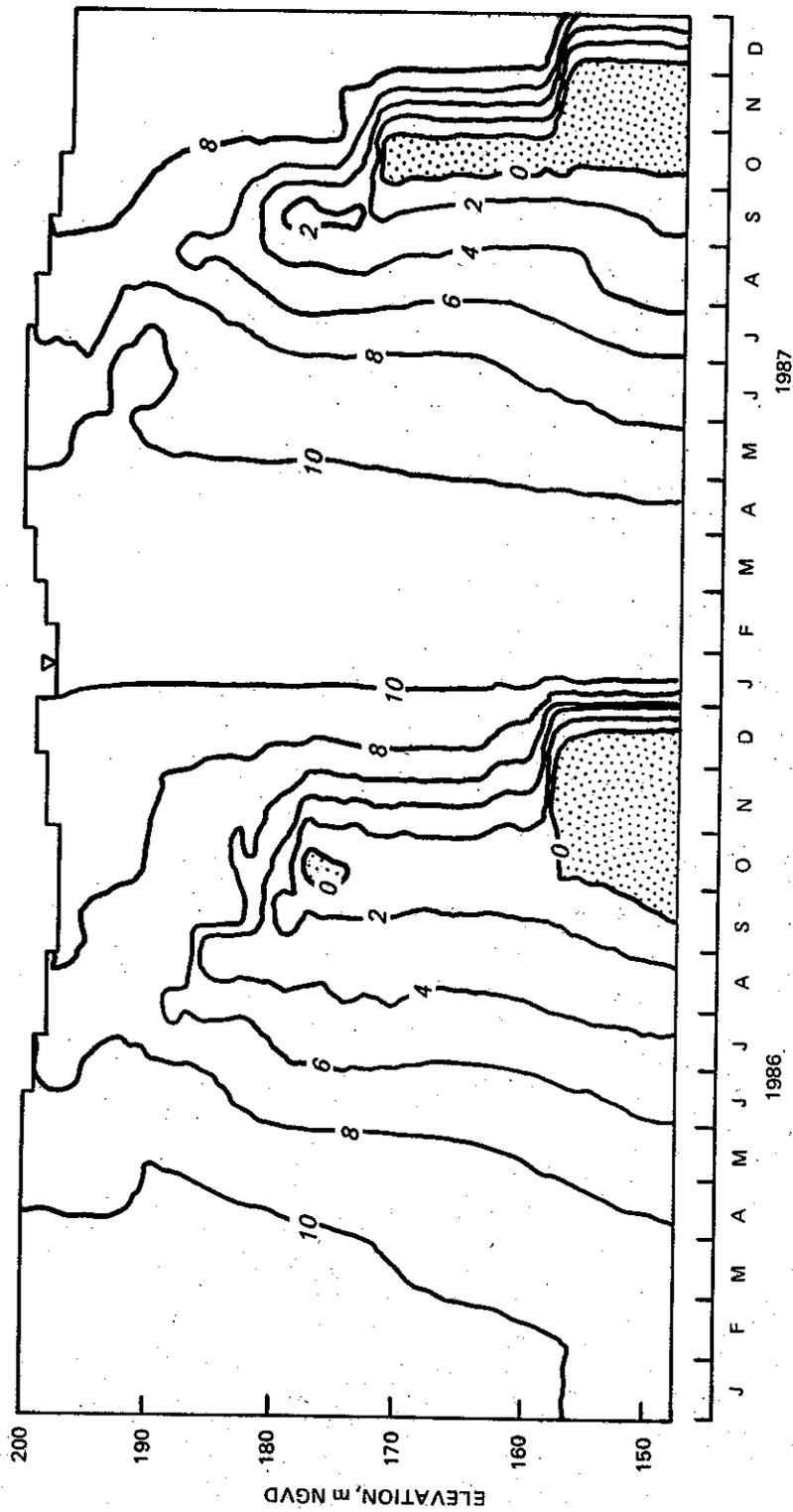


Figure 57. Temporal and vertical patterns in DO (mg/l) for Station 210, Hartwell Lake, 1986-1987

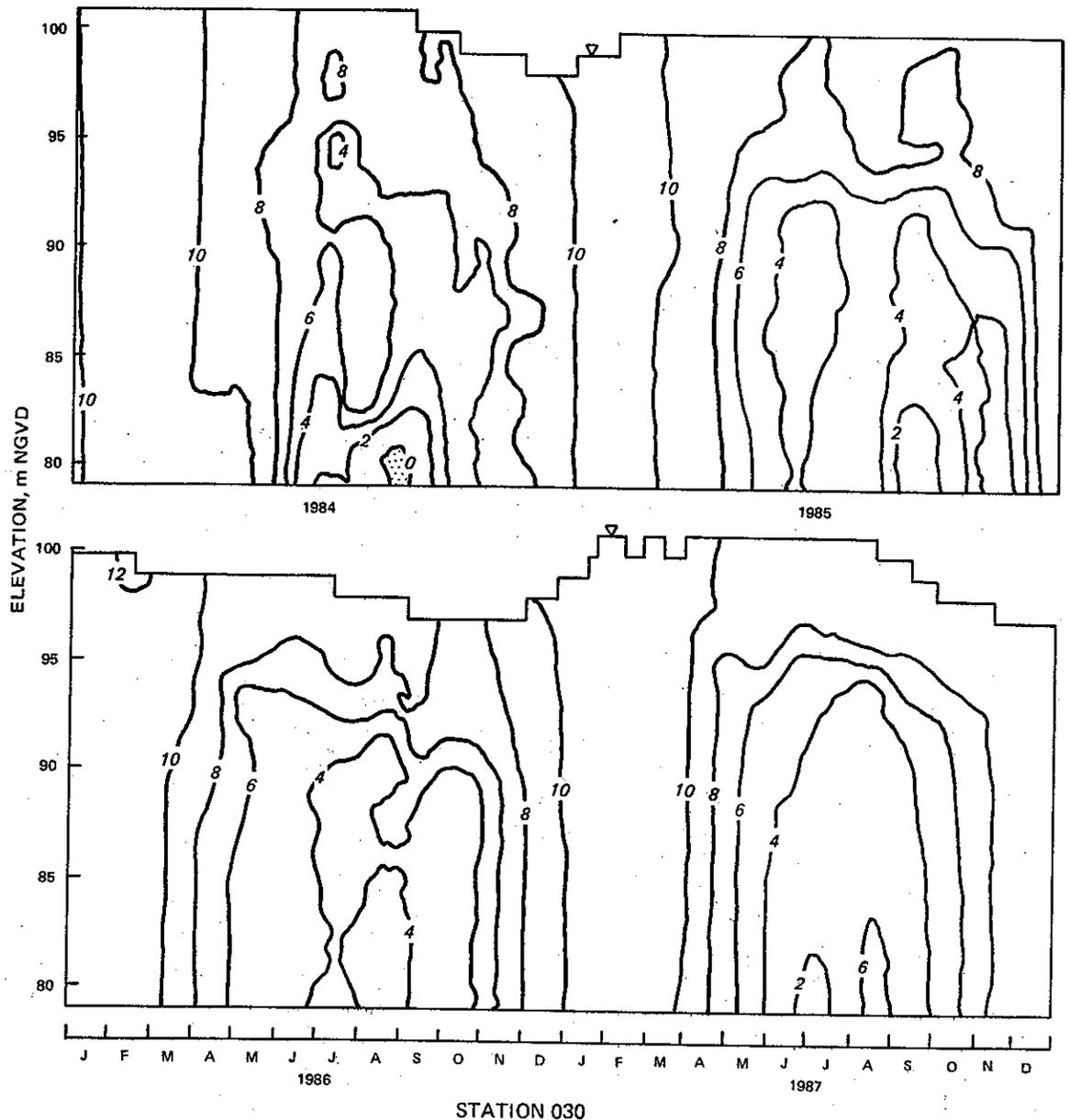


Figure 58. Temporal and vertical patterns in DO (mg/l) for Station 030, J. Strom Thurmond Lake, 1984-1987

91. Concentrations of manganese in the releases from Hartwell, Richard B. Russell, and J. Strom Thurmond Dams for the 4-year period are depicted in Figure 63. Maximum observed concentrations of dissolved manganese in the releases from Richard B. Russell Dam remained near 0.4 mg/l during the first 3 years but were somewhat lower in 1987 (0.2 to 0.3 mg/l). Concentrations of dissolved manganese in the releases from Hartwell Dam during 1986 and

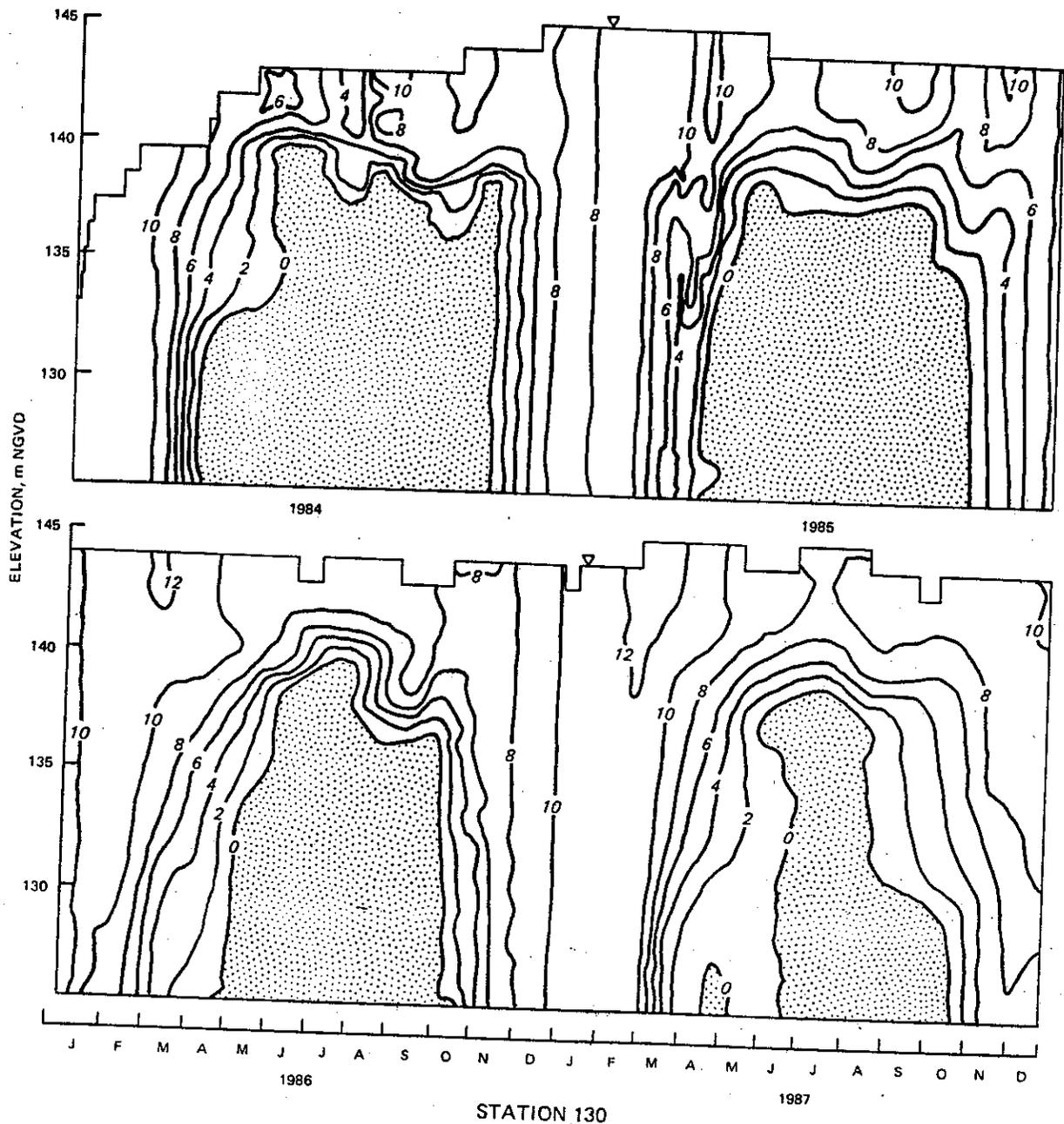


Figure 59. Temporal and vertical patterns in DO (mg/l) for Station 130, Richard B. Russell Lake, 1984-1987

1987 were similar to those observed in the releases from Richard B. Russell Dam. In contrast, maximum concentrations of dissolved manganese in releases from J. Strom Thurmond Dam appear to be lower than concentrations in

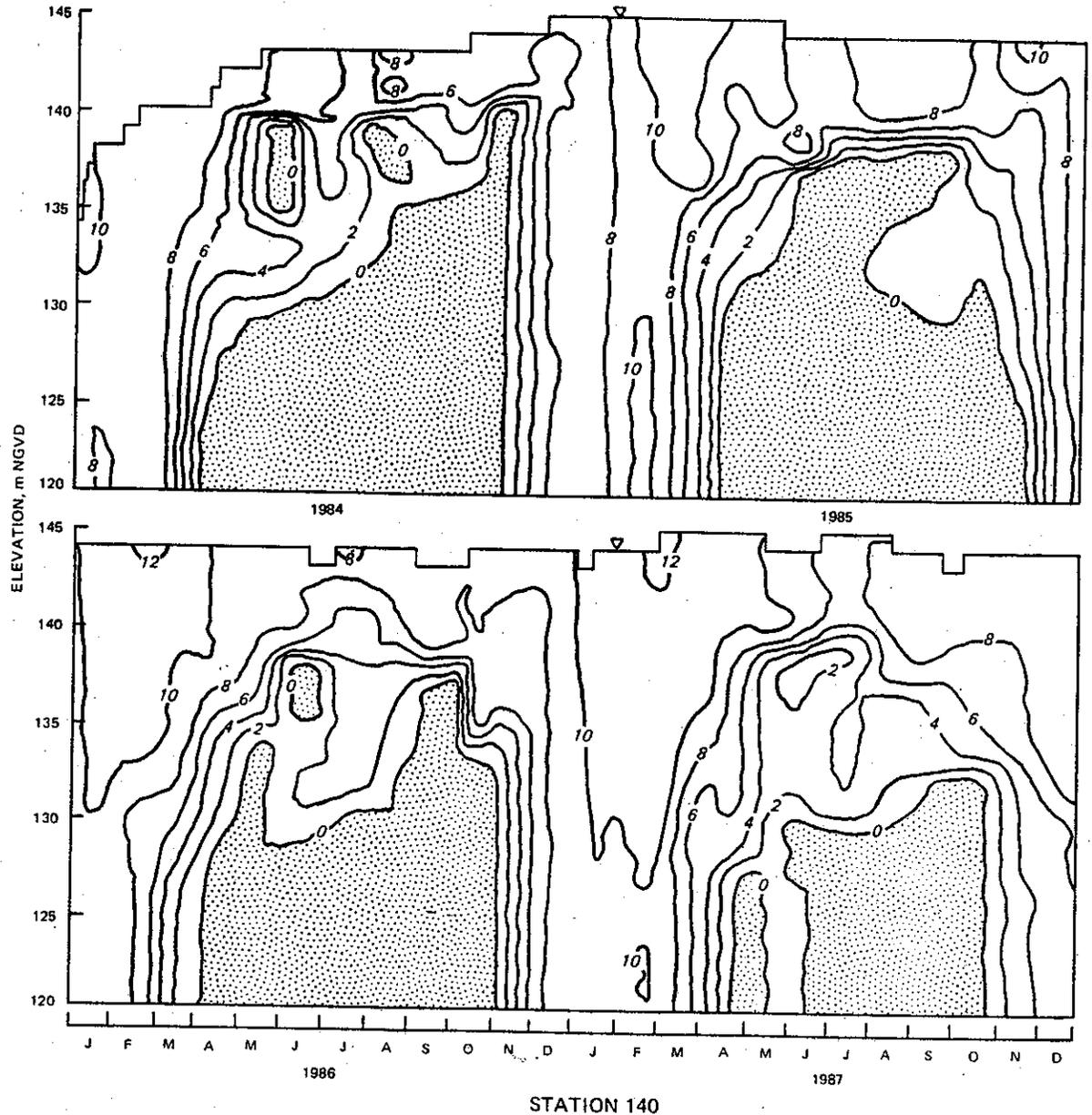


Figure 60. Temporal and vertical patterns in DO (mg/l) for Station 140, Richard B. Russell Lake, 1984-1987

Richard B. Russell and Hartwell Dam releases, except for 1987 when maximum concentrations increased to near 0.3 mg/l.

92. Annual and spatial trends in dissolved and particulate iron concentrations in the releases from the three dams were similar to those observed for manganese (Figure 64). While maximum concentrations of particulate iron

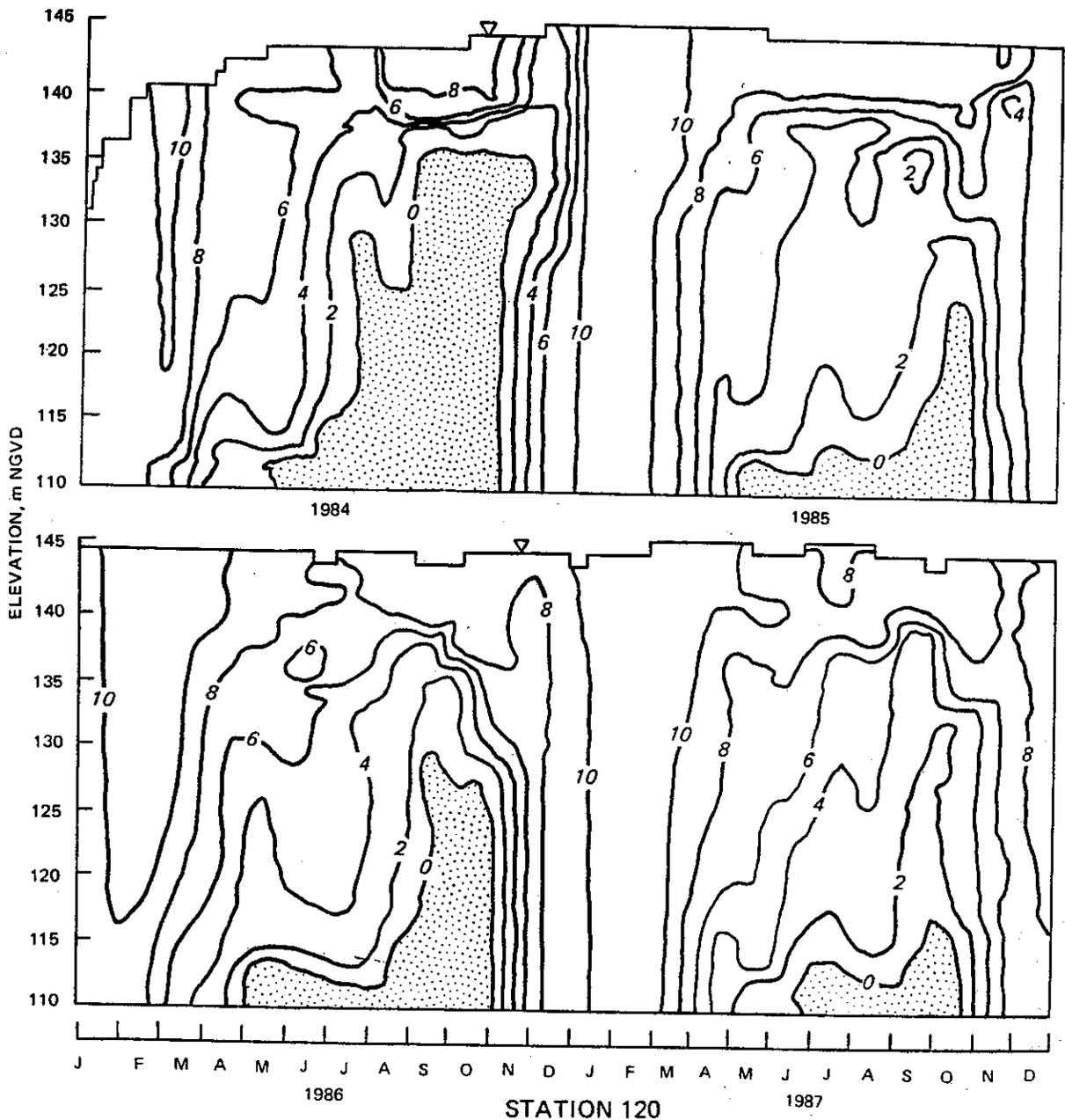


Figure 61. Temporal and vertical patterns in DO (mg/l) for Station 120, Richard B. Russell Lake, 1984-1987

in the releases from Hartwell Dam were similar for 1984 to 1986, increased maximum concentrations were observed in 1987 and may be the result of annual variability. Maximum concentrations of particulate iron in the releases from J. Strom Thurmond Dam varied annually as well. Particulate iron

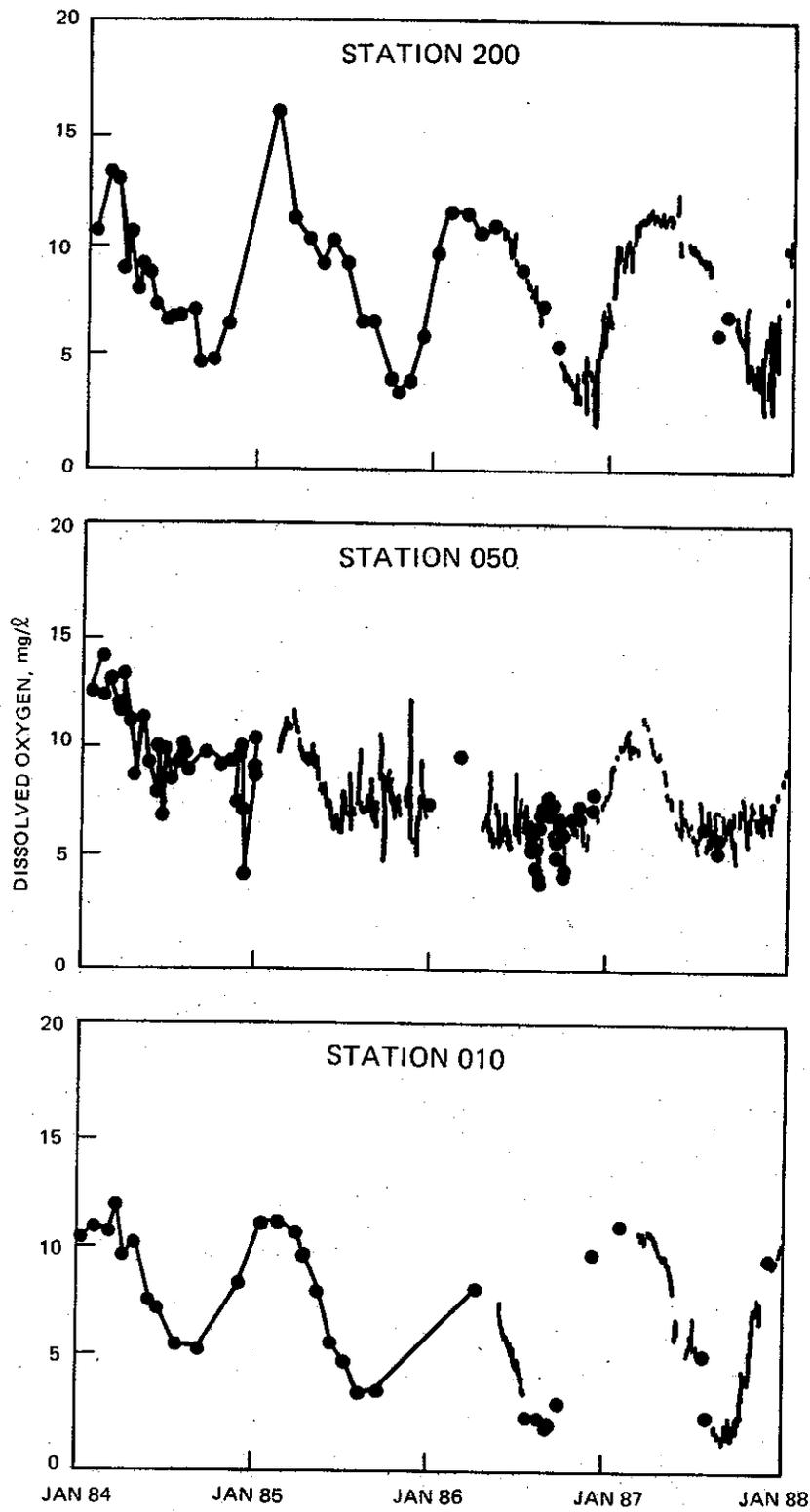


Figure 62. Dissolved oxygen concentrations in release waters from Hartwell Dam (Station 200), Richard B. Russell Dam (Station 050), and J. Strom Thurmond Dam (Station 010), 1984-1987

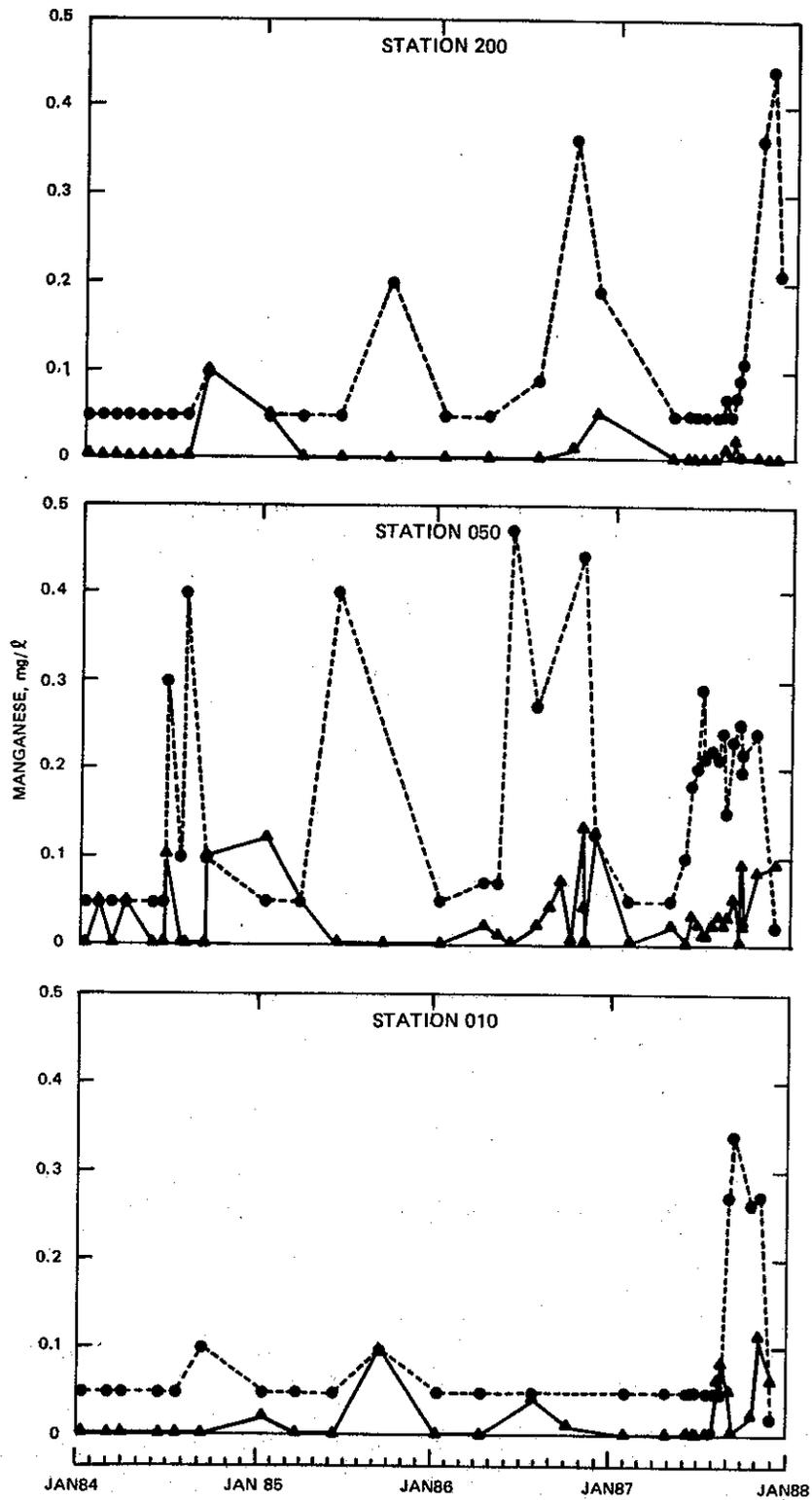


Figure 63. Dissolved (--) and particulate (-) manganese concentrations (mg/l) in release waters from Hartwell Dam (Station 200), Richard B. Russell Dam (Station 050), and J. Strom Thurmond Dam (Station 010), 1984-1987

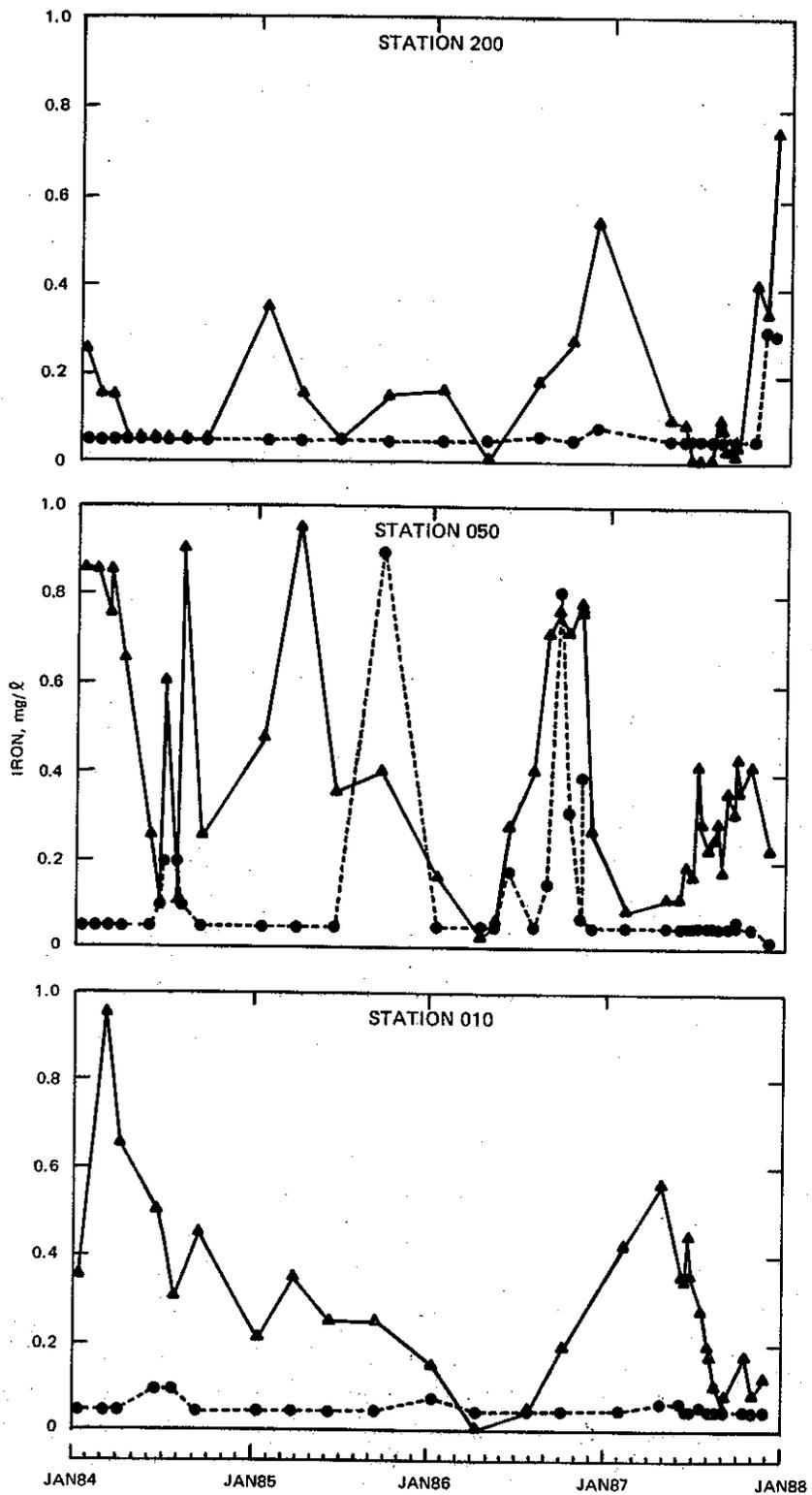


Figure 64. Dissolved (--) and particulate (-) iron concentrations (mg/l) in release waters from Hartwell Dam (Station 200), Richard B. Russell Dam (Station 050), and J. Strom Thurmond Dam (Station 010), 1984-1987

concentrations were highest in 1984, decreased in 1985 and 1986, and increased again in 1987. Maximum concentrations of particulate iron in the releases from Richard B. Russell Dam remained near 0.4 mg/l for 1984 to 1987, and annual variability was less apparent than that of Hartwell and J. Strom Thurmond Lakes. With the exception of concentrations in the releases from Richard B. Russell Dam in 1986 and Hartwell Dam in 1987, dissolved iron concentrations in the release waters were negligible during the study period.

93. While actual calculations of the quantities of manganese and iron transported through the three-lake system have not been made, outflow concentrations identify the forms of these parameters available for transport. Manganese is transported in dissolved or reduced forms while iron is transported primarily in particulate or oxidized forms. Currently, Richard B. Russell Lake probably transports more manganese and iron than either Hartwell or J. Strom Thurmond Lake.

94. The implications of trends in manganese and iron transport in the three-lake system are not readily apparent. Annual variations in water quality conditions in each lake and uncertainties of the effects of inflow mixing patterns and residence time of inflows further compound assessment of transport effects. Increased sampling of outflow concentrations will allow mass balance calculations and more rigorous comparisons in the future.

95. As previously mentioned, the oxygenation system in Richard B. Russell Lake affects the cycling of manganese and iron in the lower region of the lake differentially. While the impact of these effects on the transport of manganese and iron in the three-lake system is not easily quantified, initial assessment of the effects of system operation is possible. System operation has varied each year, with the upstream system primarily operated in 1985, the downstream system in 1986, and both systems in 1987 (the upstream system was turned on in early July). As depicted in Figure 63, effects of system operation on concentrations of dissolved and particulate manganese in the releases were similar annually. Conversely, with the exception of a single peak in 1985 (coincident with a brief period of inoperation of the oxygenation system), high concentrations of particulate iron were not observed in release waters except during 1986, when the downstream system was in operation (see Figure 64). Assessment of long-term trends in effects of the oxygenation system on the cycling of manganese and iron is limited, however, by only 3 years of data, each under different operating regimes.

PART VI: CONCLUSIONS

96. Temporal trends in water quality observed in Hartwell, Richard B. Russell, and J. Strom Thurmond Lakes in 1987 were similar to those observed following the first year of impoundment of Richard B. Russell Lake. While concentrations of total organic carbon, phosphorus, and nitrogen were similar to those of previous years, spatial differences in concentrations of manganese, iron, and chlorophyll varied somewhat from trends observed in previous years.

97. Manganese and iron cycles are quite dynamic in the three-lake system, and effects of annual cycles are apparent within and among the three lakes. Manganese concentrations increase seasonally in the hypolimnion and, due to minimal oxidation, manganese is transported in the three-lake system primarily in the dissolved form. Conversely, iron, which is oxidized more readily than manganese, is transported primarily as particulates. Additionally, as reflected in release concentrations, J. Strom Thurmond Lake retains most of the manganese and iron transported from upstream. Richard B. Russell Lake, due to operation of the oxygenation system, retains some of the iron (as particulates) and potentially reduces the transport downstream.

98. Chlorophyll concentrations were similar to those of previous years suggesting that primary productivity in the three-lake system has changed little during the study period. Unlike 1986, when chlorophyll a concentrations were greater in Richard B. Russell Lake than in J. Strom Thurmond Lake, similar concentrations were observed in the lakes in 1987. Annual trends in chlorophyll a concentrations suggest that primary productivity in Richard B. Russell Lake is decreasing from postimpoundment levels and approaching levels in J. Strom Thurmond Lake.

99. Water quality in the main stem region of Richard B. Russell Lake appears to be improving annually, as evidenced by decreasing maximum concentrations of chemical parameters and decreased anoxic regions. Conditions in the tributary embayments remained similar for the 4-year period, however. Differences in water quality between main stem and embayment stations suggest that inflow quality to these regions has a pronounced effect on water quality within each region. However, concentrations of parameters in the discharge reflected conditions in the forebay region of the lake, and influences of tributary water quality were minimal.

100. Operation of the oxygenation system greatly influences the water quality in the forebay and discharge from Richard B. Russell Lake. Operation of the oxygenation system successfully maintained dissolved oxygen concentrations near the target level of 6 mg/l in the releases of Richard B. Russell Dam throughout the period of stratification. Calculations of DO concentrations in the releases with and without oxygenation indicate that the oxygenation system increases DO concentrations approximately 2 mg/l under current operating conditions. As mentioned previously, the oxidation and resultant precipitation of iron is enhanced due to operation of the oxygenation system. Effects of the system on reduced or dissolved manganese are less pronounced, however.

101. Annual trends in the distribution of temperature and dissolved oxygen in the main stem region of J. Strom Thurmond Lake were apparent. Hypolimnetic temperatures in J. Strom Thurmond Lake are approximately 2° C lower since 1984 due to cooler inflows from Richard B. Russell Dam. Dissolved oxygen concentrations in the hypolimnion appear to be lower in the forebay region but are greater in the midlake region since 1984.

102. Data from dye and diel studies conducted in J. Strom Thurmond Lake suggest that complex inflow mixing patterns exist in the headwater region of the lake and are associated with generation cycles at Richard B. Russell Dam and existing basin morphometry in the headwater region of J. Strom Thurmond Lake. Water quality of the release from Richard B. Russell Dam dominates the water quality in the headwater region of the lake. The inflow travels through the headwater region as a plug flow for approximately 3 km. The inflow then plunges and moves through the lake as an underflow, at least as far downstream as the midlake region, at an average velocity of 0.11 m/sec. Reduced retention of release waters containing elevated concentrations of dissolved manganese and particulate iron markedly affects the distribution of these metals in J. Strom Thurmond Lake. Additionally, cold, oxygenated releases are transported to the hypolimnion of the midregion of the lake and may account for decreased temperatures and the increased concentrations of dissolved oxygen observed annually.

PART VII: RECOMMENDATIONS

103. Continued monitoring of physical, chemical, and biological parameters in Hartwell, Richard B. Russell, and J. Strom Thurmond Lakes will allow continued evaluation of the impacts of impoundment of Richard B. Russell Lake on the water quality of J. Strom Thurmond Lake. Additionally, continued monitoring in the secondary tributaries and main stem of Richard B. Russell Lake will further the evaluation of maturation in the lake and allow assessment of future impacts on water quality in J. Strom Thurmond Lake.

104. Monitoring of physical and chemical parameters in the forebay and releases from Richard B. Russell Dam and Lake will allow additional assessment of the effects of the oxygenation system on the water quality in this vicinity. Continued monitoring of temperature and DO concentrations will provide data necessary for operation of the oxygenation system to maintain DO concentrations at 6 mg/l in the release from Richard B. Russell Dam. Additionally, variable effects of operation of the oxygenation system on water quality suggest that further evaluation of operational effects is necessary for optimization of system operation.

105. Water quality sampling should continue to address the dynamics of manganese and iron in the three-lake system with respect to cycling and transport within and between the lakes. Trends in the distribution of manganese and iron concentrations observed for the three lakes suggest that cycling of these metals varies temporally and spatially. Additionally, varied operation of the oxygenation system results in variations in particulate formation of iron in the forebay of Richard B. Russell Lake. Consequently, impacts on water quality conditions, due to changes in the cycling of these metals, will continue to vary. Additionally, ongoing sediment trap and light transmittance studies, to identify and quantify the distribution of particulates in the forebay and tailrace of Richard B. Russell, should continue.

106. Phytoplankton dynamics provide an indicator of water quality conditions, and continued monitoring of phytoplankton populations in J. Strom Thurmond and Richard B. Russell Lakes is recommended to assess impacts of changes in water quality on the biota of the lakes. Changes in community structure of phytoplankton populations in each lake may occur due to changes in nutrient availability and maturation of Richard B. Russell Lake.

107. Lastly, water quality sampling should continue to address water quality processes in the tailrace and forebay region of Richard B. Russell Dam and Lake to provide a baseline of water quality conditions prior to initiation of pumped-storage operations. Additionally, water quality sampling should continue to supplement ongoing fisheries studies in the tailrace.

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Table 1
Physical Characteristics of J. Strom Thurmond,
Richard B. Russell, and Hartwell Lakes

Characteristic	J. Strom Thurmond Lake	Richard B. Russell Lake	Hartwell Lake
Maximum conservation pool elevation, m NGVD	100.6	144.8	201.2
Minimum conservation pool elevation, m NGVD	95.1	143.2	190.5
Flood control pool elevation, m NGVD	102.1	146.3	202.7
Surface area, sq km*	283.2	107.9	226.6
Volume, 10 ⁶ cu m*	3,023.3	1,271.0	3,146.7
Maximum depth, m*	45	47	55
Mean depth, m*	11	12	14
Reservoir length, km*	63	45	79 Tugaloo R. 72 Seneca R.
Shoreline length, km*	1,930	885	1,548
Shoreline development ratio*	32.0	24.5	29.0
Drainage area, sq km	14,906	7,508	5,406
Residence time, day*	144	102	306
Mean discharge, cu m/sec	243.6**	143.8†	119.0**
Top of penstock elevation, m NGVD	88.4	133.2	181.4
Bottom of penstock elevation, m NGVD	69.5	110	160.9

* At maximum conservation pool elevation.
** Mean discharge for the period 1925-1973.
† Mean river discharge for 31 years.

Table 2
Sampling Schedule

Parameter	Winter		Spring High Flow			Stratification				Postmixing		
	Jan	Feb	Mar	Apr	May	Early		Late		Oct	Nov	Dec
						Jun	Jul	Aug	Sep			
In situ	X	X	X	X	X	X	X	X	X	X	X	X
Physicochemical	X			X	X	X	X	X	X	X	X	X
Biological	X	X	X	X	X	X	X	X	X	X	X	X
Intensive studies						X			X			

Table 3
In Situ and Physicochemical Parameters Monitored During 1987

In situ	Biological
Temperature	Chlorophyll <u>a</u>
Dissolved oxygen	
pH	Nutrients
Specific conductance	Total organic carbon
Oxidation-reduction potential	Dissolved organic carbon
	Total phosphorus
Physicochemical	Total soluble phosphorus
Total alkalinity	Soluble reactive phosphorus
	Total nitrogen
Metals	Total dissolved nitrogen
Total iron	Ammonia nitrogen
Dissolved iron	Nitrate-nitrite nitrogen
Total manganese	Sulfide
Dissolved manganese	

Table 4

Minimum and Maximum Values for Selected Chemical Parameters
Hartwell Lake Forebay

Parameter	Total Nitrogen		Dissolved Nitrogen		Ammonia Nitrogen		Nitrate-Nitrite Nitrogen		Total Phosphorus		Soluble Phosphorus		Total Organic Carbon		Dissolved Organic Carbon		Total Alkalinity		Specific Conductance µS
	mg/l		mg/l		mg/l		mg/l		mg/l		mg/l		mg/l		mg/l		mg/l	CaCO ₃	
Minimum value	0.18	Feb	0.10	Feb	<0.02	Feb-Jul	<0.04	Jul-Oct	<0.005	Jul	<0.005	Annually	0.07	Feb	0.07	Feb	7.4	April	22
Date of occurrence																			Annually
Maximum value	0.94	Jul	0.79	Jul	0.22	Oct	0.52	Jul	0.015	Oct/Feb	0.015	Oct	1.9	Jul	1.5	Jul	14.5	Oct	73
Date of occurrence																			Oct

Table 5

Maximum Concentrations (mg/l) of Chemical Parameters
in Richard B. Russell Lake, 1987

Station	Total Manganese		Total Iron		Total Organic Carbon		Total Nitrogen		Total Phosphorus	
Tributaries										
130	1.41		4.69		5.6		2.30*		0.067	
140	1.78		7.75		7.1		1.81		0.205*	
150	2.14*		10.04*		7.4*		1.85		0.068	
Main stem										
060B	1.07		1.71		2.4		0.98		0.017	
100B	1.56		5.79		2.3		1.03		0.033	
120	1.38		5.41		2.5		1.46		0.041	
160	0.67		0.74		2.3		0.74		0.022	
180	0.30		0.61		2.5		1.26		0.018	

* Denotes maximum values observed in 1987.

Table 6
Dates, Times (Hour), and Location of Diel Sampling at J. Strom Thurmond Lake

Station	Round								
	1 (Sep 20)	2* (Sep 21)	3 (Sep 21)	4 (Sep 21)	5 (Sep 21)	6* (Sep 21)	7 (Sep 22)	8 (Sep 22)	9* (Sep 22)
40	1845	1105	1240	1600	1900	2310	0105	0850	1225
42	1835	1045	1230	1550	1850	2250	0050	0840	1210
44	1825	1025	1220	1540	1840	2210	0040	0825	1150
45	1815	1010	1210	1525	1825	2155	0030	0820	1135
47	1810	0950	1205	1510	1810	2140	0020	0810	1125
50	1750	0930	1200	1500	1800	2100	0000	0800	1110

* Samples collected for manganese and iron analyses.

Table 7
Mean Hypolimnetic Temperatures (°C) in the Forebay Region of
 J. Strom Thurmond Lake, 1984-1987*

Year	Mean	N	Duncan Grouping**
1984	16.9	152	A
1985	14.1	116	C
1986	15.5	108	B
1987	14.7	100	C

* Calculated for the stratified period (May through October) at depths > 12 m.
 ** Means with the same letter are not significantly different at $\alpha = 0.05$.

Table 8
Volumetric Depletion Rates (mg/l/day) for Richard B. Russell
 and J. Strom Thurmond Lakes Based on PROFILE Calculations

Station	Zone	1981	1984	1985	1986	1987
020	Metalimnion	0.042	0.040	0.064	0.064	0.078
020	Hypolimnion	0.039	0.047	0.064	0.062	0.072
030	Metalimnion	NA	0.056	0.030-0.031	0.035-0.046	0.052-0.058
030	Hypolimnion	NA	0.082	0.027-0.028	0.035-0.045	0.067-0.080
120	Metalimnion	NA	0.062-0.07	0.052-0.053	0.034-0.040	0.031-0.074
120	Hypolimnion	NA	0.070	0.063-0.067	0.031-0.036	0.055-0.068
130	Metalimnion	NA	0.088-0.22	0.102-0.18	0.073-0.090	0.054-0.138
130	Hypolimnion	NA	0.197-0.29	0.184-0.20	0.117	0.130-0.299
140	Metalimnion	NA	0.070-0.20	0.073-0.16	0.072-0.115	0.053-0.184
140	Hypolimnion	NA	0.221-0.59	0.217-0.18	0.125-0.137	0.070-0.147

Note: A range of values indicates variation of the estimate due to subjective variation of choice of depths, dates, or both.

APPENDIX A: ANALYTICAL PROCEDURES

Quality Control

1. Replicate samples were obtained from four to six randomly selected sampling locations during each sampling trip. These samples, which generally represented approximately 10 percent of the total number of samples, provided a means for estimating errors due to sampling and intrinsic variability. Coefficients of variation (CV) were calculated for each variable for each replicate, and then a mean of the CVs was calculated. These means (Table A1) represent the relative sampling precision and provide a method for comparing different analytical procedures.

2. The analytical precision of each assay was evaluated by splitting samples in the laboratory and analyzing each subsample separately. As with replicates, split samples were randomly selected for each sampling period. These samples provided a test of analytical reliability and a measure of the normal variability due to analysis. The CV was calculated for each split that had values above the detection limit, and mean CVs were calculated for each variable (Table A1).

3. The accuracy, or how close the analyzed values are to the actual values, was evaluated by the analysis of spiked samples prepared in the laboratory. Laboratory values were compared with spike values and recorded as percent recovery (i.e., the lab value expressed as a percent of the actual value). These results are presented in Table A2.

Table A1
Mean Coefficients of Variation for Replicate and Split Samples

<u>Variable</u>	<u>Replicate Samples</u>	<u>Split Samples</u>
Total alkalinity	1.8	1.9
Total organic carbon	5.4	2.1
Dissolved organic carbon	6.7	2.0
Total phosphorus	6.6	9.5
Total soluble phosphorus	11.1	3.2
Soluble reactive phosphorus	7.6	4.0
Total nitrogen	7.3	7.5
Total dissolved nitrogen	7.3	8.9
Ammonia nitrogen	3.1	6.5
Nitrate-nitrite nitrogen	1.9	0.5
Total iron	7.3	4.4
Dissolved iron	9.5	1.6
Total manganese	4.8	2.1
Dissolved manganese	2.7	0.6

Table A2
Mean Percent Recovery for Laboratory Spiked Samples

<u>Variable</u>	<u>Mean Percent Recovery</u>
Total alkalinity	86.8
Total organic carbon	124.0
Total phosphorus	101.9
Total soluble phosphorus	94.2
Soluble reactive phosphorus	93.1
Total nitrogen	107.1
Total dissolved nitrogen	97.8
Ammonia nitrogen	100.1
Nitrate-nitrite nitrogen	99.0
Total iron	91.6
Dissolved iron	102.5
Total manganese	104.8
Dissolved manganese	114.8

Analytical Methods

Water column depth

Method: Depth sounding.
Detection limit: 0.1 m.

Secchi disc transparency

Method: Mean depth of disappearance and reappearance of disc.
Detection limit: 0.1 m.
Equipment: 20-cm Secchi disc with alternating black and white quadrats.

Water temperature*

Method: Thermistor thermometer.
Detection limit: 0.1° C.
Calibration: National Bureau of Standards certified thermometer.

Dissolved oxygen*

Method: Membrane electrode.
Detection limit: 0.1 mg/l.
Calibration: Air calibration.
Reference: Hydrolab Corporation (1985**).

Specific conductance*

Method: Electrometric.
Detection limit: 1 μ S.
Calibration: Conductivity standard solutions.
Reference: Hydrolab Corporation (1985).
Comments: All readings were corrected for temperature to 25° C.

pH*

Method: Electrometric.
Detection limit: 0.1 pH unit.
Calibration: Determination of pH with pH 7 and pH 4 buffer solutions.
Reference: Hydrolab Corporation (1985).

Oxidation-reduction potential*

Method: Electrometric.
Calibration: Ferric/ferrous iron solution standardized to 475 mV.
Reference: Hydrolab Corporation (1985).

Alkalinity

Method: Potentiometric titration.
Detection limit: 1.0 mg/l as CaCO₃.
Calibration: pH meter; Beckman Model Zeromatic IV (Beckman Instruments, Inc., Fullerton, CA).
Reference: American Public Health Association (1980).
Sample handling: Analyzed within 24 hr of sample collection.

* In situ measurements were made with Hydrolab Surveyor.
** See References at the end of the main text.

Carbon

A. Total organic carbon (TOC)

Method: Acid-sparge; infrared analysis.

B. Total filterable organic carbon (DOC)

Method: Acid-sparge; infrared analysis on sample filtered through a glass fiber filter.

Detection limit: 0.2 mg C/l.

Calibration: Per manufacturer's guidelines; standard curves.

Equipment: Carbon analyzer (Beckman Model 915B, Beckman Instruments, Inc., Fullerton, CA).

Reference: US Environmental Protection Agency (1979).

Sample handling: Stored at 4° C prior to analyses. Filtered on day of collection. Analyses performed within 2 weeks.

Phosphorus

A. Total phosphorus (TP)

Method: Sulfuric acid-persulfate oxidation digestion; automated ascorbic acid colorimetric method.

B. Total soluble phosphorus (TSP)

Method: Sulfuric acid-persulfate oxidation digestion on sample filtered through 0.45- μ membrane filter; automated ascorbic acid colorimetric method.

C. Soluble reactive phosphorus (SRP)

Method: Automated ascorbic acid colorimetric methods after filtration through a 0.45- μ membrane filter.

Detection limit: 0.005 mg P/l (dependent upon range used in analyses).

Calibration: Standard curves at beginning and end of each batch of samples.

Equipment: Autoanalyzers (Technicon Auto Analyzer II, Technicon Instruments Corporation, Tarrytown, NY).

Reference: American Public Health Association (1980).

Sample handling: Stored at 4° C prior to analysis; filtered day of collection. Anoxic samples filtered in field and held anoxic in syringes. Digestion on day of collection. SRP analyzed within 48 hr of collection. TP and TSP analyzed within 72 hr of collection.

Nitrogen

A. Total nitrogen (TN)

Method: Sulfuric acid-persulfate oxidation digestion; DeVarda's alloy reduction (Raveh and Avnimelech 1979); automated phenol-hypochlorite colorimetric method.

B. Total soluble nitrogen (TSN)

Method: Same as above except sample was filtered through a 0.45- μ membrane filter prior to digestion.

C. Ammonia nitrogen (NH₄-N)

Method: Automated phenol-hypochlorite colorimetric method.

D. Nitrate-nitrite nitrogen ($\text{NO}_3/\text{NO}_2\text{-N}$)

Method: Automated cadmium reduction colorimetric method; sample filtered through a 0.45- μ membrane filter prior to analysis.

Detection limit: 0.02 mg N/l for TN, TSN, and $\text{NH}_4\text{-N}$; 0.04 mg N/l for $\text{NO}_3/\text{NO}_2\text{-N}$ (dependent upon range used in analysis).

Calibration: Standard curves at beginning and end of each batch of samples.
Equipment: Autoanalyzers (Technicon Auto Analyzer II, Technicon Instrument Corporation, Tarrytown, NY).

Reference: American Public Health Association (1980).

Sample handling: Stored at 4° C prior to analyses; filtered day of collection. Anoxic samples filtered in the field and held anoxic in syringes.

Digestion on day of collection, DeVarda's alloy added 16 to 20 hr prior to analyses. $\text{NH}_4\text{-N}$ and $\text{NO}_3/\text{NO}_2\text{-N}$ analyzed within 48 hr of sample collection. TN and TSN analyzed within 96 hr of sample collection.

Comments: TN and TSN analyses performed on sample digested for TP and TSP, respectively (i.e., one digestion for both elements).

Sulfide

Method: Lead sulfide.

Detection limit: 0.1 mg/l.

Reference: Hach Chemical Company (1978).

Metals

A. Total iron and manganese (TFe, TMn).

Method: Hydrochloric/nitric acid reflux digestion, atomic absorption spectrophotometry.

B. Dissolved iron and manganese (DFe, DMn)

Method: Sample filtered through a 0.1- μ membrane filter, atomic absorption spectrophotometry.

Detection limit: 0.05 mg/l.

Calibration: Standard curves per manufacturer's guidelines.

Equipment: Atomic absorption spectrophotometer (Model 4000, Bodenseewerk Perkin-Elmer, and Company, Uberlingen, West Germany).

Reference: American Public Health Association (1980).

Sample handling: Filtered, acidified (pH < 2), and stored at 4° C.

Anoxic samples filtered in field and held anoxic in syringes. Digestion and analysis within 72 hr of collection.

Chlorophyll a

As in the previous 3 years of this study, samples for analysis of chlorophyll a were taken as integrated depth samples at depths equivalent to twice the Secchi disc depth. Chlorophyll a and other phytopigments were extracted using a modified procedure that employs dimethyl-formamide as the solvent. This method is more rapid and efficient and has been previously described (Speziale et al. 1984, Hains 1985). Otherwise, the analysis is identical to the procedure used in previous years of this study.