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

Third Annual Interim Report

by

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

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SUMMARY

This report is the third in a series of annual interim reports documenting the results of a comprehensive water quality study at Hartwell and Richard B. Russell Lakes and J. Strom Thurmond Dam and Reservoir (formerly called Clarks Hill Dam and Lake) and pertains to the period January to December 1986. This report also summarizes the results of all studies during the 3-year period following impoundment of Richard B. Russell Lake.

Water quality conditions in Richard B. Russell Lake were markedly improved in 1986 compared to those of the preceding 2 years. Oxygen depletion rates in the main portion of the reservoir were lower; however, metal concentrations in the release waters were similar to those in previous years. Additionally, conditions in the major tributary arms were similar to those of previous years. Continued improvement in water quality is anticipated over the next several years due to continued decomposition of organic material inundated during impoundment.

Dissolved oxygen concentrations in Richard B. Russell Lake releases during summer months were maintained at or above 6 mg/ℓ. Due to inoperation of the continuous oxygenation system, the pulse oxygenation system was operated continuously from 30 April to 28 November 1986. An exception was an 8-day period during which the pulse-oxygenation system was inoperable. Dissolved oxygen concentrations in releases during this period dropped to 4 mg/ℓ. Comparison of oxygen data before and following this event indicates that the pulse system is able to raise release dissolved oxygen concentrations by 2 to 3 mg/ℓ at an injection rate of 80 tons (72,575 kg)/day.

Few impacts on the water quality of J. Strom Thurmond Lake are apparent. However, reductions in the quantity of nutrients entering the lake have occurred due to the trapping effect of Richard B. Russell Lake. At present, phosphorus loading to the lake from the Broad River is greater than from Richard B. Russell Lake.

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 1986, is the third 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 Dr. John J. Hains of Clemson University, Clemson, SC, and Mr. Robert C. Gunkel, Jr., Mr. Joe H. Carroll, Mr. Steven L. Ashby, and Dr. Robert H. Kennedy of the Environmental Laboratory (EL), WES. Participating in the study were Mr. Michael Potter, Mr. William Jabour, Mr. Harry Eakin, Dr. Robert F. Gaugush, Dr. Stephen Schreiner, Ms. Vicki Vance, and Ms. Gwen Yates, EL. Dr. Kennedy and Mr. Carroll were responsible for the conduct of the study and for preparation of this report. 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. The report was edited by Mr. Bobby Odom, assigned to the Information Technology Laboratory under the Intergovernmental Personnel Act.

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

Third Annual Interim Report

PART I: INTRODUCTION

1. 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 a three-phase 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 on J. Strom Thurmond Lake.

c. To evaluate the effectiveness of the oxygen-injection system in eliminating potential water quality problems in Richard B. Russell Lake and its tailwater.

2. The US Army Engineer Waterways Experiment Station (WES), 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 third year of the investigation and summarizes the major results of 3 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, J. Strom Thurmond, and Hartwell Lakes at representative sampling stations established in the lakes and their tailwaters. Other studies of specific events or processes influencing water quality were conducted over shorter time periods and with greater sampling intensity.

PART II: GENERAL SITE DESCRIPTION

3. The Savannah River Basin (Figure 1) 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 sq km. 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.

4. 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 and Reservoir) 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 HR 18233) to provide power generation, incidental flood control, recreation, fish and wildlife habitat, streamflow regulation, and water supply. Richard B. Russell Dam, completed in December 1983, impounds the Savannah River between Hartwell and J. Strom Thurmond Lakes. 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 8 for Russell Dam and Reservoir (US Army Engineer District, Savannah, 1974) and summarized below.

5. 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.

6. Rock formations of the mountain section and the Piedment 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 metres, and the surface is largely formed of

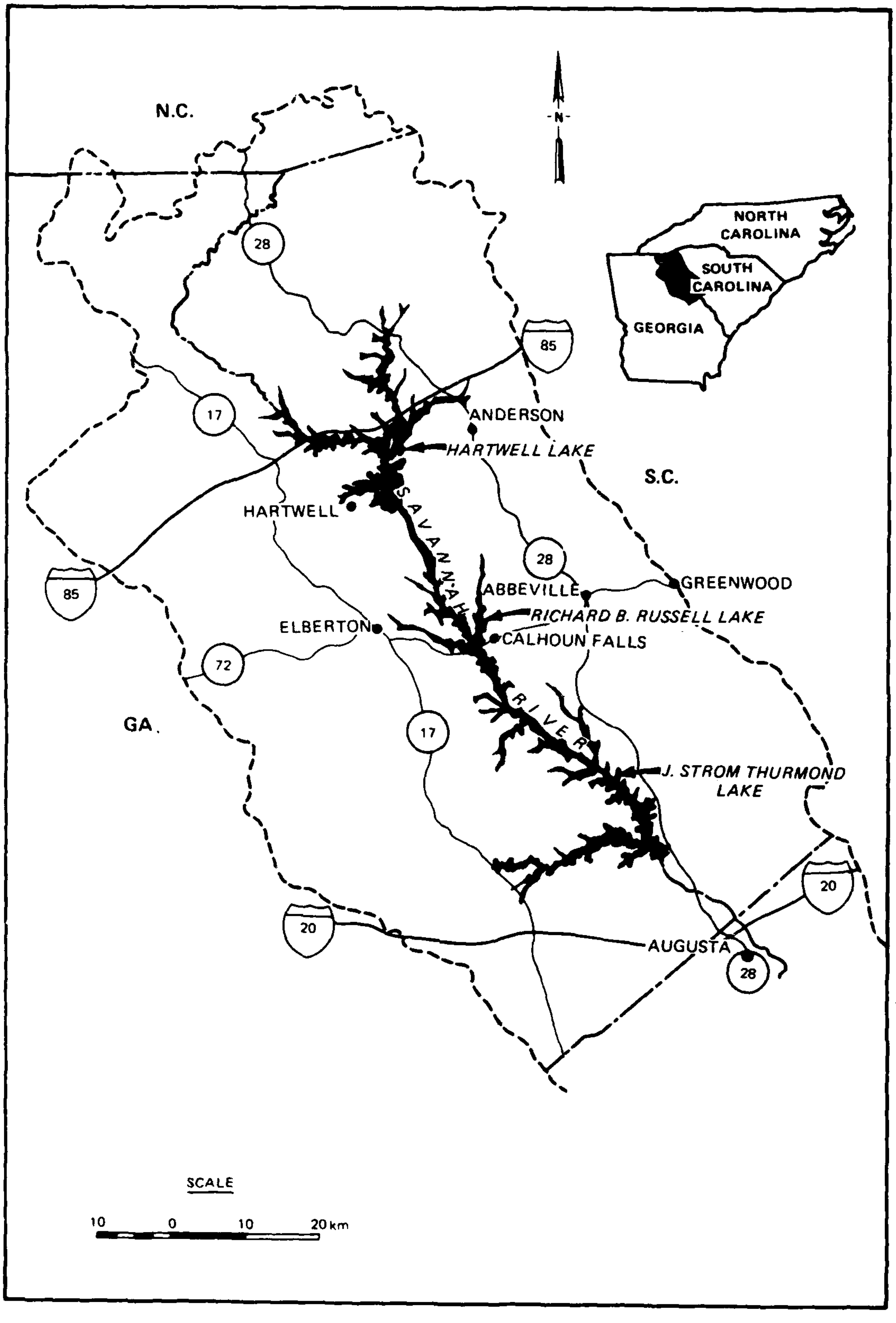

Figure 1. Locations of Hartwell, Richard B. Russell, and J. Strom Thurmond Lakes in the upper Savannah River watershed

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

7. The basin experiences a maritime climate with mild winters, long summers, and moderate to high rainfall (114 to 152 cm/year). While subject to continental influences, the basin 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. The region experienced abnormally low rainfall for much of the calendar year 1986. The significance of this condition is discussed elsewhere in this report.

8. 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, whose timber provides one of the major industries of the area. Cleared lands are devoted primarily to cultivated crops and pasture.

9. 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. A recent advisory recommended limitations on consumption of fish from Hartwell Lake due to polychlorinated biphenyl (PCB) contamination (South Carolina Department of Health and Environmental Control 1985). Numerous small wastewater treatment plants, textile mills, and various other industries discharge to streams and lakes within the study area. Due to the abundance of granitic rock, poorly drained soils, and the steepness of slopes, surface waters tend to have low dissolved solids and alkalinity, and a low buffering capacity.

PART III: METHODS AND MATERIALS

10. Detailed descriptions of the methods and materials used during the third 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). 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 analyses of seasonally collected water samples.

11. In addition to routine water quality monitoring, the area near Richard B. Russell Dam was intensively sampled to describe influences of the oxygen-injection system. From the onset of thermal stratification until November, weekly in situ measurements were collected at sta 060B, 100B, 115, and 120. Additional stations and dates were often included to supplement these data. From August until November, in situ measurements were collected weekly at sta 040, 045, and 050. Monthly physicochemical data were also collected at sta 040, 045, 050, 060B, 100B, and 120. Temperature, dissolved oxygen, pH, specific conductance, and oxidation-reduction potential data were collected in situ using a Hydrolab Surveyor II (Hydrolab Corp., Austin, TX). Monitoring instruments were calibrated prior to each field use. Temperature was calibrated to the nearest 0.1° C against an NBS thermometer; dissolved oxygen 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 sta 010, 050, and 200 with Schneider Water Quality Monitors (Model RM25, Schneider Instrument Company, Madeira, Cincinnati, OH).

12. 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 (American Public Health Association 1980, US Environmental Protection Agency 1979) were used for laboratory analyses of water samples.

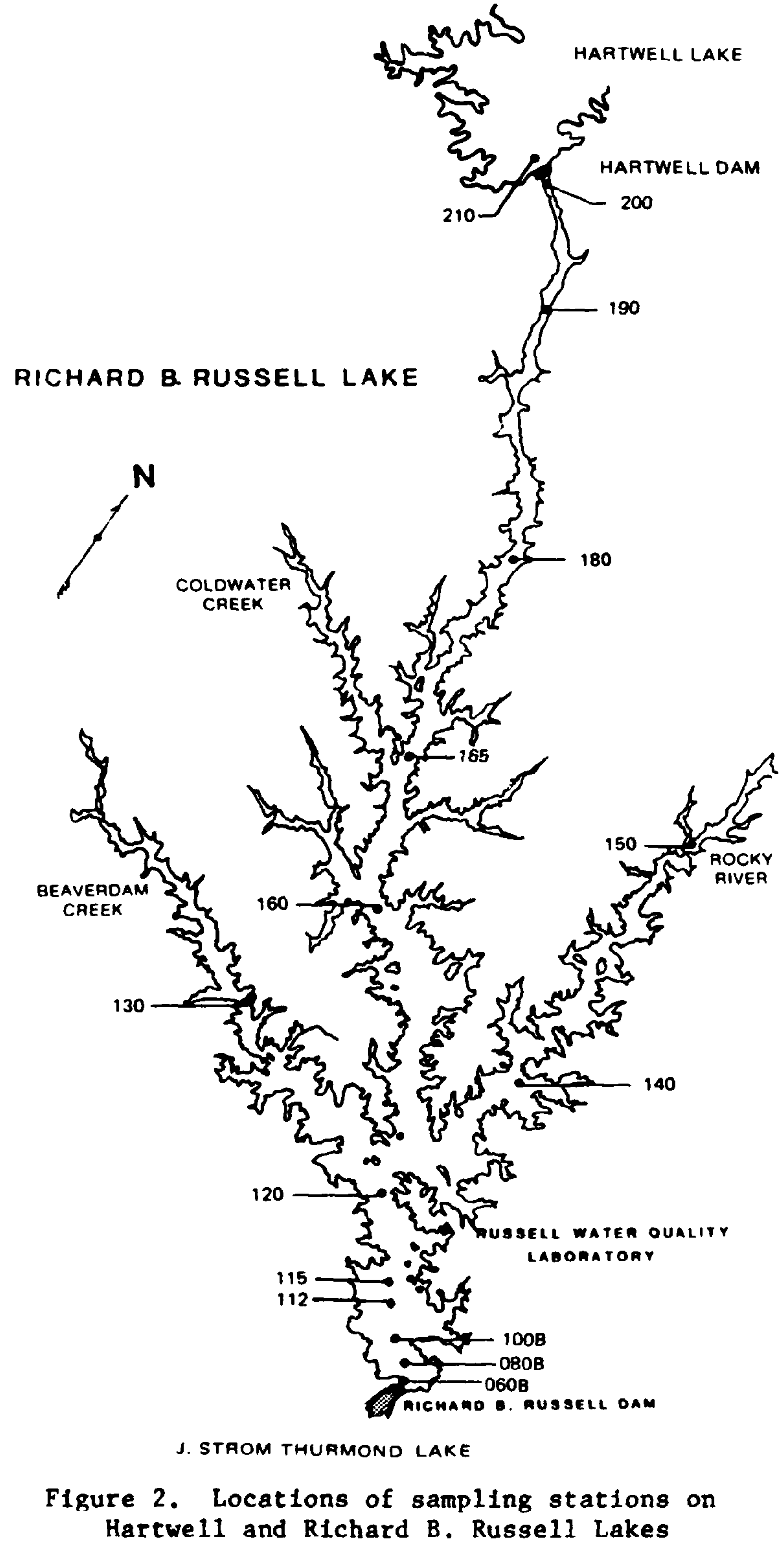

Figure 2. Locations of sampling stations on Hartwell and Richard B. Russell Lakes

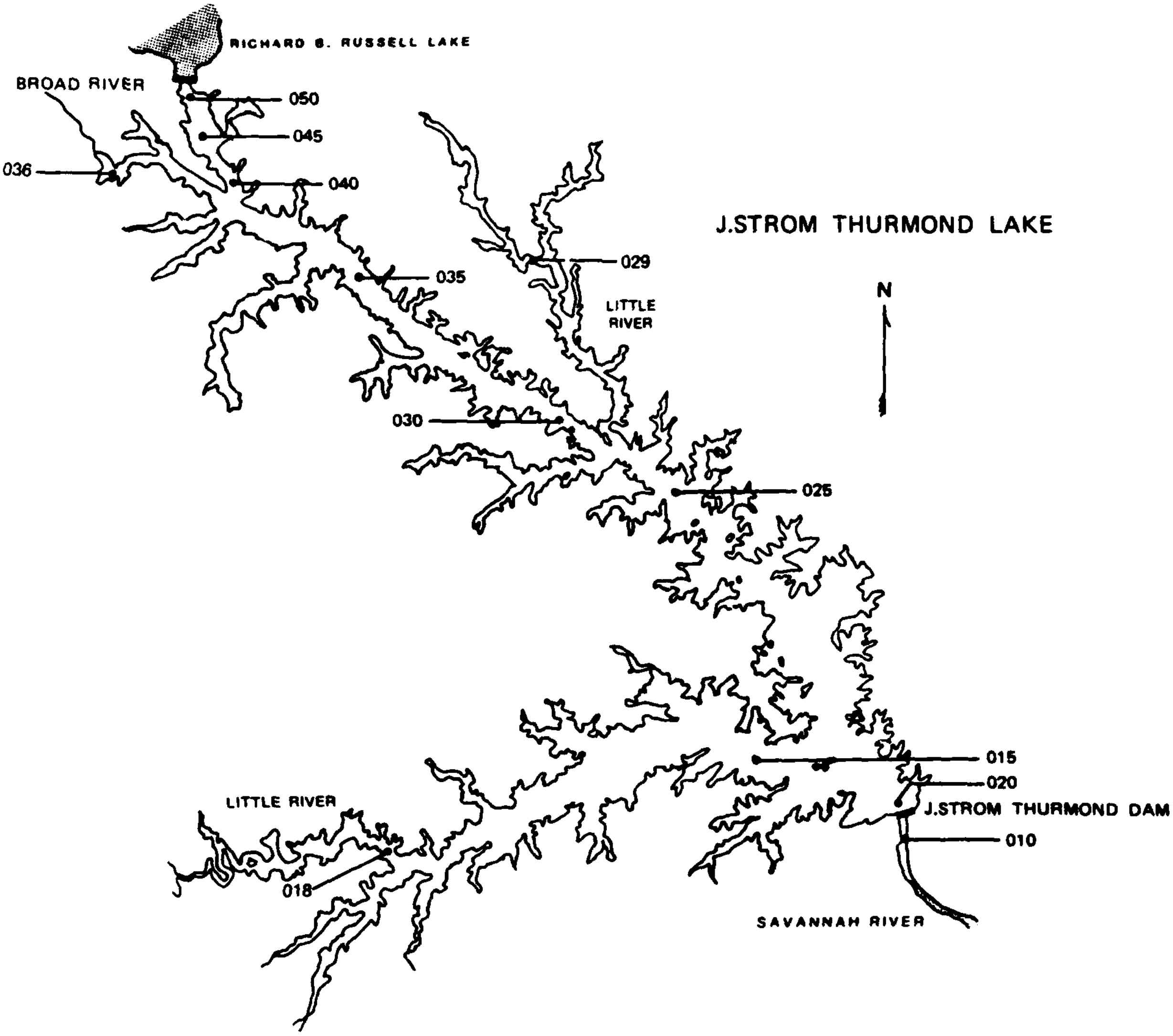

Figure 3. Locations of sampling stations on J. Strom Thurmond Lake

PART IV: RESULTS

Introduction

13. The Savannah River Basin and much of the surrounding region experienced severe drought conditions during 1986. The drought extended through the warmest months of the year and resulted in lowered water tables and minimal inflows to reservoirs. The impact of the drought on lake elevations was dramatic; the impact on lake water quality was difficult to assess.

Hartwell Lake

14. Pool elevation, monthly precipitation, mean daily inflow, and mean daily discharge for Hartwell Lake during 1984-1986 clearly indicate extreme hydrologic conditions in 1986 (Figure 4). Below-normal inflows and operational requirements for releases resulted in abnormally low elevations during 1986-1987.

15. Seasonal trends were identified for temperature, dissolved oxygen concentrations, and conductivity values. Data for sta 210 in the forebay of Hartwell Lake indicated isothermal conditions in January followed by the onset of stratification in March (Figure 5). Warming continued into the summer, and by July 1986, surface temperatures exceeded 30° C. Warming and deepening of the thermocline continued into September, followed by rapid cooling and a return to isothermal conditions in December.

16. Oxygen remained at relatively high concentrations throughout the water column until summer (Figure 6). In May, concentrations exceeded 6 mg/ℓ at all depths. However, in July concentrations at depths below the thermocline were <4 mg/ℓ, and by October oxygen concentrations were 1 mg/ℓ or less at depths >18 m. Although the lake was nearly isothermal by December, hypolimnetic oxygen concentrations did not increase due, presumably, to insufficient wind mixing.

17. Conductivity values averaged approximately 30 μS for most depths and times (Figure 7). However, increases in the hypolimnion accompanied oxygen depletion during the summer and fall months. Depths at which oxygen concentrations were <1 mg/ℓ exhibited values as high as 60 μS.

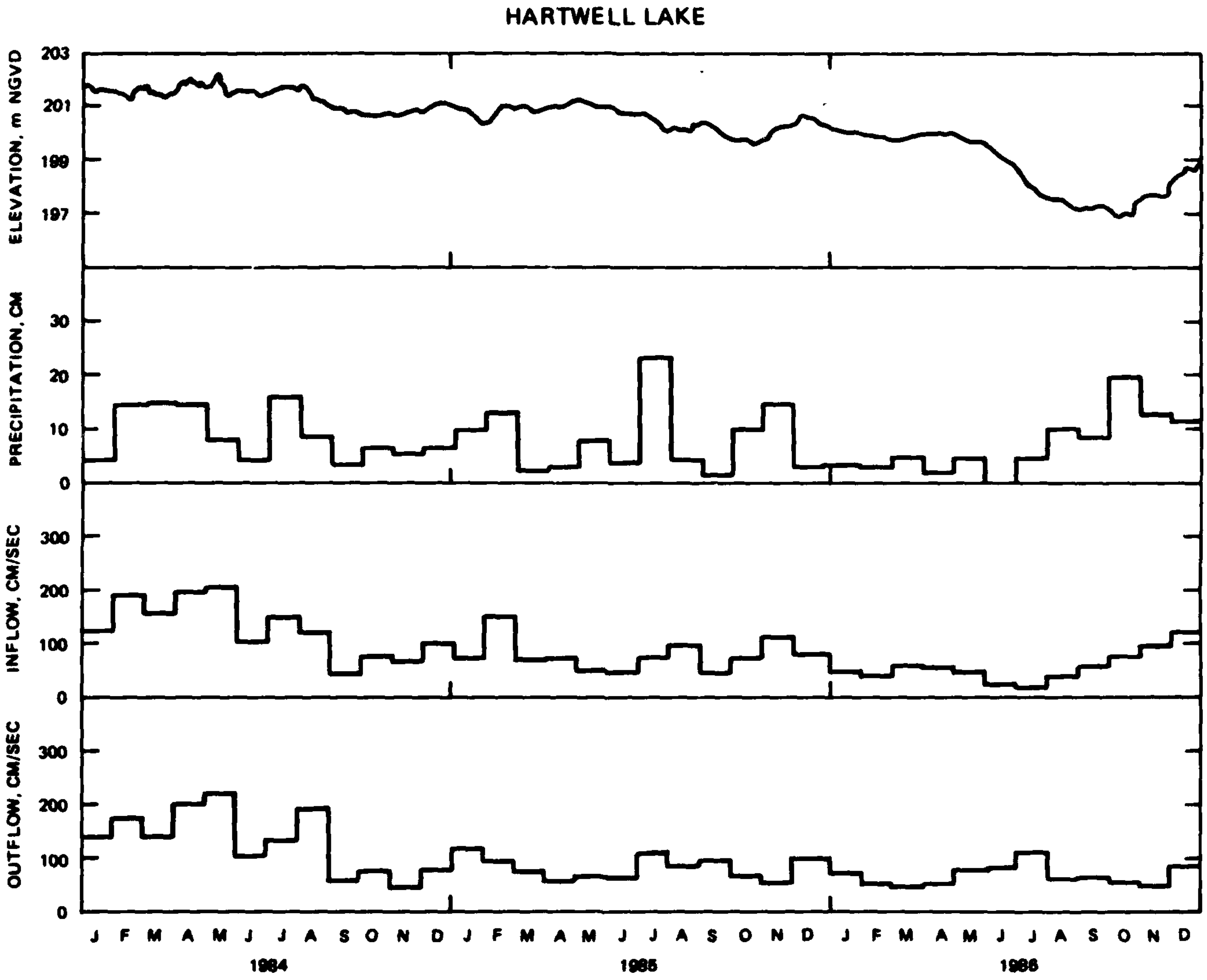

Figure 4. Pool elevation, precipitation, inflows, and outflows for Hartwell Lake, 1984-1986

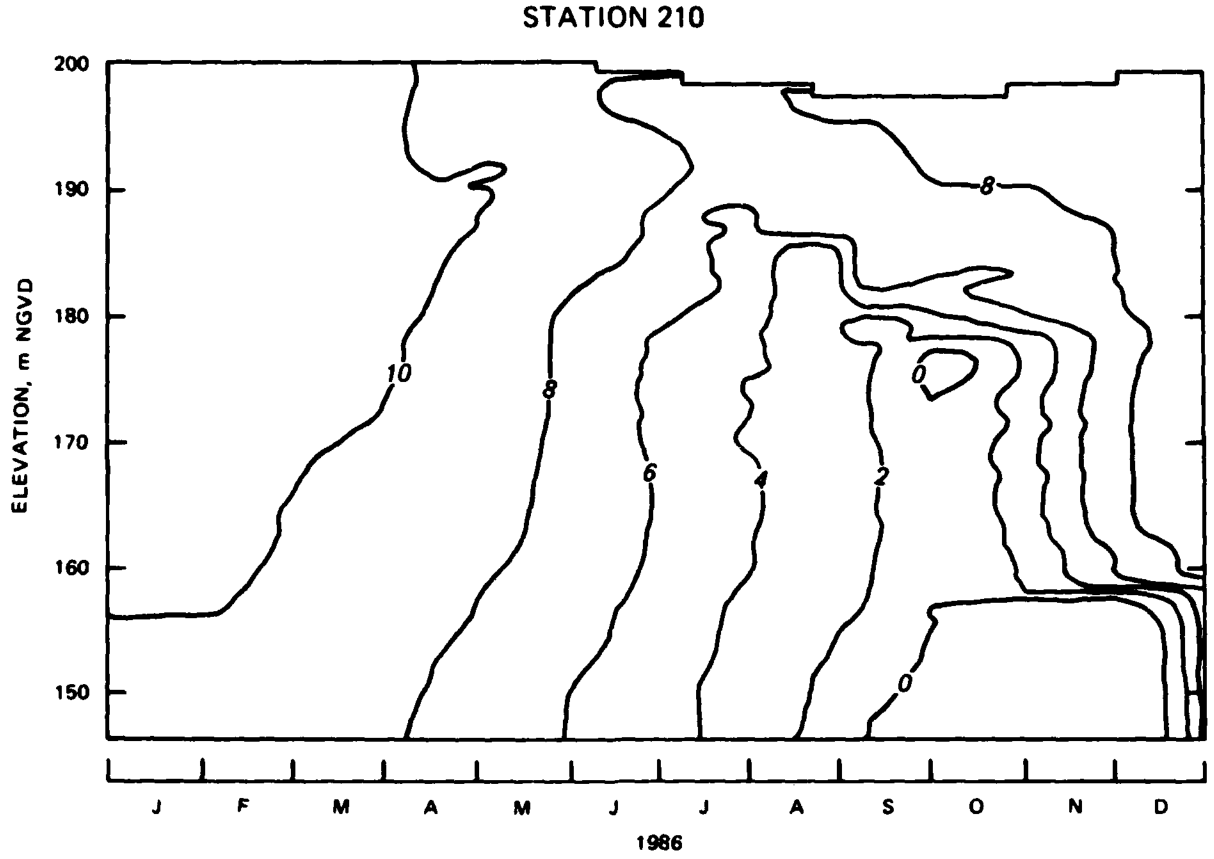

Figure 5. Pattern of spatial and temporal variation of temperatures (°C) at sta 210, the Hartwell Lake forebay

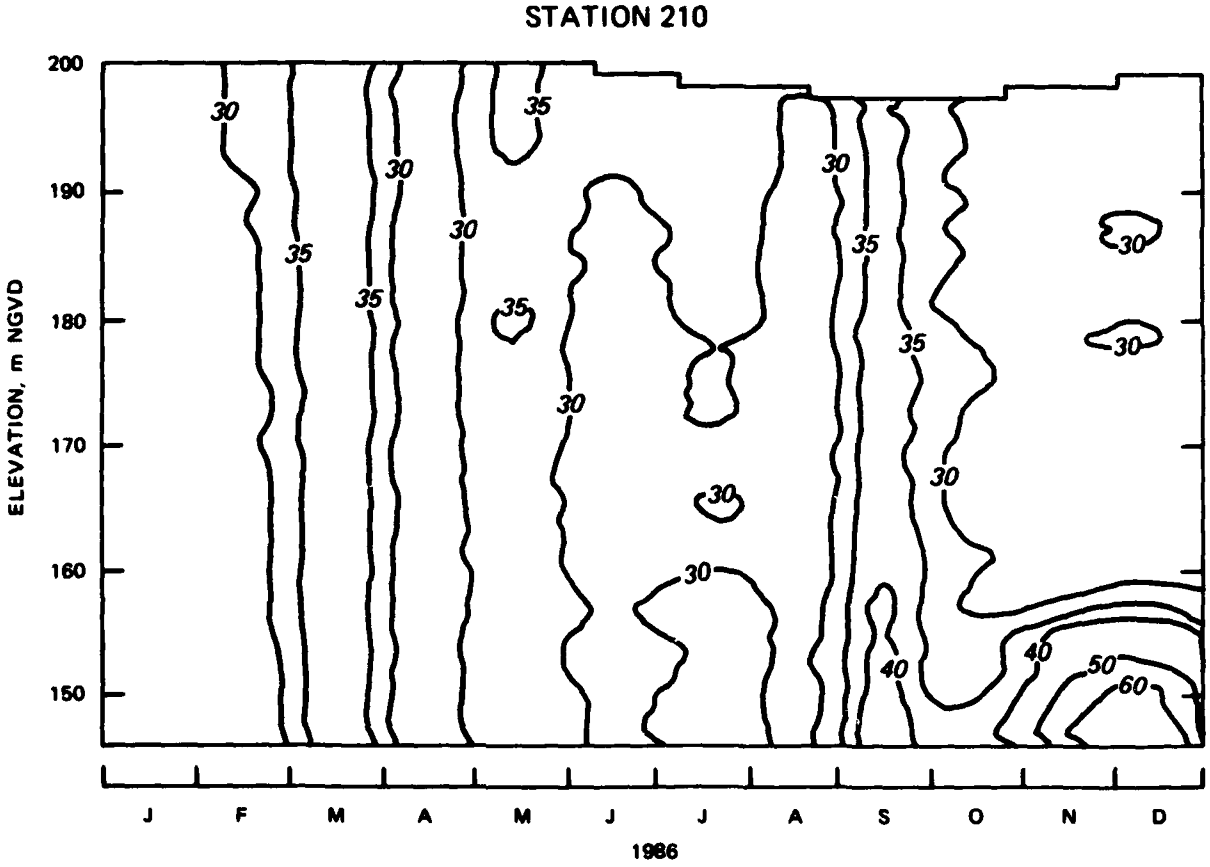

Figure 6. Pattern of spatial and temporal variation of dissolved oxygen concentrations (mg/ℓ) at sta 210, the Hartwell Lake forebay

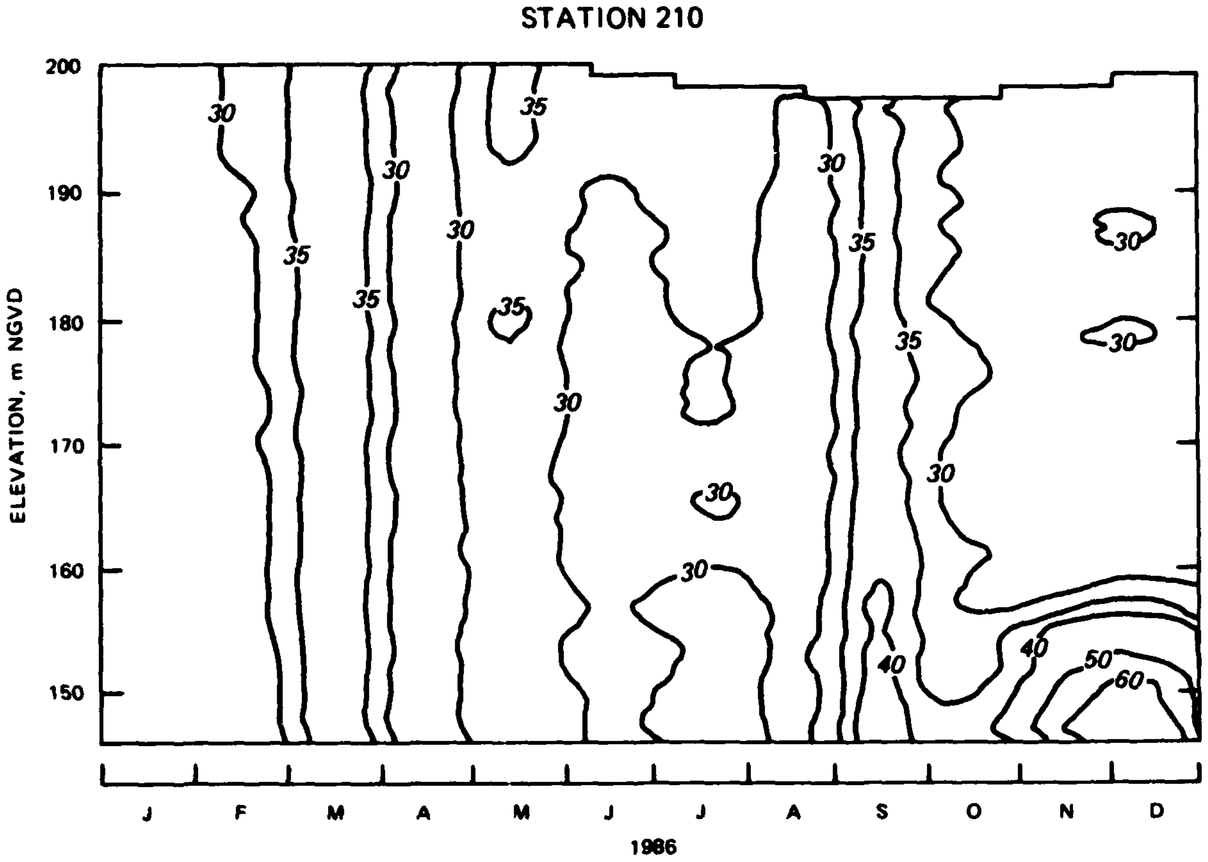

Figure 7. Pattern of spatial and temporal variation of conductivity (μS) at sta 210, the Hartwell Lake forebay

18. Other variables displayed less pronounced seasonal trends. Values for pH were indicative of circumneutral to mildly acidic waters with most values between pH 6 and 7. Oxidation-reduction potential values were indicative of oxidizing environments at most times and depths.

19. Chemical analyses indicated few seasonal trends. Total phosphorus concentrations were generally low (<0.010 mg/ℓ) at all depths and times with the greatest concentrations (0.010 to 0.020 mg/ℓ) observed in bottom waters during July 1986. Dissolved phosphorus concentrations were often near or below detection limit (0.005 mg/ℓ). However, during July, dissolved phosphorus concentrations exceeded 0.010 mg/ℓ and, therefore, composed the largest fraction of total phosphorus in Lake Hartwell.

20. Total nitrogen concentrations were always <1 mg/ℓ with concentrations occasionally as great as 0.5 mg/ℓ (observed in January). In January, dissolved inorganic nitrogen (composed of ammonia nitrogen and nitrate-nitrite nitrogen) and dissolved organic nitrogen, which combined ranged from 0.11 to 0.14 mg/ℓ, were a small fraction of total nitrogen concentrations. During April, July, and October, dissolved nitrogen occurred in greater concentrations, usually 0.1 to 0.4 mg/ℓ, and represented a greater proportion of the total nitrogen pool. Total and dissolved organic carbon concentrations were very similar throughout 1986 and ranged from 0.6 to 1.7 mg/ℓ for all depths and dates.

21. Concentrations of iron and manganese showed dissimilar trends. While concentrations of manganese were often at or below the detection limit (0.05 mg/ℓ), measurable concentrations were usually observed in the dissolved or reduced form rather than the particulate or oxidized form (Figure 8). These concentrations reached 1.59 mg/ℓ at the 50-m depth in October. In contrast, iron, which was often observed in measurable concentrations (>0.05 mg/ℓ), occurred more often as particulate or oxidized than as dissolved or reduced iron. At depths near 50 m, total iron concentrations were as great as 2.6 mg/ℓ while the maximum dissolved iron concentration was 1.39 mg/ℓ (Figure 8).

22. Conditions in release waters were reflective of conditions in the forebay. From January through late summer, the discharge (i.e., sta 200) showed a gradual increase in temperature (from approximately 10° to 18°C) and a gradual decrease in dissolved oxygen concentrations (from approximately 11 to 3 mg/ℓ). During October, temperatures began to decline, and dissolved

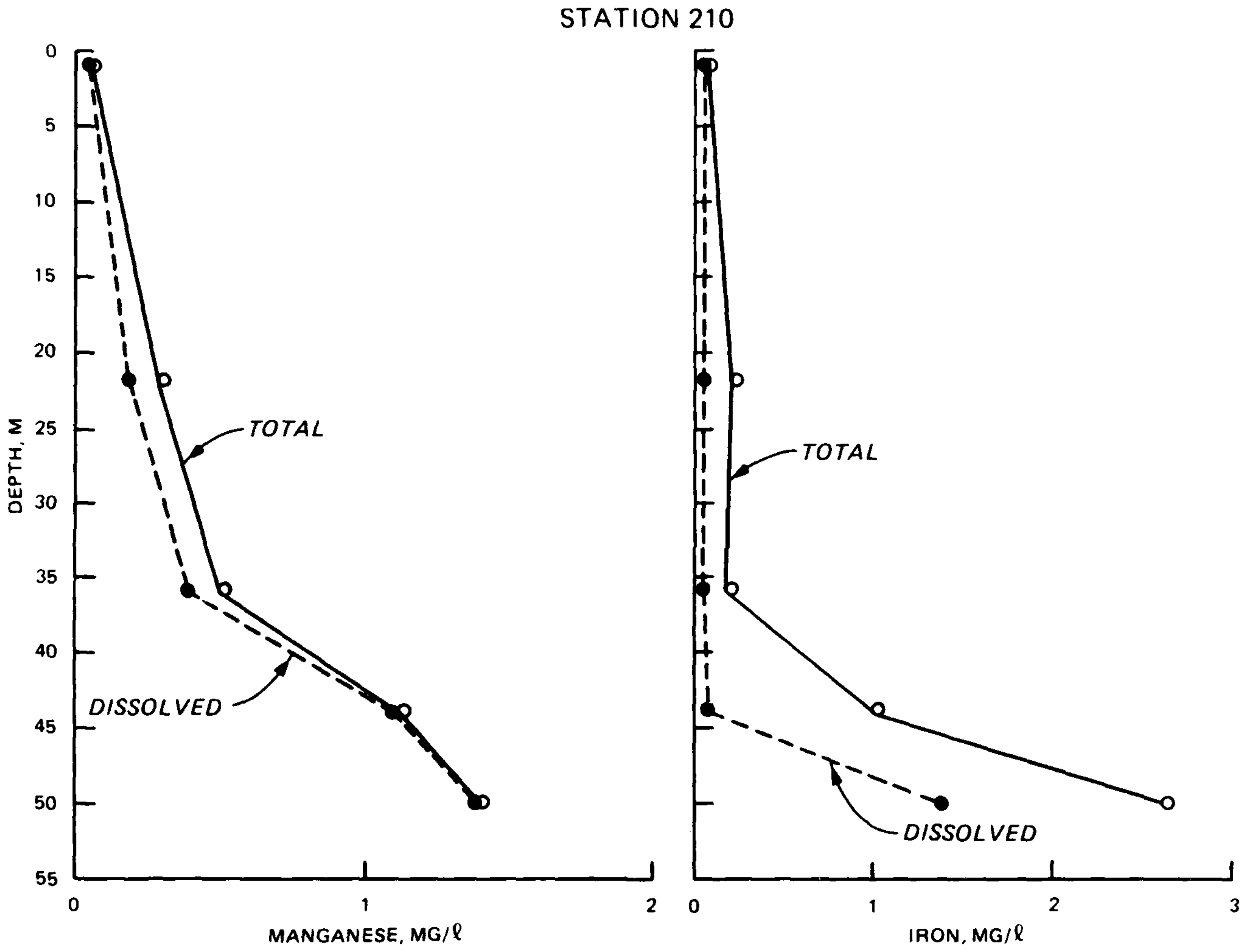

Figure 8. Concentrations of total and dissolved iron and manganese at sta 210, October 1986

oxygen concentrations began to increase (Figure 9) coincident with the onset of fall mixing.

23. Concentrations of total and dissolved manganese at sta 200 (Figure 9) remained near detection limits until July and increased to a maximum concentration of approximately 0.4 mg/ℓ during September. This coincided with the period of maximal thermal stratification in Hartwell Lake. Concentrations decreased to approximately 0.2 mg/ℓ by the end of October. Total and dissolved manganese concentrations were nearly identical at all times, indicating that manganese was exported from Hartwell Lake in the dissolved or reduced form.

24. Concentrations of total and dissolved iron at sta 200 were dissimilar for much of the year (Figure 9). Total iron concentrations remained near 0.2 to 0.4 mg/ℓ into October. Maximum total iron concentrations of approximately 0.6 mg/ℓ were observed in November. In contrast, dissolved iron concentrations never exceeded 0.1 mg/ℓ in the Hartwell Lake tailrace during 1986. Thus, in contrast with manganese, iron was exported from the lake primarily in the particulate or oxidized form.

25. As was observed in the forebay, total phosphorus and total nitrogen concentrations in the tailrace (i.e., sta 200) were maximal during mid to late summer. Total phosphorus concentrations peaked at 0.022 mg/ℓ in November, at which time the total dissolved phosphorus concentration was 0.009 mg/ℓ. At other times, concentrations of these forms of phosphorus were near the detection limit (0.005 mg/ℓ). Soluble reactive phosphorus was near or below the detection limit at all times.

26. Total nitrogen concentrations were maximal at sta 200 in July. During the times of greatest concentration (July-November), total and dissolved nitrogen concentrations were very similar, peaking near 0.6 mg/ℓ in July and decreasing to approximately 0.3 mg/ℓ in late November. Consistently lower concentrations of ammonia nitrogen and nitrate-nitrite nitrogen indicated that the majority of dissolved nitrogen was in an organic form.

27. Carbon concentrations in the Hartwell Lake tailrace were nearly identical to those in the Hartwell Lake forebay and showed no significant trends other than a small increase from spring to fall 1986.

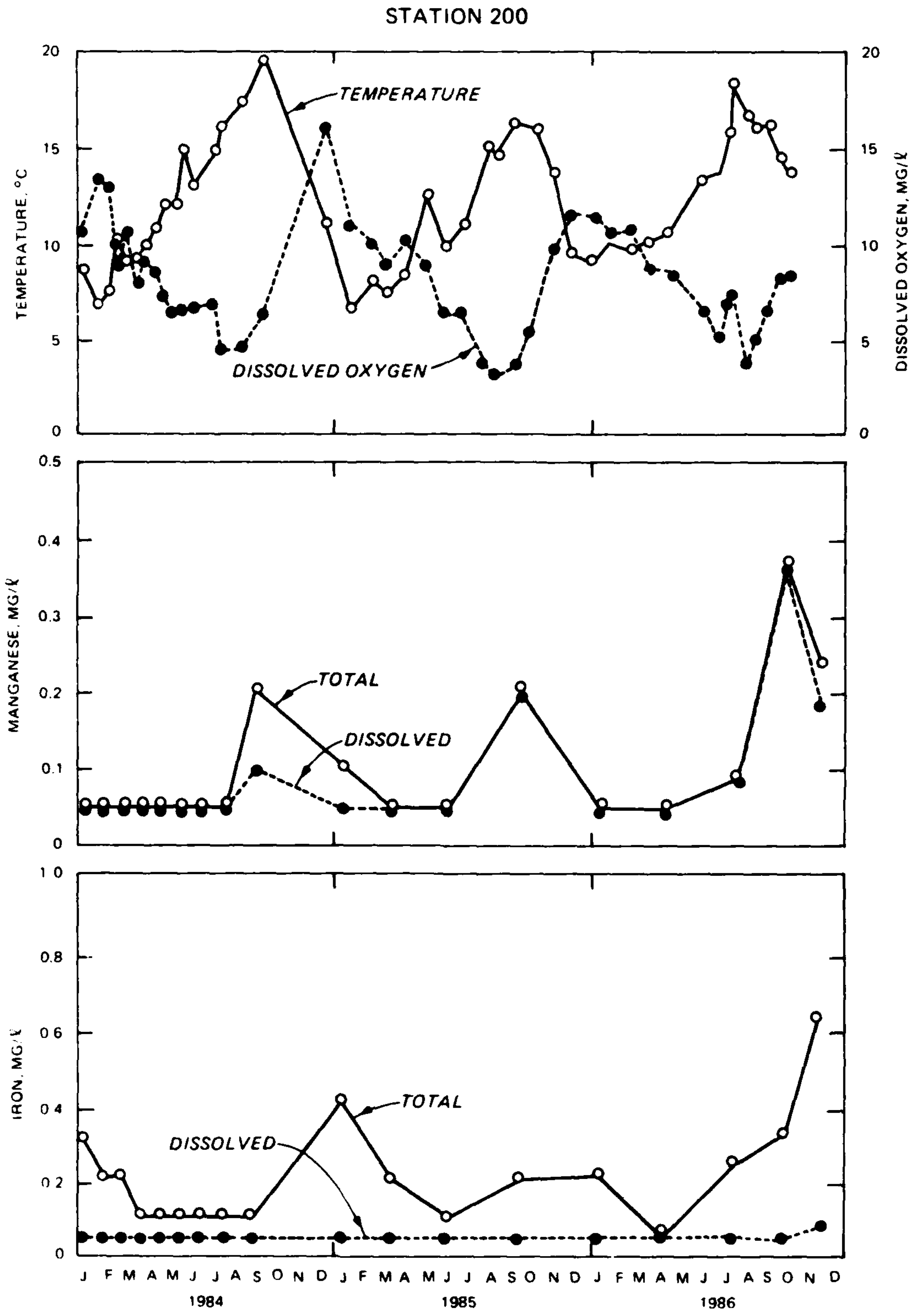

Figure 9. Dissolved oxygen concentrations, temperatures, and total and dissolved iron and manganese concentrations in the Hartwell Dam release, sta 200, 1984-1986

Richard B. Russell Lake

28. Pool elevation, monthly precipitation, mean daily inflow, and mean daily discharge for Richard B. Russell Lake during 1984-1986 (Figure 10) show that relatively stable pool elevations were maintained in Richard B. Russell Lake, despite drought conditions, due to the small design drawdown between maximum and minimum power pools.

29. Seasonal trends in temperature, pH, conductivity, ORP, and dissolved oxygen concentration in 1986 were similar, overall, to those observed in 1985. At most mainstem locations, as typified by sta 120, warming began in March, and stratified conditions were established by the end of April (Figure 11). Throughout most of the summer stratified period, the thermocline was located at a depth of 10 to 12 m. Surface temperatures reached a maximum of approximately 30° C during the summer months while deep hypolimnetic waters gradually warmed to a maximum of approximately 17° C just prior to mixing in November (Figure 12). Surface cooling in the fall led to complete mixing of Richard B. Russell Lake by early December.

30. Oxygen concentrations remained relatively near to saturation concentrations in the epilimnion throughout the summer at most locations in Richard B. Russell Lake (Figure 13). Below the thermocline, oxygen concentrations decreased to <6 mg/ℓ by late April. By July, concentrations at depths >20 m had decreased to <4 mg/ℓ for most lake locations. By October, hypolimnetic dissolved oxygen concentrations at locations uninfluenced by the oxygenation system (i.e., sta 115 and upstream) were <1 mg/ℓ at depths >20 m. Subsequent fall mixing gradually increased oxygen concentrations to 7 to 8 mg/ℓ at most locations and depths by December. These trends are typified by conditions observed at sta 120 (Figure 14).

31. Using the in situ data for Richard B. Russell Lake, volumetric and areal oxygen depletion rates were calculated using the computer technique PROFILE (Walker 1987; Tables 4 and 5). In 1986, volumetric depletion rates were greater in the Richard B. Russell Lake forebay (sta 060B) and less in the mainstem (sta 120) and tributary arms (sta 130 and 140) than in 1985 or 1984. Similar trends were observed for areal depletion rates. The average volumetric depletion rate for the forebay in 1984 was 0.066 mg/ℓ/day. This rate decreased to 0.057 mg/ℓ/day in 1985 but increased to 0.077 mg/ℓ/day in 1986. However, the operation of the oxygen diffuser system during 1985 and 1986

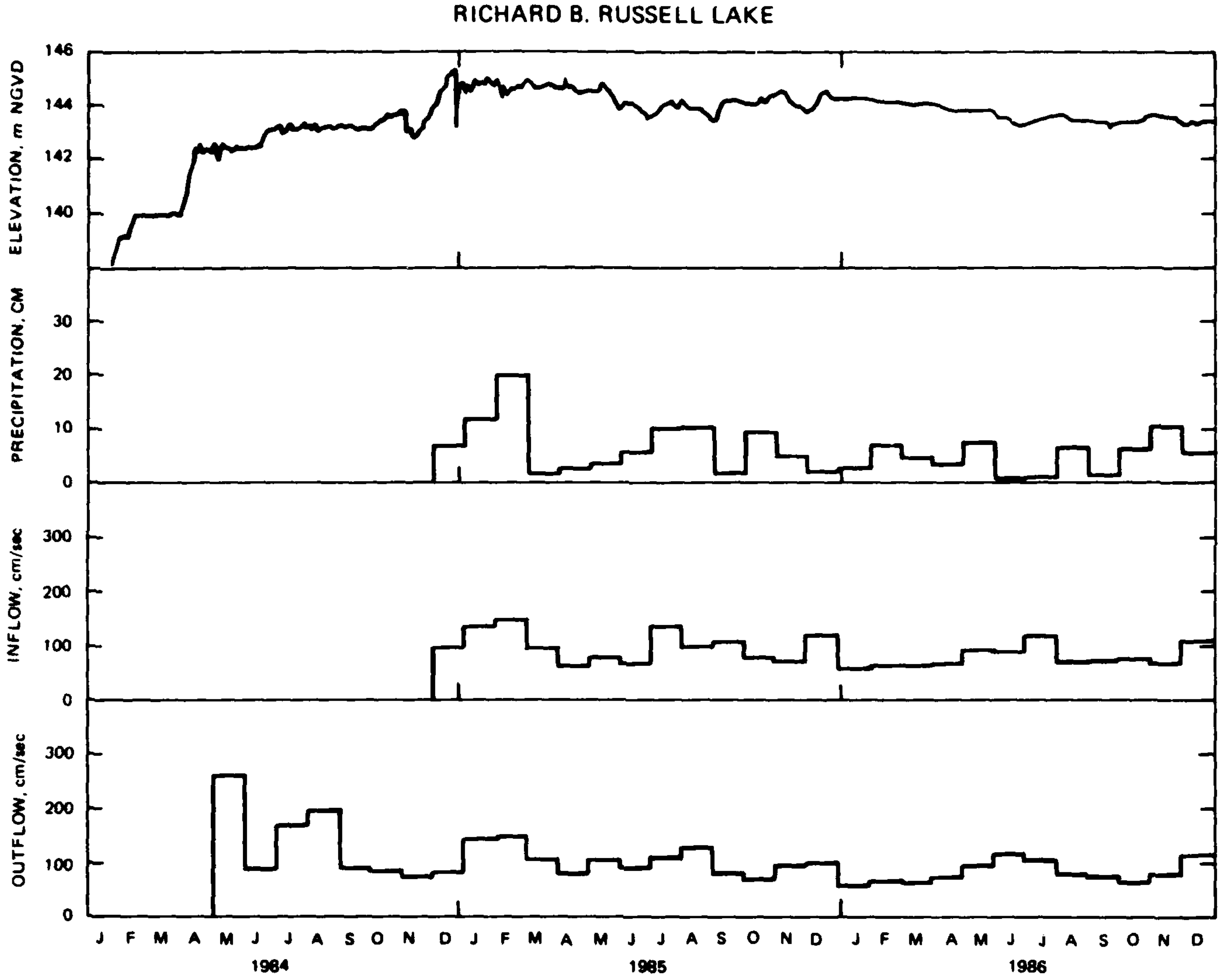

Figure 10. Pool elevation, precipitation, inflows, and outflows for Richard B. Russell Lake, 1984-1986

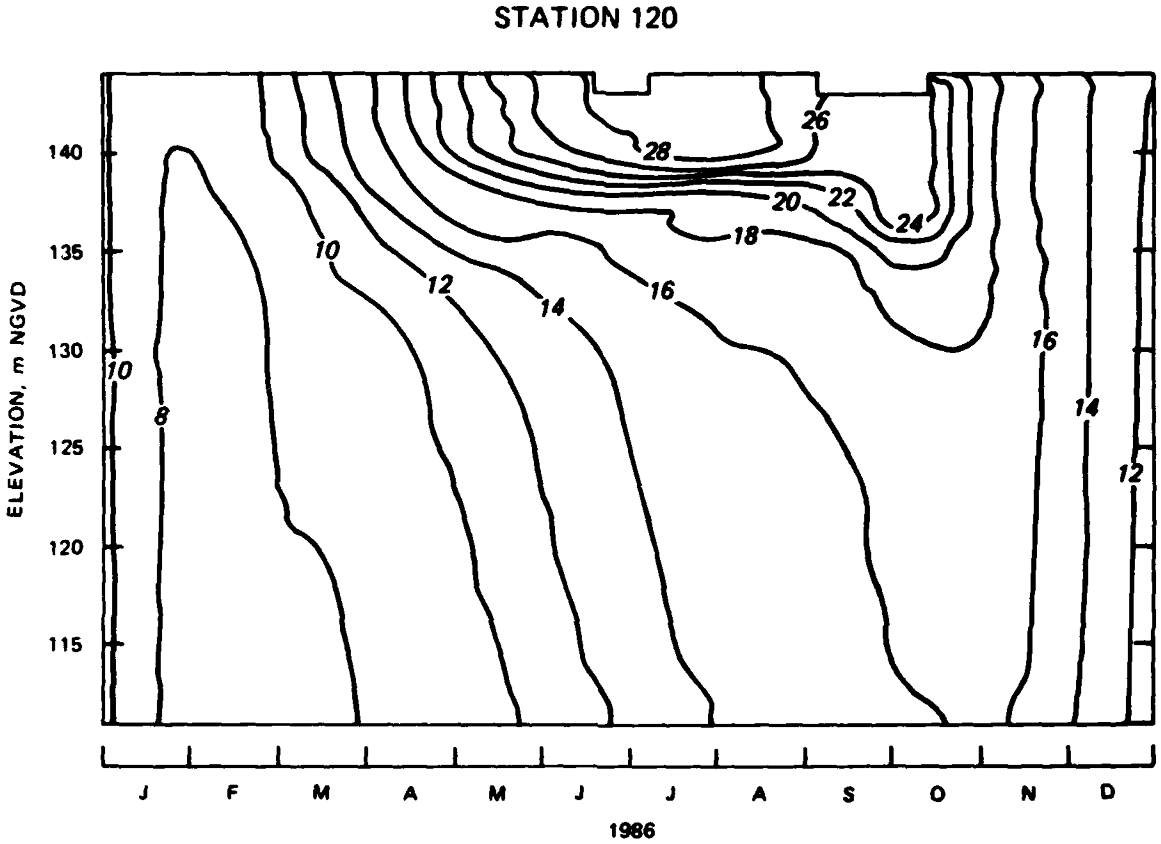

Figure 11. Pattern of spatial and temporal variation of temperature (°C) at sta 120, Richard B. Russell Lake mainstem

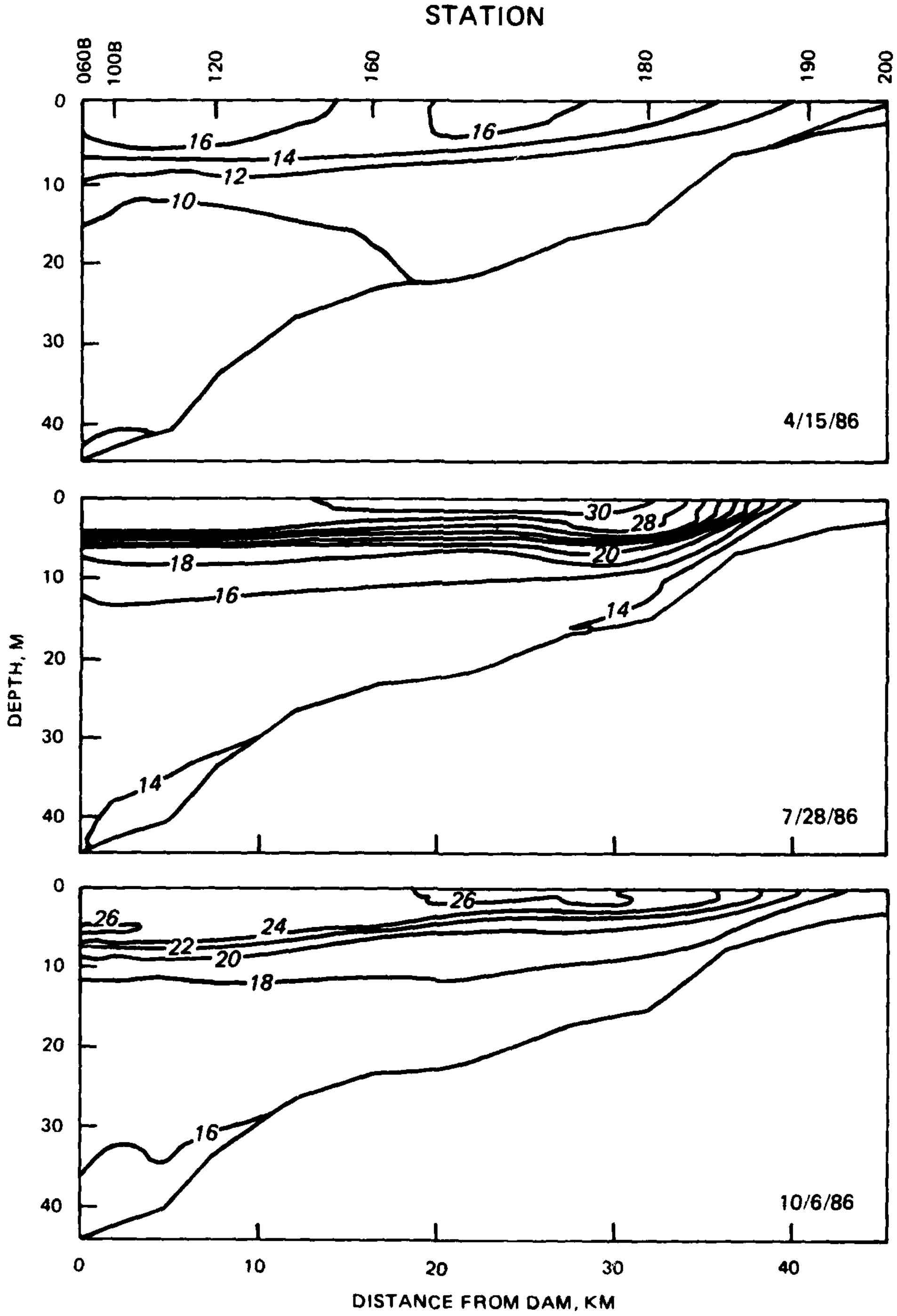

Figure 12. Patterns of spatial distribution of temperatures (°C) in the Richard B. Russell Lake mainstem for April, July, and October 1986

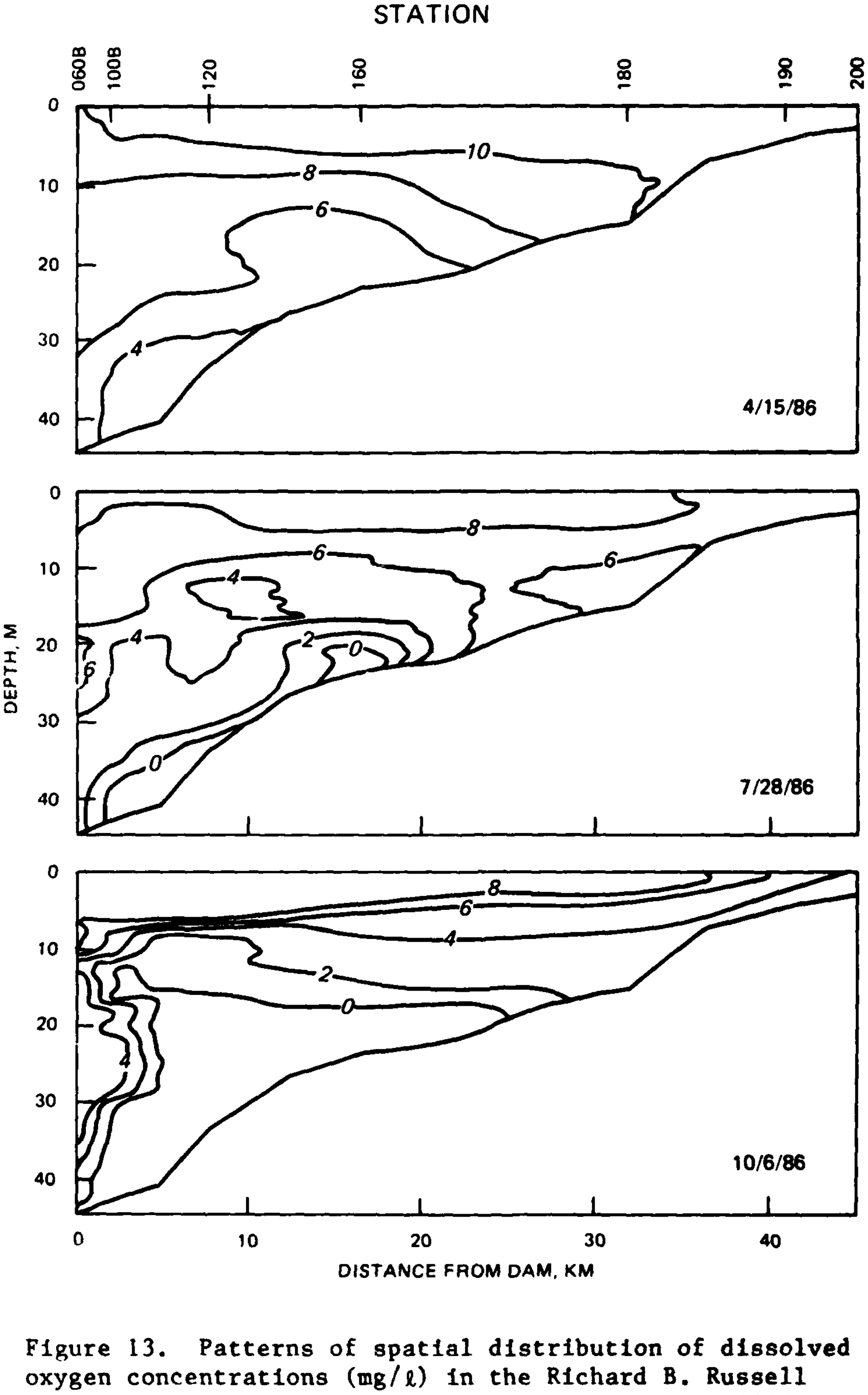

Figure 13. Patterns of spatial distribution of dissolved oxygen concentrations (mg/ℓ) in the Richard B. Russell Lake mainstem for April, July, and October 1986

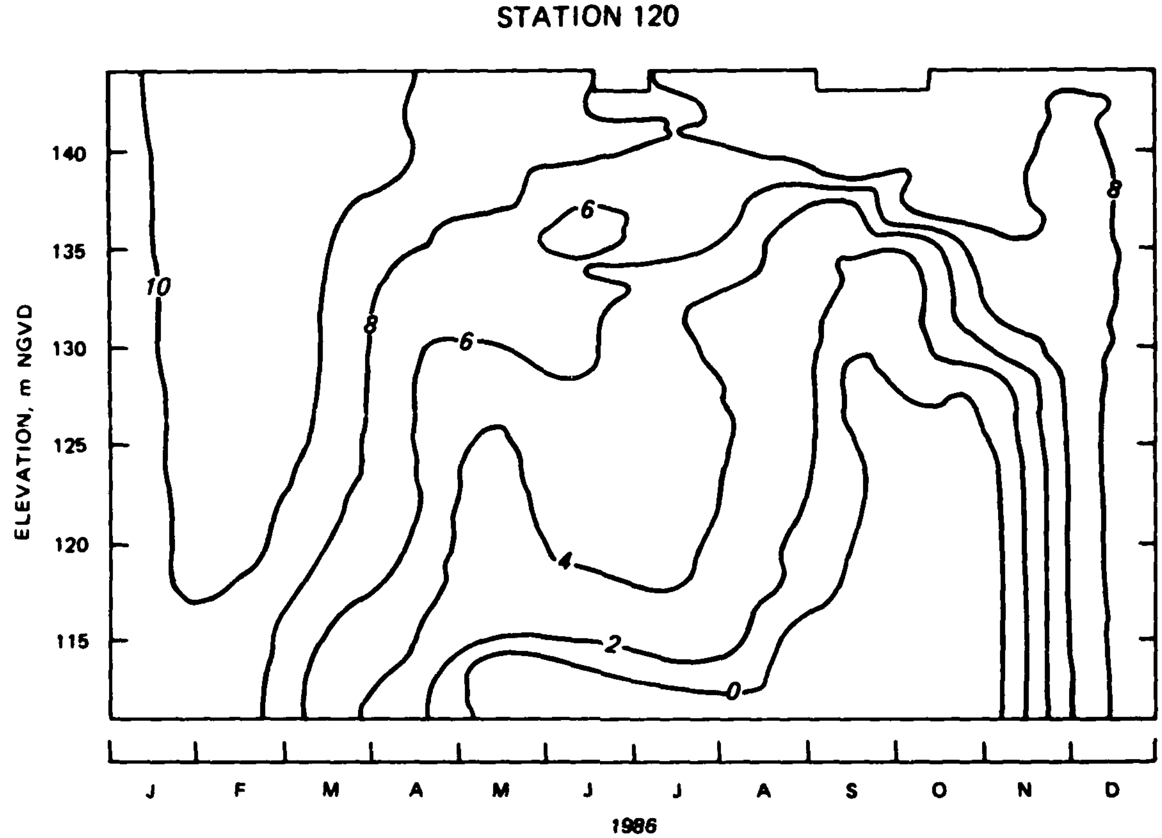

Figure 14. Patterns of spatial and temporal variation of dissolved oxygen concentrations (mg/ℓ) at sta 120, Richard B. Russell Lake mainstem

limited this calculation to times in the spring, prior to operation and before clear patterns of summer oxygen demand were established. PROFILE could not be employed with data at sta 060B taken during operation of the oxygenation system. Hence, early spring depletion rates are the only estimates available for the years 1985 and 1986 and are not directly comparable to estimates using data for 1984. Furthermore, in 1984, tainter gate releases affected hydrodynamics in a different manner than did penstock releases in 1985 and 1986.

32. At sta 120, a trend of decreasing volumetric oxygen depletion rate was observed (0.068 mg/ℓ/day in 1984; 0.056 mg/ℓ/day in 1985; and 0.039 mg/ℓ/day in 1986). Depletion rates at sta 130 and 140 were much greater than for the mainstem each year although a strong trend of decrease for oxygen depletion rate was observed.

33. Conductivity values closely followed the seasonal pattern established for oxygen concentrations. While values remained typical for surface

waters in the region, approximately 30 μS for most depths and times (Figure 15), oxygen depletion in the hypolimnion led to greater values for conductivity. Depths at which oxygen concentrations were <1 mg/ℓ had relatively high conductivity values, sometimes >60 μS.

34. Values for pH were indicative for circumneutral to mildly acidic waters and mostly varied between pH 6 and 7. Oxidation-reduction potential values were indicative of oxidizing environments at most times and depths.

35. Nitrogen concentrations ranged from detection limit (0.02 mg/ℓ) to approximately 1.5 mg/ℓ, and seasonal trends were reflected in the spatial and temporal distribution of total nitrogen (Figure 16). Most pronounced were gradients in total nitrogen concentrations in the hypolimnion of the lower and mid-lake regions. Vertical gradients were observed coincidentally with the development of anoxic conditions and subsequent release of ammonia nitrogen from the sediments (i.e., July). Maximum concentration gradients were observed in October at the height of stratification. Nitrogen in the hypolimnion was present primarily in reduced forms (i.e., ammonia) at this time. Additionally, maximum concentrations were observed upstream of the oxygenation system. In contrast, total nitrogen concentrations in the surface waters were relatively consistent, and seasonal trends were not apparent.

36. Phosphorus concentrations ranged from detection limit (0.005 mg/ℓ) to approximately 0.130 mg/ℓ and displayed trends similar to nitrogen (Figure 17). Vertical gradients of total phosphorus were most pronounced at the height of stratification (October) and were confined to the anoxic region of the hypolimnion. Dissolved phosphorus comprised the majority of the phosphorus pool in the hypolimnion, and concentration increases may have been attributed to solubilization and subsequent release of phosphorus from the sediments, coincident with development of anoxic conditions. As was observed with nitrogen, maximum concentrations of total phosphorus were observed upstream of the oxygenation system. Additionally, seasonal trends in phosphorus concentrations in the surface waters were not apparent.

37. Organic carbon concentrations ranged from detection limit (0.2 to 3.0 mg/ℓ). Vertical concentration gradients were not well pronounced; however, maximum concentrations were observed in the hypolimnion in the lower region of the lake during late stratification. Increased concentrations were also observed in surface waters at the height of summer productivity.

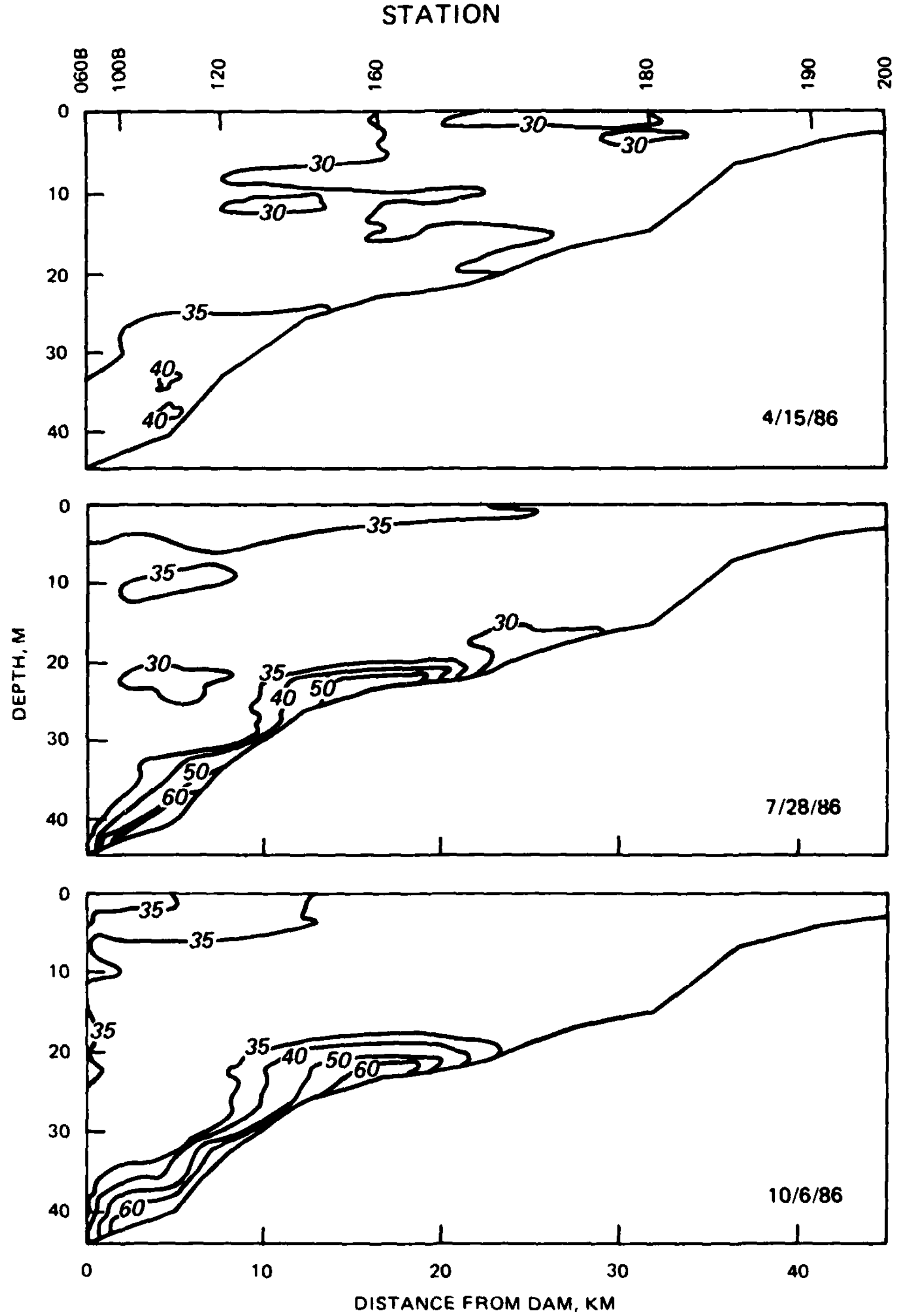

Figure 15. Patterns of spatial distribution of conductivity (μS) in the Richard B. Russell Lake mainstem for April, July, and October 1986

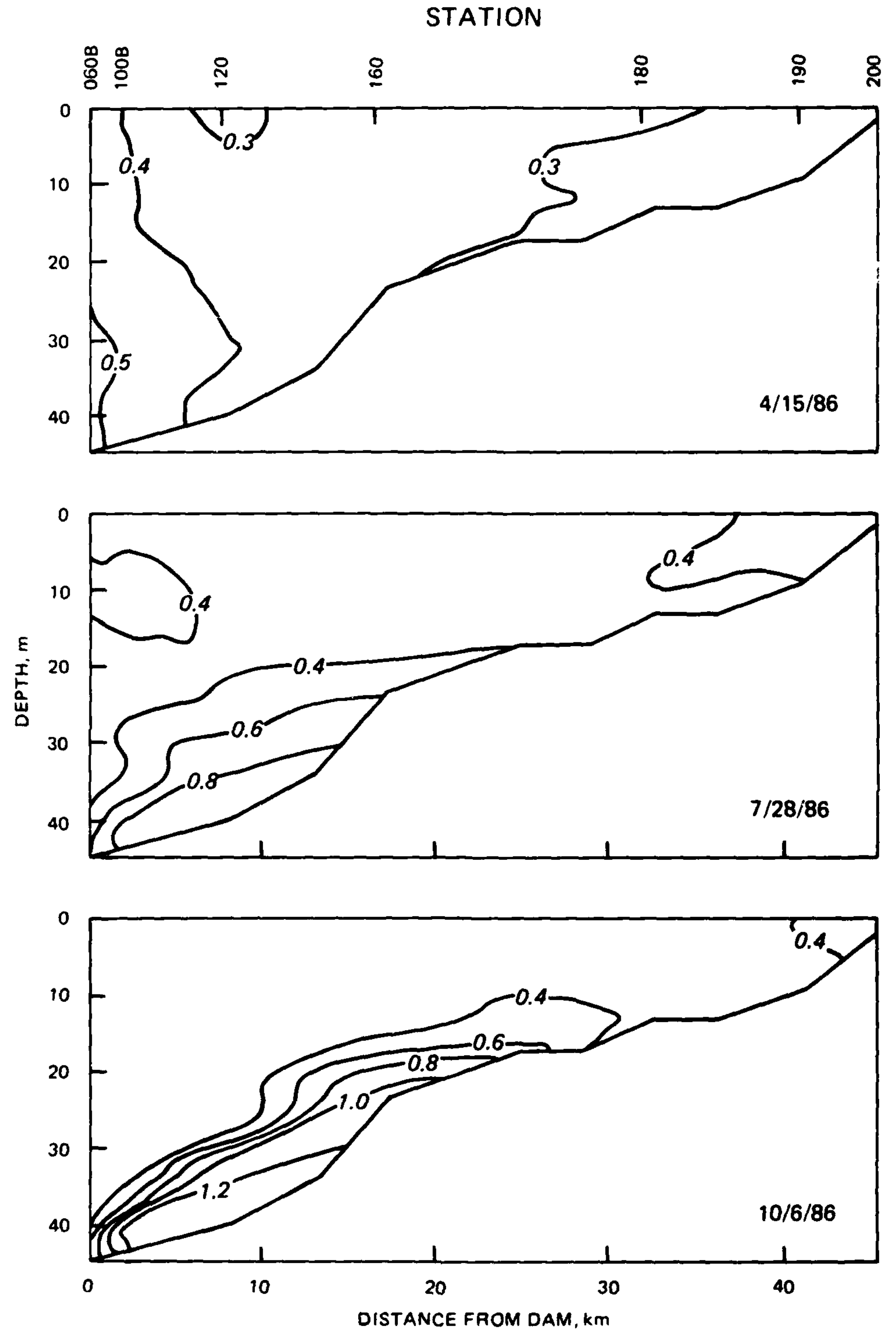

Figure 16. Patterns of spatial distribution of total nitrogen concentrations (mg/ℓ) in Richard B. Russell Lake for April, July, and October 1986

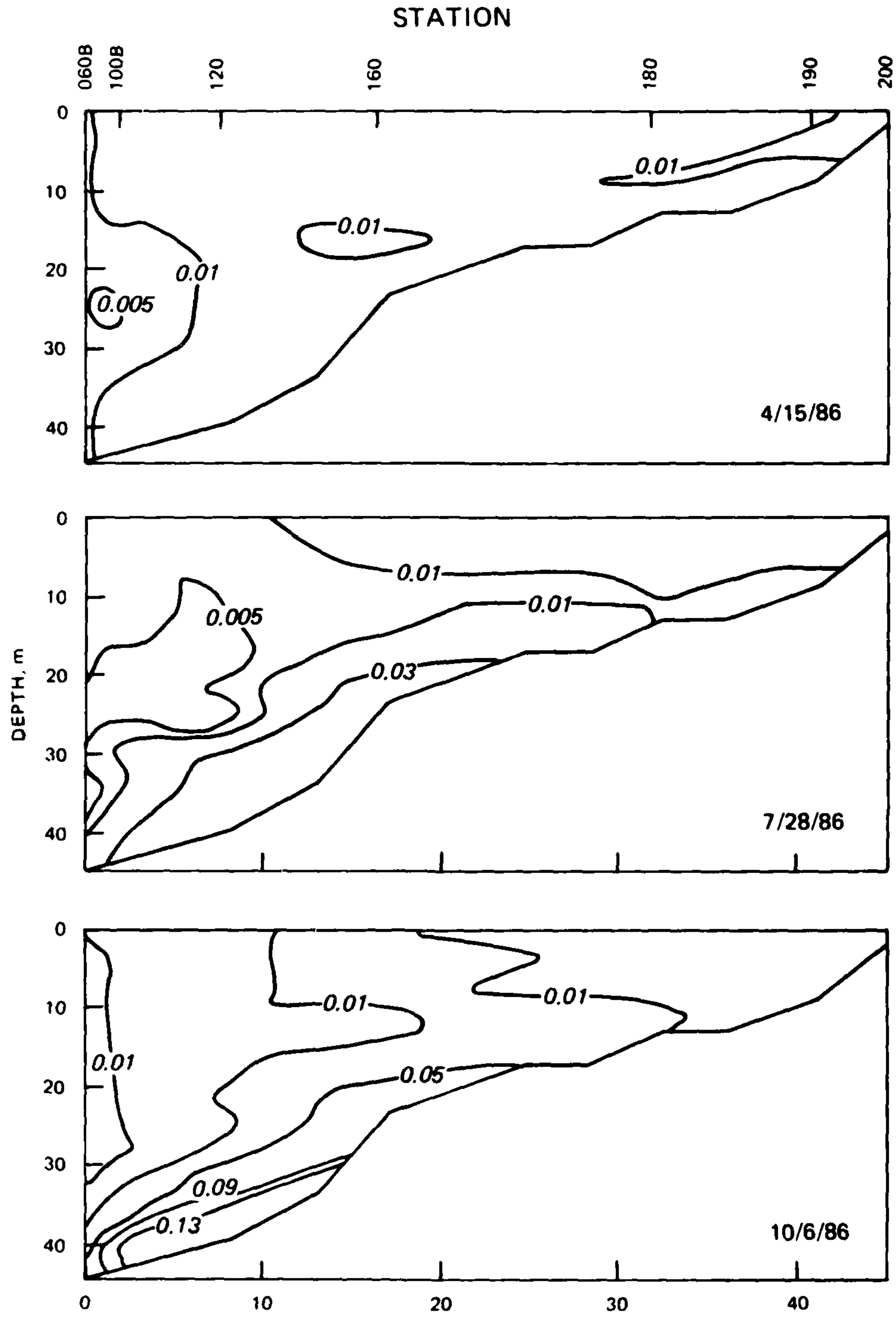

Figure 17. Patterns of spatial distribution of total phosphorus concentrations (mg/ℓ) in Richard B. Russell Lake for April, July, and October 1986

38. Low concentrations of iron and manganese occurred in Richard B. Russell Lake during the well-mixed and oxygenated winter period at most locations and depths. Total and dissolved iron concentrations during January were 0.2 and 0.05 mg/ℓ, respectively, throughout Richard B. Russell Lake. By April and the onset of stratification, total iron increased to approximately 2 mg/ℓ in the hypolimnion while dissolved iron concentrations remained <1 mg/ℓ. In July, total and dissolved iron remained low in the epilimnion but increased to approximately 8 mg/ℓ in the hypolimnion. Maximal concentrations were observed during October (Figure 18) when both total and dissolved iron concentrations increased to >10 mg/ℓ in the hypolimnion. In most instances, dissolved (or reduced) iron at areas upstream of the oxygenation system represented a majority of the total iron concentration in the hypolimnion. Downstream of the oxygenation system, the majority of the total iron was in a particulate form.

39. Changes in manganese concentration displayed a pattern similar to iron although concentrations of manganese were usually less. In January, both total and dissolved manganese concentrations were approximately 0.05 mg/ℓ throughout Richard B. Russell Lake. In April, following the onset of stratification, manganese concentrations exceeded 1.25 mg/ℓ in the hypolimnion of the tributary embayments but remained relatively low in the hypolimnion of the mainstem of the lake. By July, concentrations of both dissolved and total manganese increased to approximately 1 mg/ℓ in the hypolimnion of the lower region of the lake but remained at approximately 0.5 mg/ℓ in surface waters. Further increases were apparent in October when the concentrations of both dissolved and total manganese increased to approximately 2 mg/ℓ in the hypolimnion of the mainstem (Figure 18). As with iron, the total manganese pool was composed primarily of dissolved forms. This was true for areas downstream as well as upstream of the oxygenation system.

40. Tributary arms of Richard B. Russell Lake exhibited trends in temperature and chemistry, but not in dissolved oxygen concentration, similar to those of the mainstem. Coincident with the onset of thermal stratification, vertical gradients in specific conductance and concentrations of nitrogen, phosphorus, iron, and manganese developed. These variables were present primarily in dissolved forms due to well-established anoxic conditions in the hypolimnia of the embayments. Oxygen concentrations in the tributary arms (Figure 19) were more depleted than concentrations observed in the mainstem.

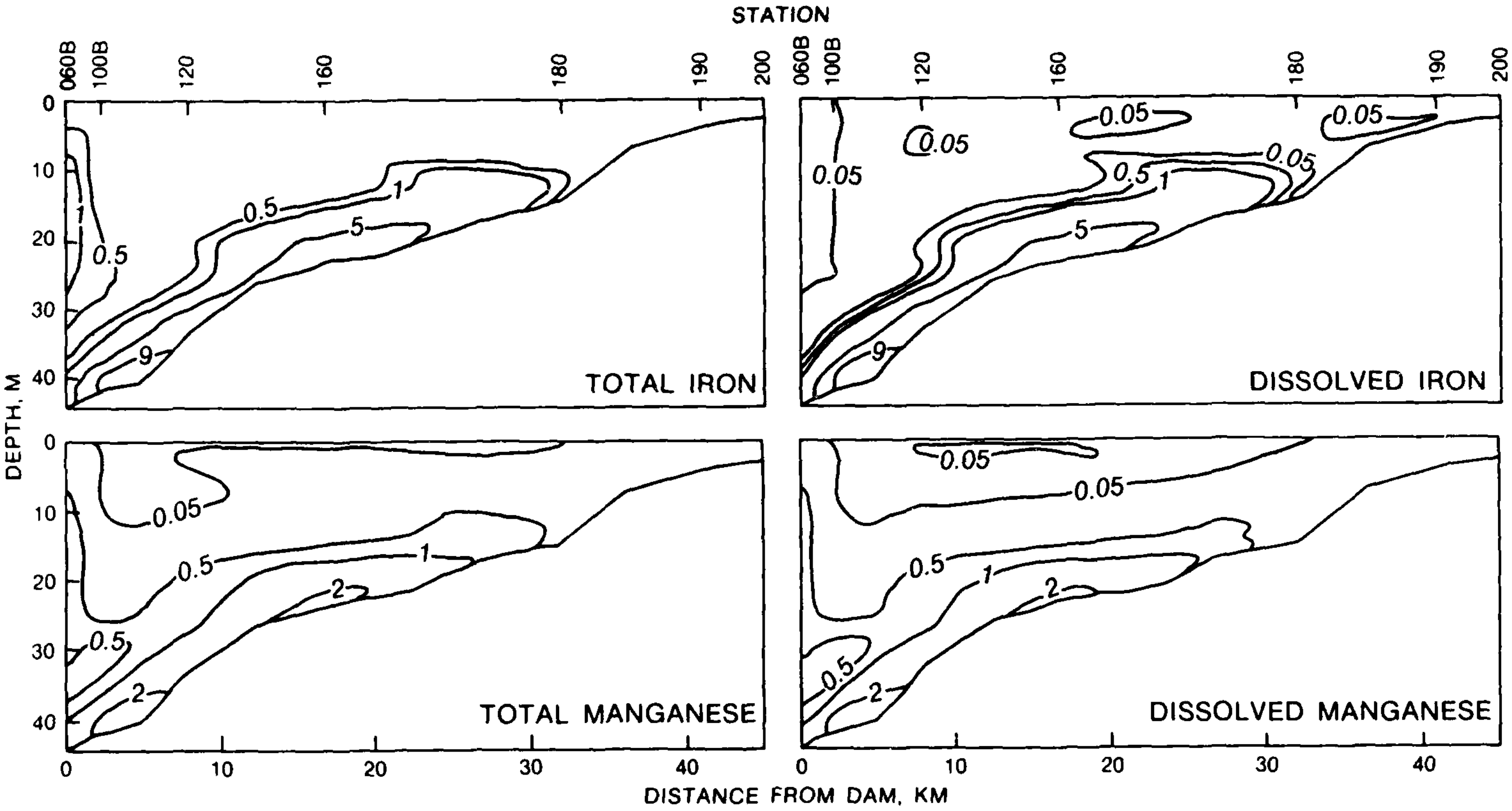

Figure 18. Patterns of spatial distribution of total and dissolved iron and manganese concentrations (mg/ℓ) in the Richard B. Russell Lake mainstem, October 1986

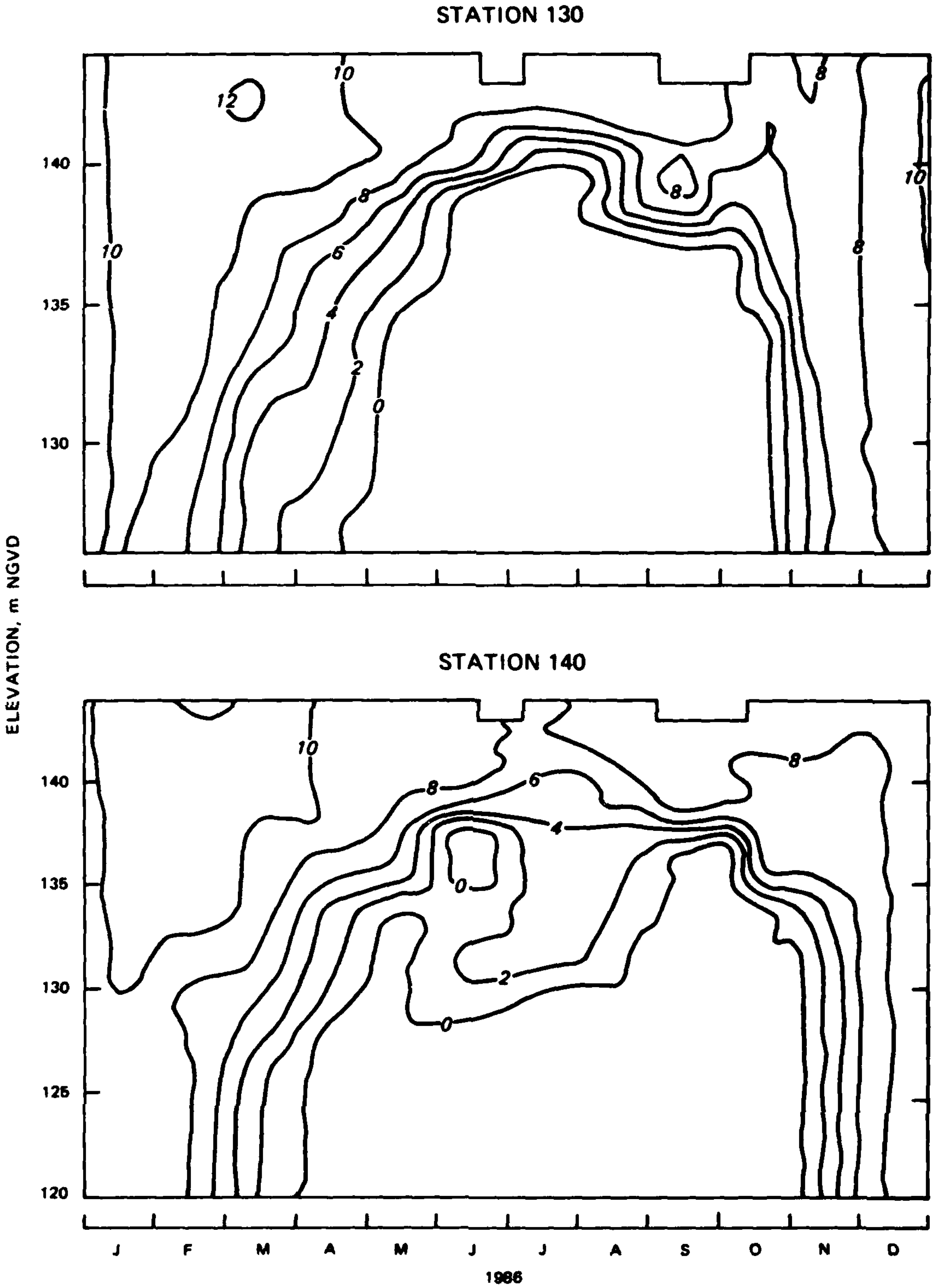

Figure 19. Patterns of spatial and temporal distribution of dissolved oxygen concentrations (mg/ℓ) in the Richard B. Russell Lake tributary embayments, sta 130 (Beaverdam Creek) and sta 140 (Rocky River), 1986

However, reduced inflows to the tributary embayments also limited the influence of tributary embayments on mainstem waters.

41. Releases from Richard B. Russell Lake had characteristics similar to those observed in 1985. Temperature varied from approximately 10° C in the late winter and spring to 18° C in the late summer and fall. Dissolved oxygen concentrations (Figure 20) were usually in the range of 6 to 10 mg/ℓ except for a brief time when malfunction of the oxygenation system allowed concentrations to fall to approximately 4 mg/ℓ.

42. Concentrations of iron in releases reflected conditions in the Richard B. Russell Lake forebay area (sta 060B). As in 1985, a large fraction of total iron was in a filterable, particulate form (Figure 20). The greatest concentrations of iron in the Richard B. Russell Lake release occurred in August and September when total iron ranged from 1.5 to 2.0 mg/ℓ and dissolved iron from 0.5 to 1.0 mg/ℓ.

43. Seasonal changes in the concentration of manganese in 1986 were similar to those observed in 1985. Concentrations of total manganese released from Richard B. Russell Lake (Figure 20) ranged from 0.05 mg/ℓ during the winter and spring to approximately 0.7 mg/ℓ during the late summer and fall. Dissolved manganese composed the major fraction of the total manganese at all times.

J. Strom Thurmond Lake

44. Pool elevation, monthly precipitation, mean daily inflow, and mean daily discharge for J. Strom Thurmond Lake during 1984-1986 (Figure 21) reflected the abnormally dry conditions of the region during 1986. Reduced flows in the Savannah River and its tributaries, due to drought conditions, and the scheduling of releases from Richard B. Russell and J. Strom Thurmond Lakes resulted in abnormally low lake-surface elevations in J. Strom Thurmond Lake for much of the year.

45. Temperature data for sta 020 indicated isothermal conditions in January and the onset of stratification in March (Figure 22). Warming continued into the summer, and by July 1986, surface temperatures exceeded 30° C. Warming and deepening of the thermocline continued into September followed by rapid cooling and a return to isothermal conditions in December. This trend was observed at most other locations on the lake (Figure 23). By October,

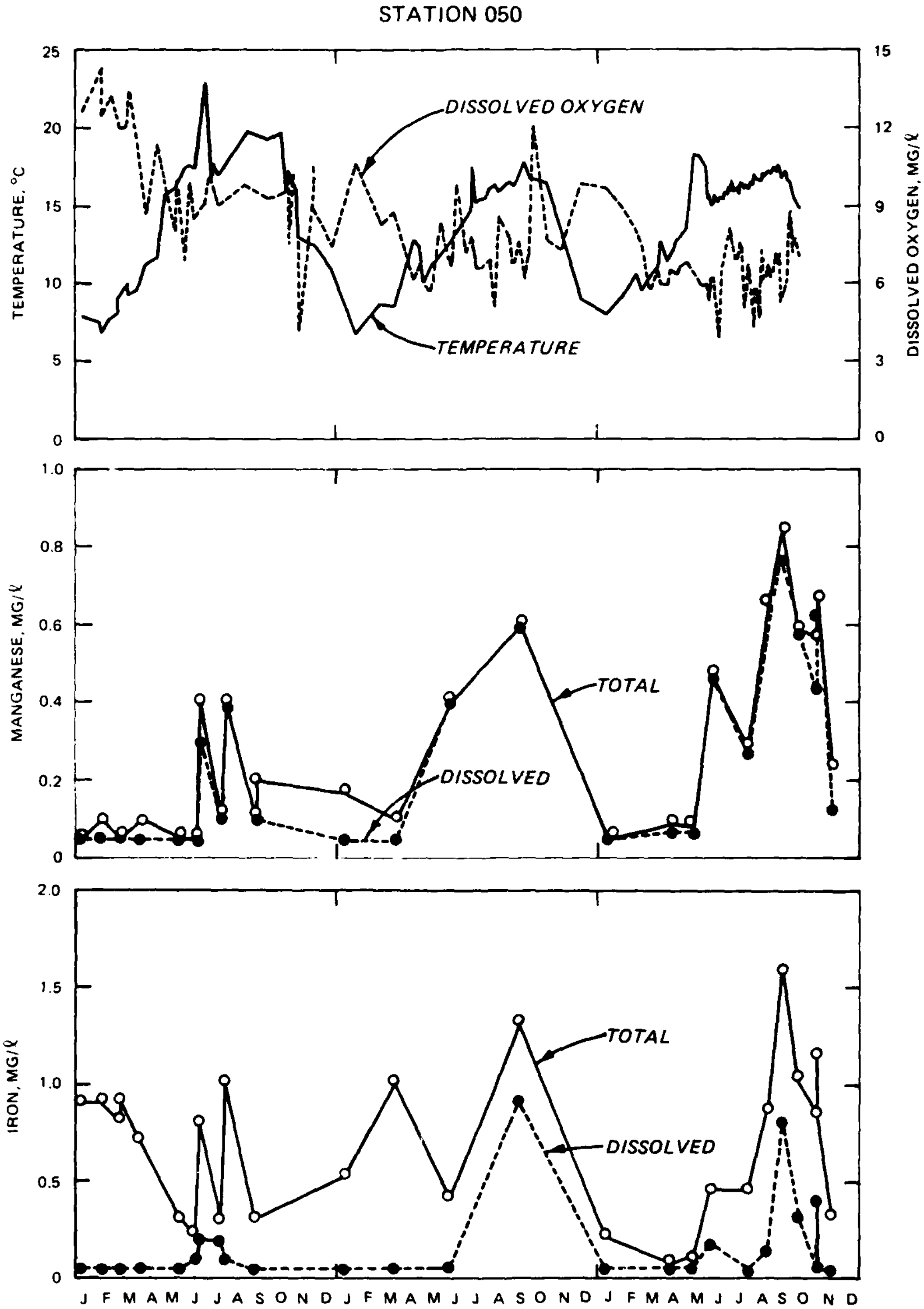

Figure 20. Patterns of temporal variation of temperature, dissolved oxygen, and total and dissolved iron and manganese concentrations in the Richard B. Russell Lake outflow, 1984-1986

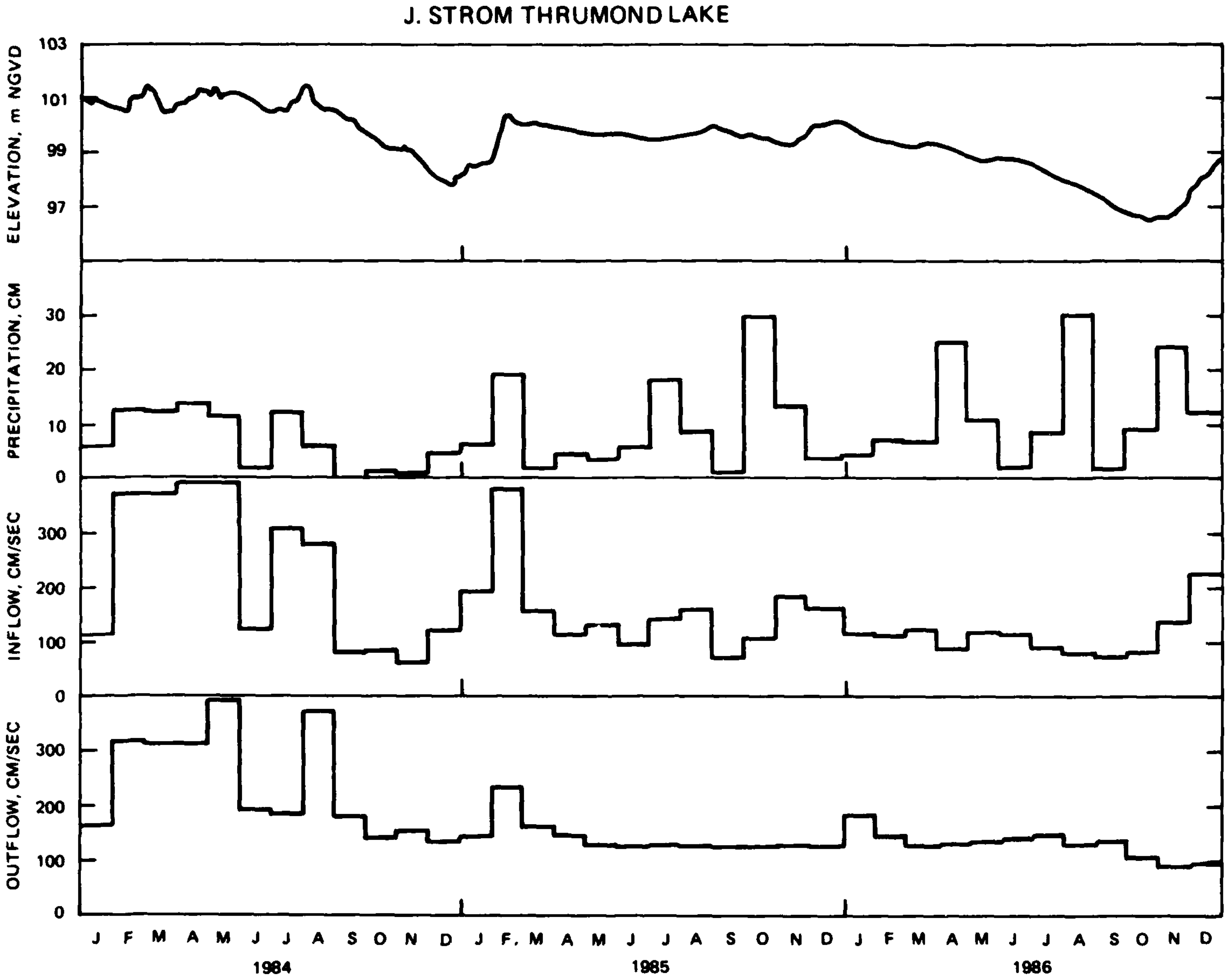

Figure 21. Pool elevation, precipitation, inflows, and outflows for J. Strom Thurmond Lake, 1984-1986

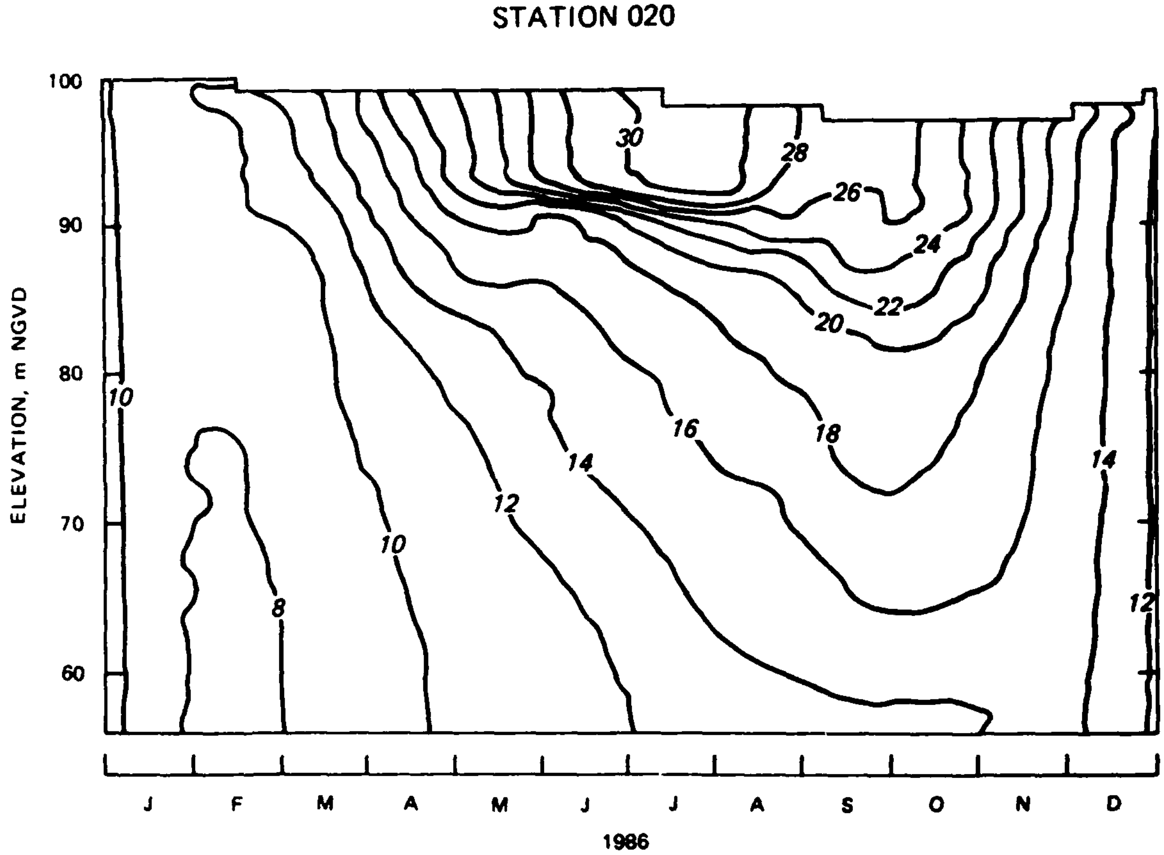

Figure 22. Patterns of spatial and temporal variation of temperatures (°C) in the J. Strom Thurmond Lake forebay, sta 020, for 1986

surface cooling caused decreased surface temperatures. Deeper waters had warmed throughout the stratified period to 14° C in the hypolimnion. During fall mixing, hypolimnetic temperatures gradually decreased to approximately 8° C.

46. Seasonal trends in dissolved oxygen concentrations in J. Strom Thurmond Lake were similar in 1986 to those observed in 1985. Minimum temperatures and lake mixing were accompanied by relatively high dissolved oxygen concentrations throughout J. Strom Thurmond Lake in winter. Dissolved oxygen concentrations observed in January varied between 10 and 12 mg/ℓ throughout the lake. By April, dissolved oxygen concentrations decreased, and a pattern similar to those observed in Hartwell Lake and Richard B. Russell Lake was observed (Figure 24). Concentrations of dissolved oxygen remained near 9 mg/ℓ in the epilimnion but decreased to <8 mg/ℓ in the deeper waters of areas farther upstream. From July to October, epilimnetic concentrations remained

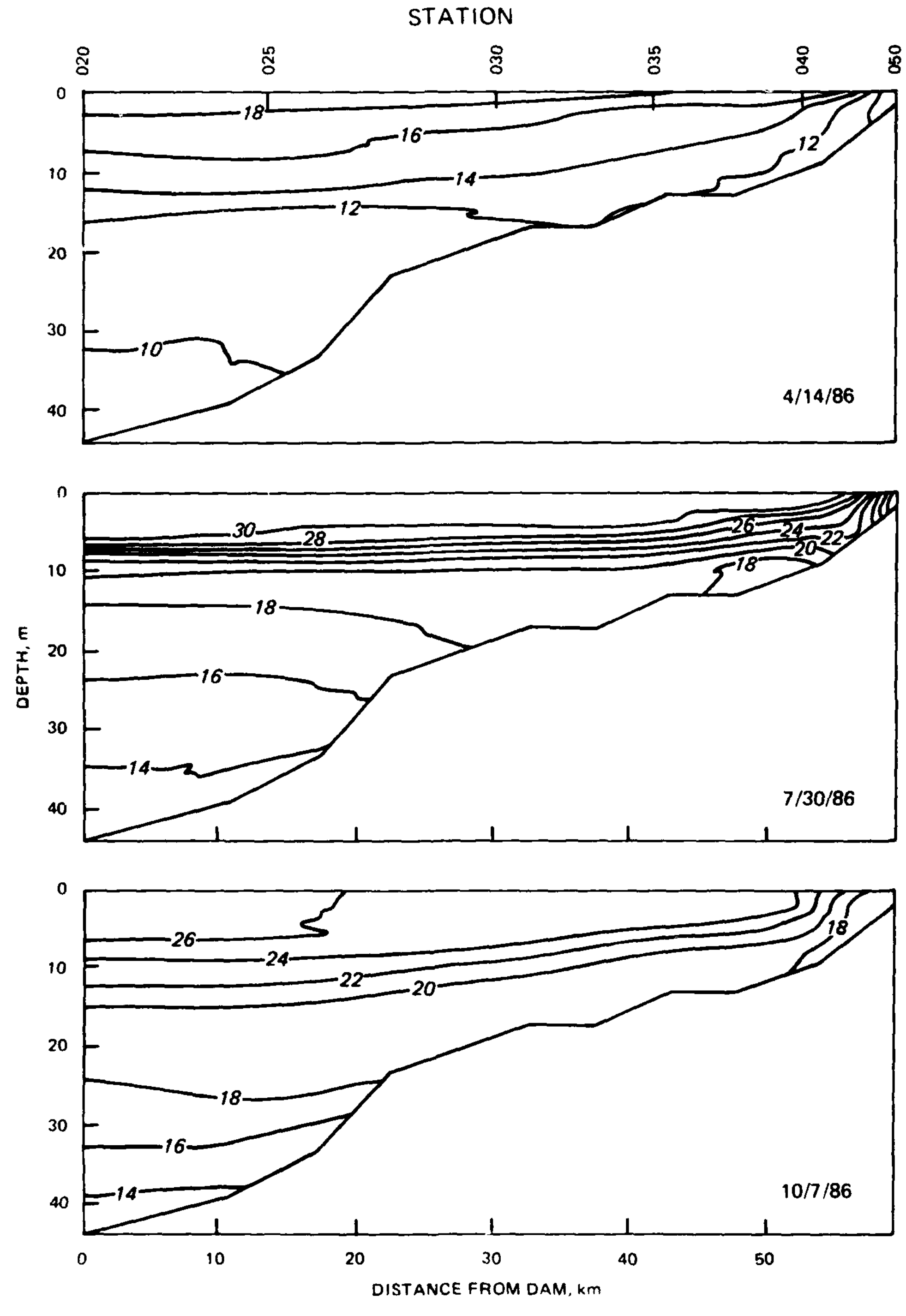

Figure 23. Patterns of spatial distribution of temperatures in the J. Strom Thurmond Lake mainstem for April, July, and October 1986

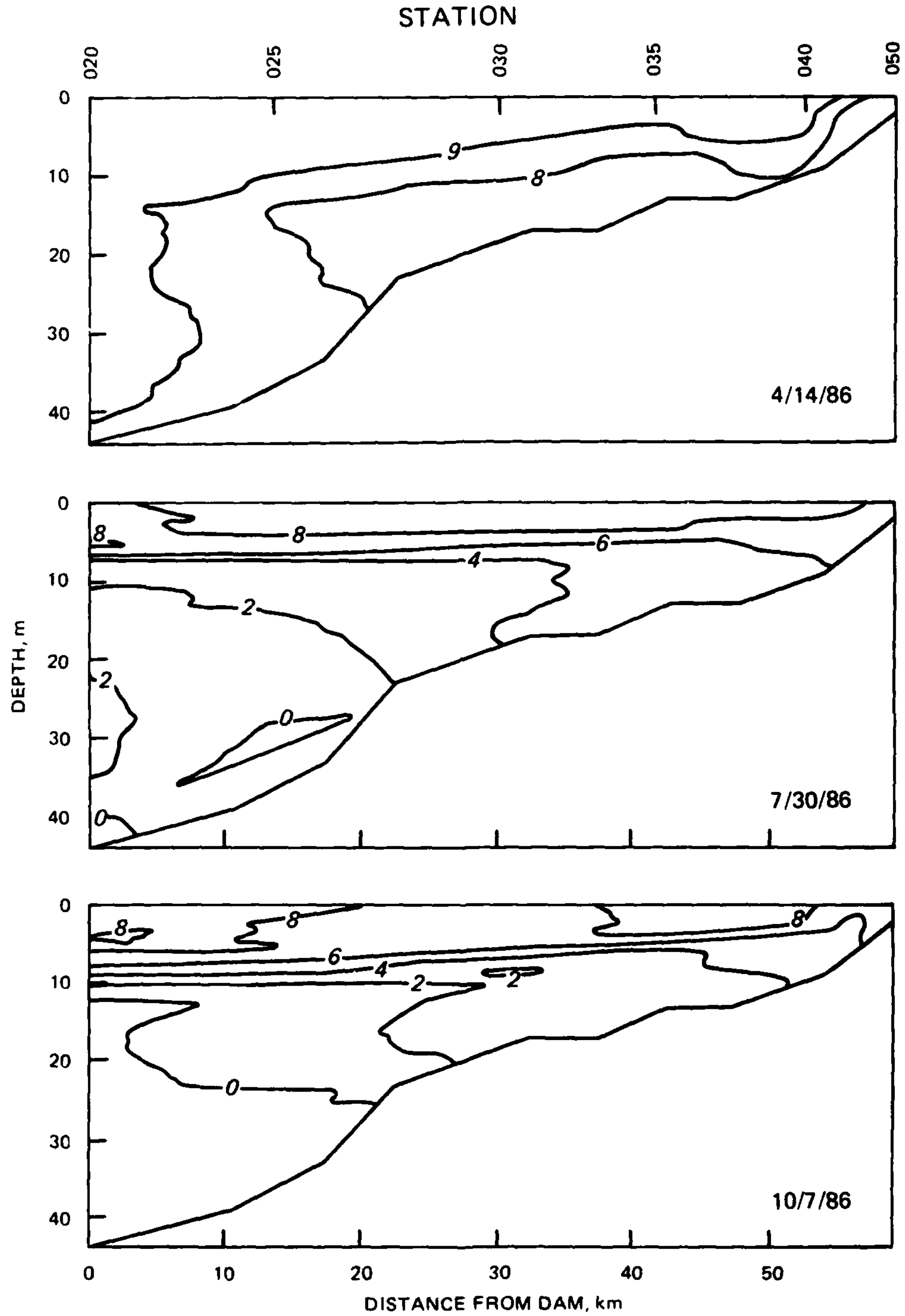

Figure 24. Patterns of spatial distribution of dissolved oxygen concentrations in the J. Strom Thurmond Lake mainstem for April, July, and October 1986

near 8 to 10 mg/ℓ while hypolimnetic concentrations decreased to <2 to 4 mg/ℓ in the mid-lake region and to <0.05 mg/ℓ in the lower region of the lake.

47. As was done for Richard B. Russell Lake, in situ data for J. Strom Thurmond Lake were used to calculate average areal and volumetric oxygen depletion rates using the computer program PROFILE (Walker 1987; Tables 6 and 7). Since preimpoundment data were available, PROFILE was applied to in situ data taken in 1981 prior to the completion of Richard B. Russell Lake. The average volumetric depletion rates for 1981 to 1986 ranged from 0.02 to 0.07 mg/ℓ/day. Slightly greater depletion rates were observed in the J. Strom Thurmond Lake forebay (sta 020) and headwater area (sta 040) than depletion rates observed near the mid-lake region (sta 030). Volumetric oxygen depletion rates calculated for J. Strom Thurmond Lake were less (<50 percent) than rates in Richard B. Russell Lake, and the depletion rates for Richard B. Russell Lake had a greater range of values than J. Strom Thurmond Lake.

48. Conductivity values ranged from 30 to 45 μS for most depths and times. Greater conductivity values in the hypolimnion accompanied oxygen depletion. Depths at which oxygen concentrations were <1 mg/ℓ had relatively high conductivity values, sometimes >60 μS. In October, conductivity data showed evidence of the interflow of the release waters from Richard B. Russell Dam at metalimnetic depths. At this time, metalimnetic conductivity values were significantly less than either surface waters of the hypolimnion.

49. Other in situ variables displayed weaker seasonal trends. Values for pH were indicative of circumneutral to mildly acidic waters and mostly varied between pH 6 and 7. Oxidation-reduction potential displayed no unusual trends with values indicative of oxidizing environments at most times and depths.

50. Total nitrogen concentrations were approximately 0.5 to 0.6 mg/ℓ throughout the lake during the winter and into the spring (January-April). During this period, the dissolved fraction represented <30 percent of the total nitrogen pool. By July, concentrations declined to 0.1 to 0.3 mg/ℓ and vertical gradients in concentration were not apparent. By October, coincident with anoxic conditions, vertical trends were apparent. While concentrations in surface waters remained low, total nitrogen concentrations as great as 0.6 mg/ℓ were observed in the hypolimnion (Figure 25).

51. Total phosphorus concentrations were usually low with maximum annual values of approximately 0.040 to 0.050 mg/ℓ in the winter at upstream

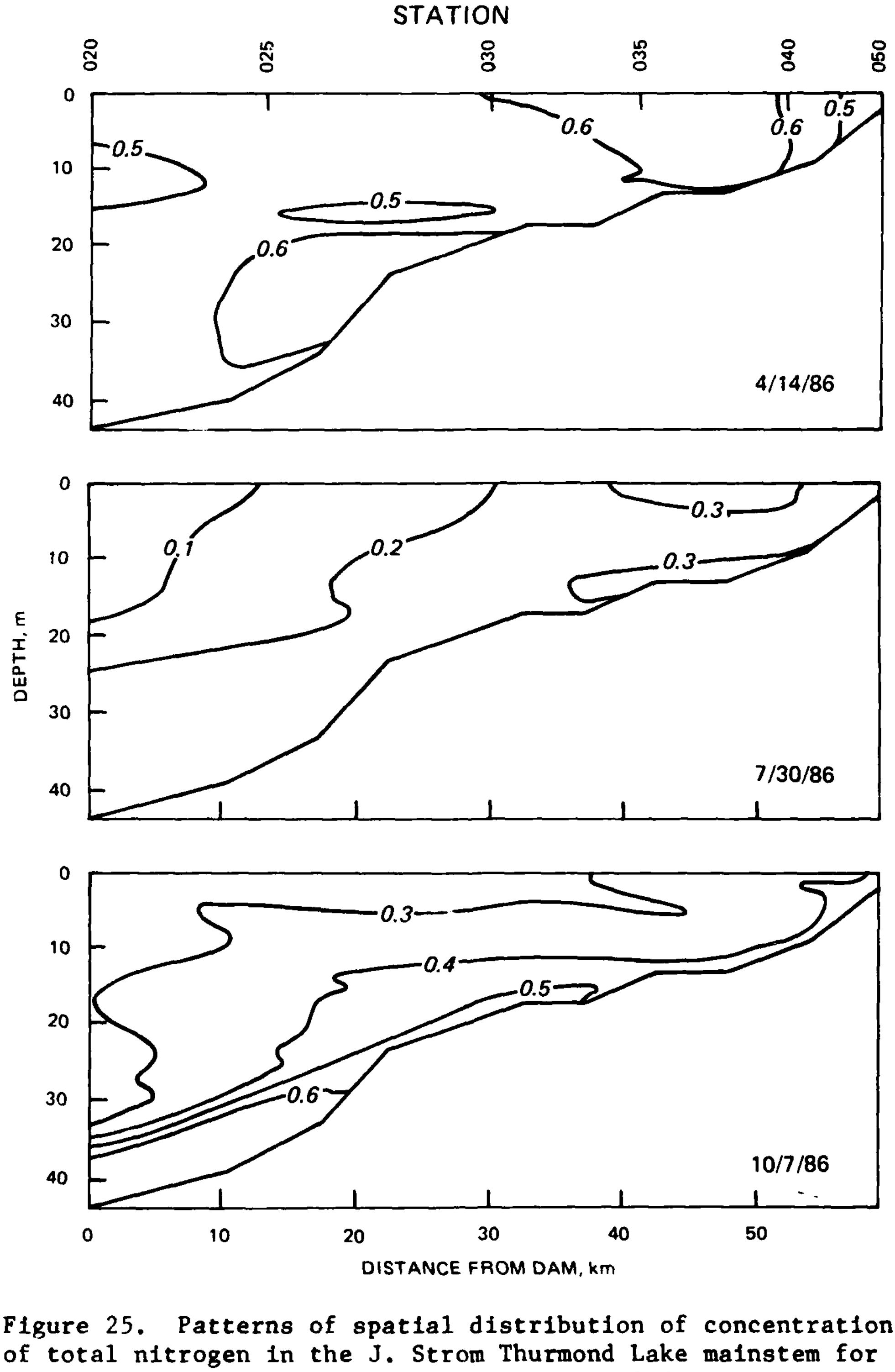

Figure 25. Patterns of spatial distribution of concentrations of total nitrogen in the J. Strom Thurmond Lake mainstem for April, July, and October 1986

locations. At other times, total phosphorus concentrations rarely exceeded 0.020 mg/ℓ (Figure 26). Downstream concentrations were often below detection limit (0.005 mg/ℓ).

52. Total and dissolved carbon concentrations showed no obvious spatial or temporal trends. Concentrations of total carbon usually ranged from 1 to 3 mg/ℓ. Dissolved carbon concentrations, although consistently less than totals, also ranged from 1 to 3 mg/ℓ.

53. Total and dissolved iron occurred in low concentrations in J. Strom Thurmond Lake during the winter and spring months. While total iron occurred in measurable concentrations (0.1 to 0.5 mg/ℓ) at all times and locations in J. Strom Thurmond Lake during the winter and spring, maximum hypolimnetic concentrations of 1 to 2 mg/ℓ occurred only during the summer and fall. During the fall, dissolved iron concentrations were below detection limits except for locations near the Richard B. Russell Lake tailrace where concentrations were approximately 0.05 to 0.08 mg/ℓ (Figure 27).

54. Total and dissolved manganese concentrations were near or below detection limits (0.05 mg/ℓ) during the winter and spring, except for locations near the Richard B. Russell Lake tailrace. In July, surface concentrations remained low, but increases were observed at greater depths especially where dissolved oxygen had been depleted. Maximum concentrations (>1 mg/ℓ) were observed in October (Figure 27) throughout the hypolimnion, and values as great as 9.5 mg/ℓ were reported for the forebay. Total and dissolved manganese concentrations were always comparable, suggesting that most manganese occurred in the dissolved or reduced form.

55. Releases from J. Strom Thurmond Dam reflected water quality conditions at the penstock depths in the forebay. In the winter and spring, dissolved oxygen concentrations were near saturation values but declined in the summer and fall to concentrations of approximately 2 mg/ℓ. Water temperature, which followed a similar pattern of variation as observed for Richard B. Russell Lake and Hartwell Lake, was significantly cooler than lake-surface waters in the summer. Minimum winter temperatures were approximately 8° C. Conductivity, pH, and ORP also reflected conditions at intermediate depths in the forebay.

56. At most times, total carbon and dissolved carbon occurred in concentrations of 1 to 3 mg/ℓ in release waters. Total and dissolved manganese occurred in measurable concentrations in the summer (0.09 mg/ℓ) and fall

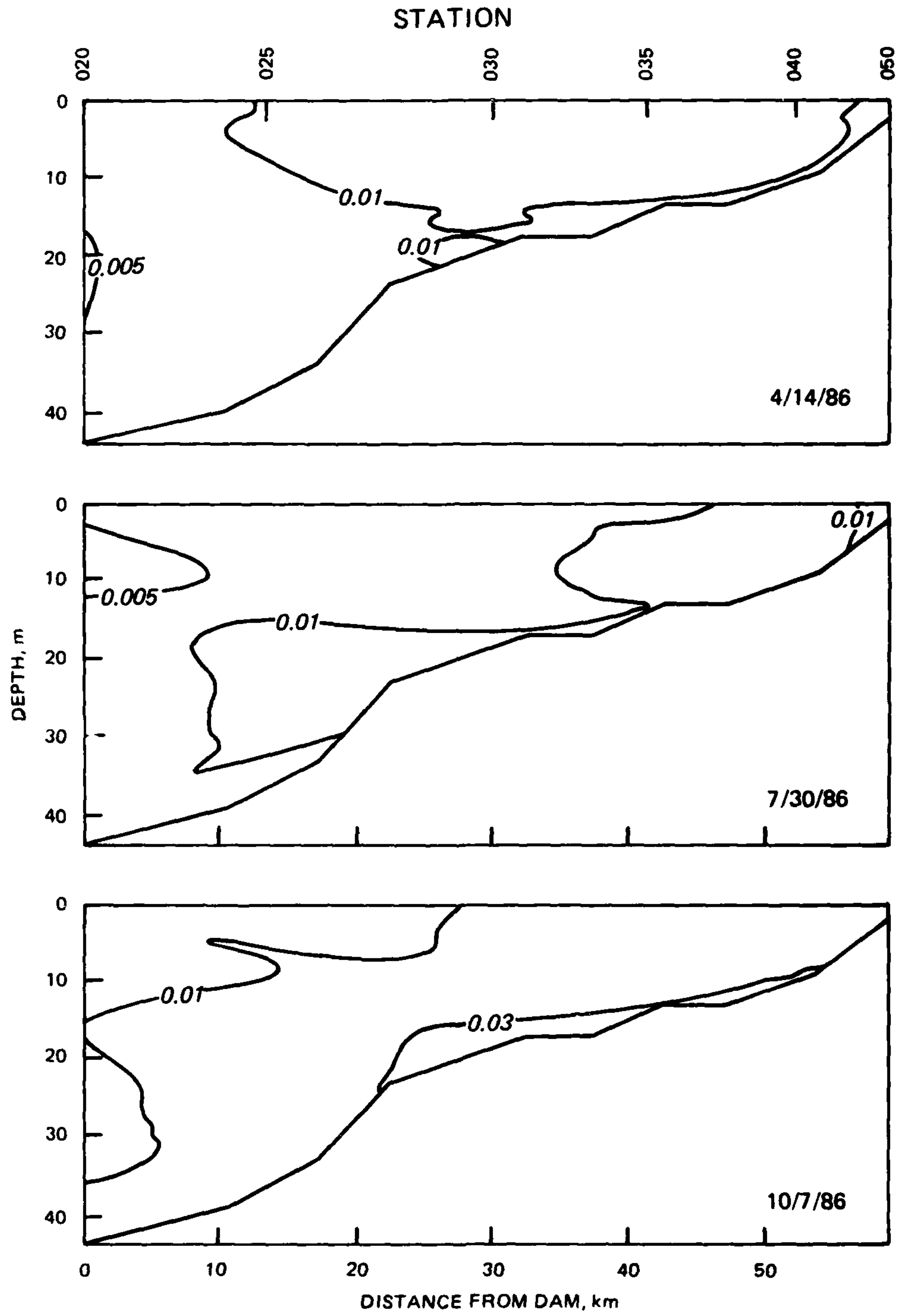

Figure 26. Patterns of spatial distribution of concentrations of total phosphorus in the J. Strom Thurmond Lake mainstem for April, July, and October 1986

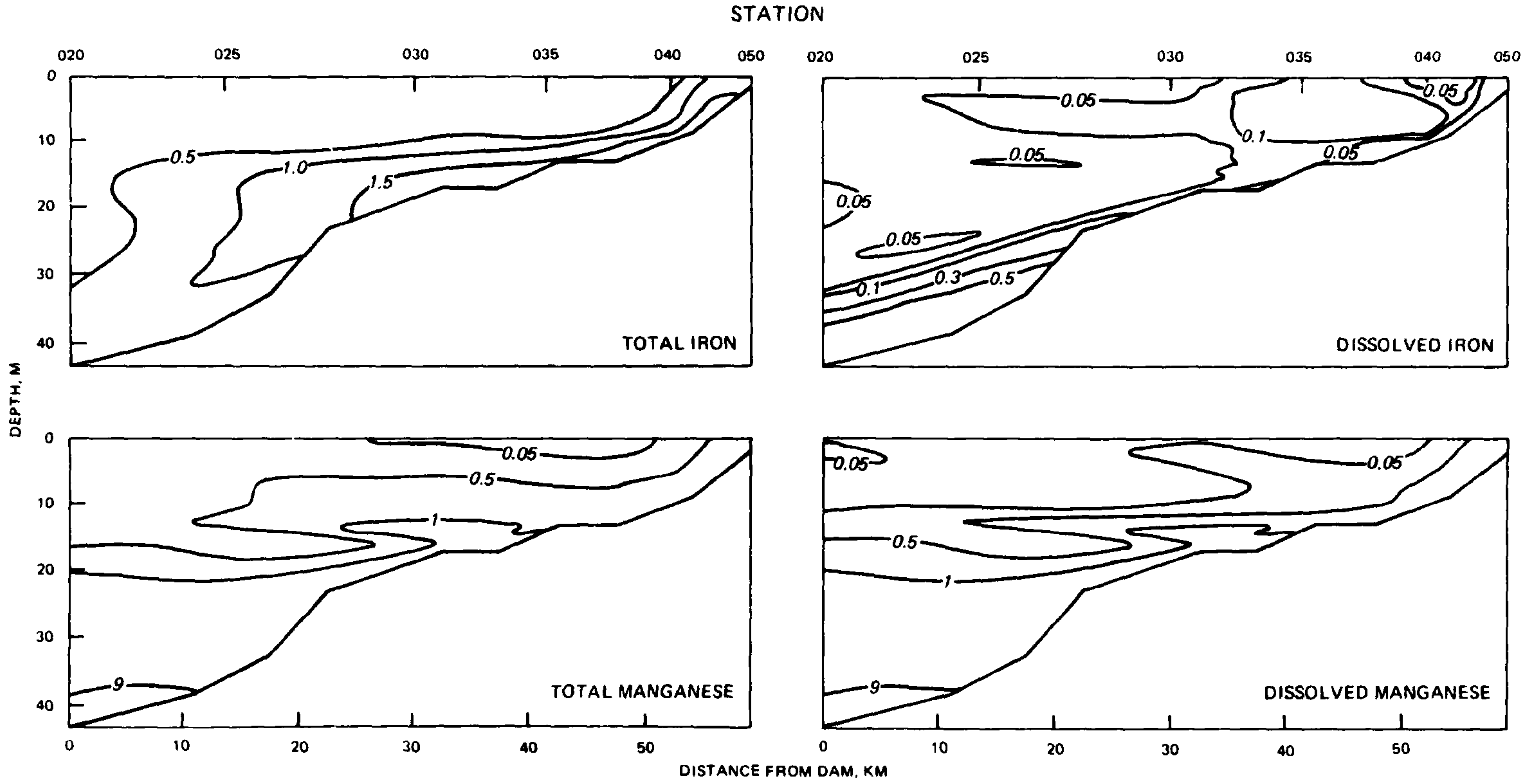

Figure 27. Patterns of distribution of total and dissolved iron and manganese concentrations in the J. Strom Thurmond Lake mainstem, October 1986

(0.57 mg/ℓ), and total iron was measurable at most times but never exceeded 0.25 mg/ℓ. Dissolved iron was only measurable in January (0.08 mg/ℓ).

Oxygenation System Operation

57. Operation of the pulse-oxygenation system was initiated 30 April 1986, and since the continuous oxygenation system was inoperable, it operated throughout the stratified season. An exception was an 8-day period from 31 July to 8 August when operation was suspended for repairs to a damaged supply line. Although initial delivery rates were modest (approximately 15 tons of oxygen per day), the need to maintain a minimum of 6 mg/ℓ dissolved oxygen in the release water required operation at capacities of 70 to 80 tons (63,500 to 72,575 kg) of oxygen per day for much of the summer and fall.

58. Although the bubble plumes were dense, they did not significantly disrupt the thermal structure of the lake in the area near the pulse-oxygenation system (Figure 28). Indeed, thermal structure in this area was similar to that observed upstream (Figure 11).

59. The pulse-oxygenation system increased the concentration of dissolved oxygen at most depths (Figure 29). Whereas dissolved oxygen concentrations were depleted to <4 mg/ℓ below the thermocline during the fall at other locations on Richard B. Russell Lake (see Figure 14), dissolved oxygen concentrations in the forebay were maintained near 6 mg/ℓ throughout much of the hypolimnion. However, this effect was restricted to the immediate area of the forebay and did not extend as far as sta 115 (Figure 30). This was confirmed by similarities in oxygen distribution at sta 115 and sta 120 (see Figure 14).

60. Oxygen transfer, inferred from analyses of the gaseous content of bubbles emerging from the diffuser plumes and expressed as percent, was measured three times during 1986 (Table 8). Midsummer (15 July 1986) values were less than similar measurements made in 1985 (James et al. 1986). Values ranged from approximately 25 to 40 percent for a series of individual diffuser plumes on lines 1, 2, and 4 of the pulse-oxygenation system. These values corresponded to gaseous oxygen losses at the lake surface of approximately 60 to 70 percent of the total volume of oxygen introduced by the pulse-oxygenation system (Table 8). On 21 August 1986, oxygen-transfer values ranged from approximately 27 to 90 percent. As was observed on 15 July,

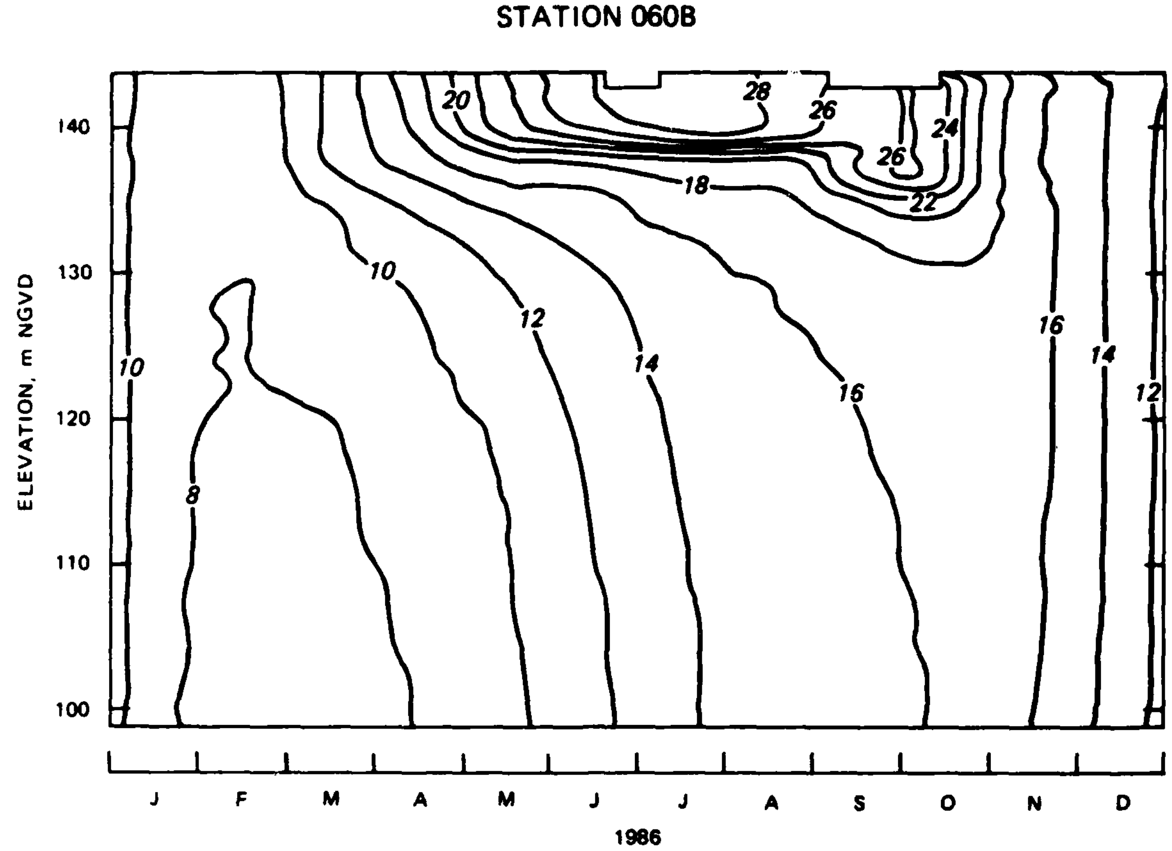

Figure 28. Patterns of spatial and temporal variation of temperature (°C) in the Richard B. Russell Lake forebay, sta 060B, for 1986

diffuser lines 1 and 2 had few visible plumes, and those which were visible were typical of "leakage" plumes (i.e., dominated by bubbles of large size). Additional bubble plumes were visible on 1 October; however, the oxygen-transfer values were not significantly different from the August measurements but clearly greater than the values measured in July (Table 8).

61. Increased oxygen-transfer values observed in August and October may be attributed to cleaning and replacement of diffuser heads after the July measurements. Maximum gas transfer will accompany conditions which maximize the exposure of bubble contents to the surrounding waters. In this sense, smaller bubbles increase the surface area to volume ratio and slow the rise of the bubbles through the water as well, both factors enhancing the transfer of the gas. System conditions, such as leakage or damaged diffuser heads, which produce large bubbles will consequently reduce the system-transfer efficiency. Selected point measurements of oxygen transfer do not imply efficiency of the

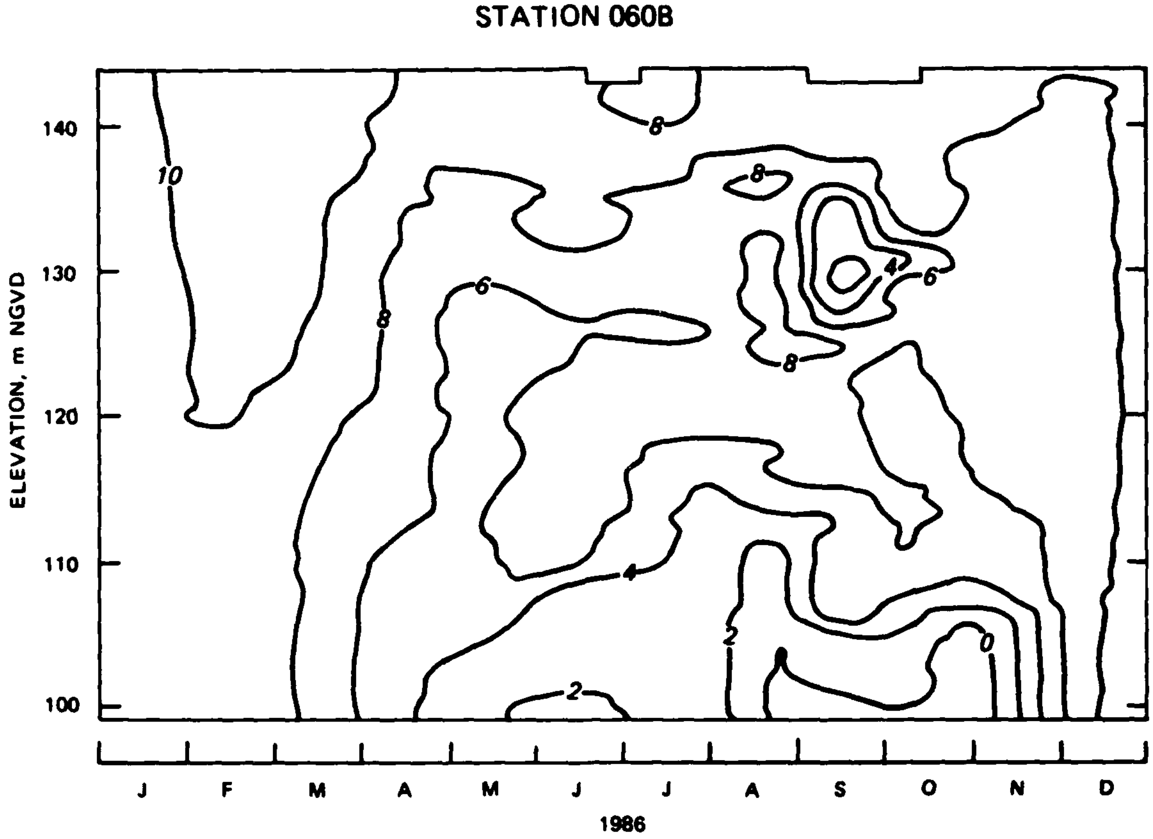

Figure 29. Patterns of spatial and temporal variation of dissolved oxygen concentrations (mg/ℓ) in the Richard B. Russell Lake forebay, sta 060B, for 1986

oxygenation system but provide a range of values dependent upon system conditions, operations, and sampling variability.

62. Dissolved oxygen concentrations in releases from Richard B. Russell Dam during the stratified period were markedly altered by the pulse-oxygenation system. Although dissolved oxygen concentrations in Richard B. Russell Lake and in the releases from Hartwell and J. Strom Thurmond Dams decreased throughout the stratified period, the concentrations of dissolved oxygen in water released from Richard B. Russell Dam remained near 6 mg/ℓ for much of the summer (Figure 31).

63. The water quality model SELECT (Davis et al. 1987) was employed to predict outflow oxygen concentrations based on lake data from sta 60 and 120 in the presence and absence, respectively, of oxygen-system operation. These predictions and the actual outflow concentrations are shown in Figure 32.

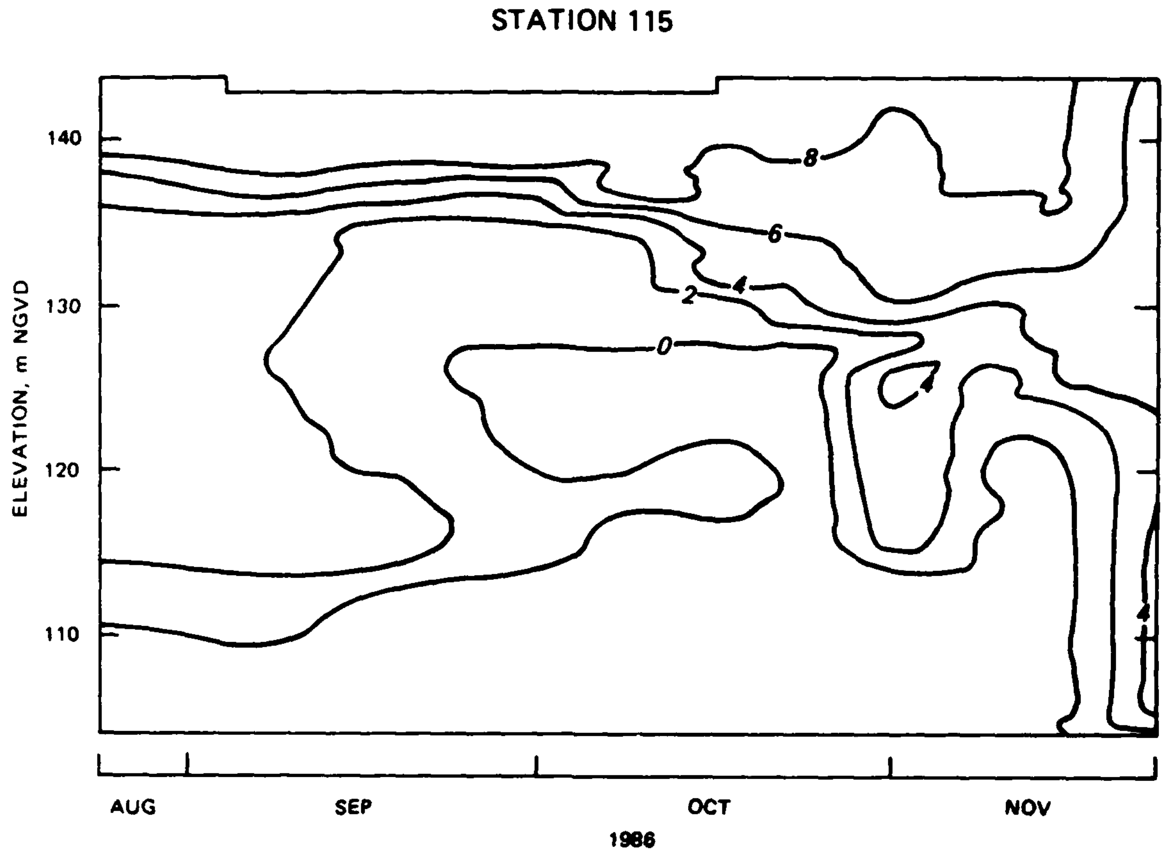

Figure 30. Patterns of spatial and temporal variation of dissolved oxygen concentrations (mg/ℓ) at sta 115 for late summer (August-November), 1986

Results from SELECT indicate that the oxygenation system adds approximately 2 to 4 mg/ℓ dissolved oxygen to Richard B. Russell Dam releases.

64. Due to the forced inoperation of the pulse oxygenation system from 31 July to 8 August, a before/after comparison of the effectiveness of operation was possible. Prior to, and after, that period, the pulse oxygenation system operated at a capacity of approximately 80 tons of oxygen per day. During the 5 days preceding 31 July, dissolved oxygen concentrations in the Richard B. Russell Dam release were approximately 6 mg/ℓ. Within 24 hr after the pulse-oxygenation system became inoperative, dissolved oxygen concentrations in the release waters decreased to approximately 5.5 mg/ℓ and in another 24 hr to 4.5 mg/ℓ. In 4 days, dissolved oxygen stabilized at concentrations of approximately 4 mg/ℓ and remained at this value until the pulse-oxygenation system returned to operation on 8 August.

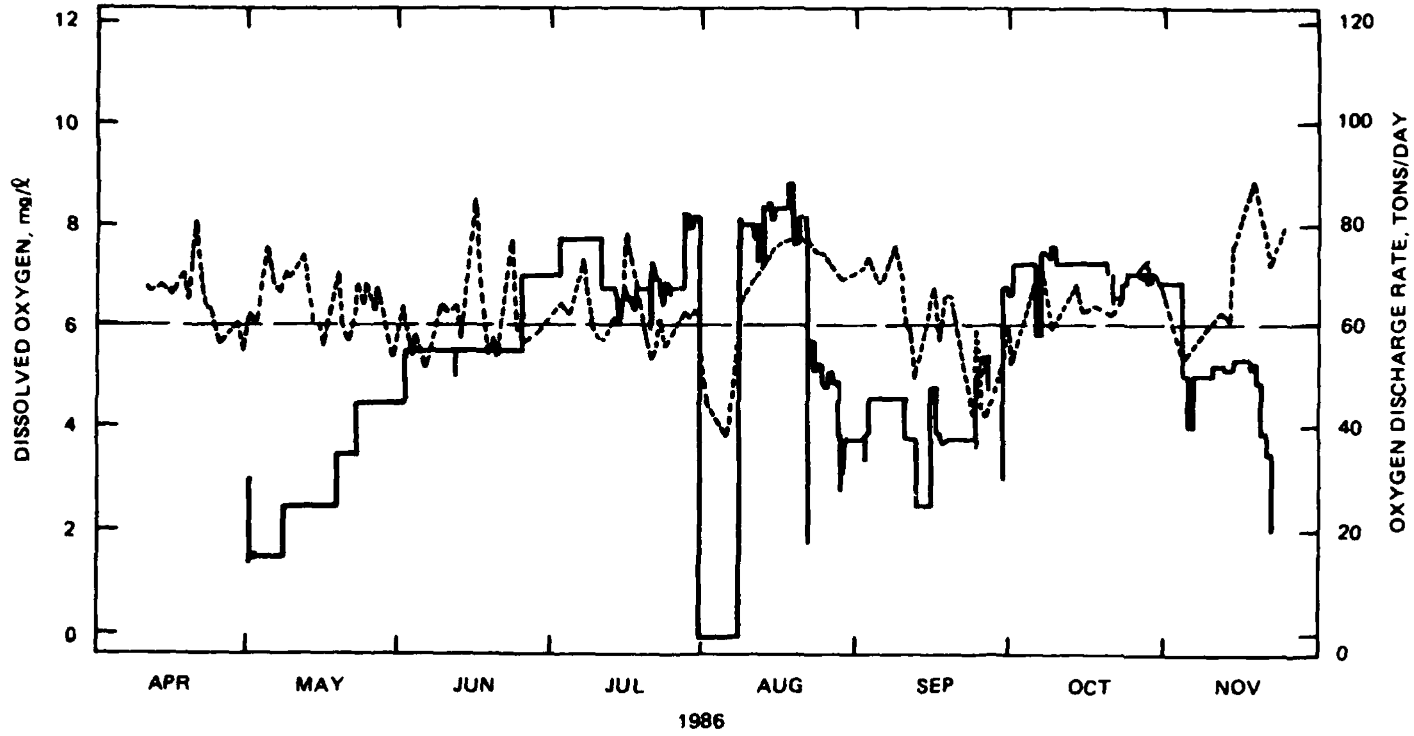

Figure 31. Dissolved oxygen concentrations (dashed line) in the Richard B. Russell Lake outflow and the oxygen delivery rate from the pulse-oxygenation system (solid line). Horizontal large dashed line indicates the 6 mg/ℓ target dissolved oxygen concentration

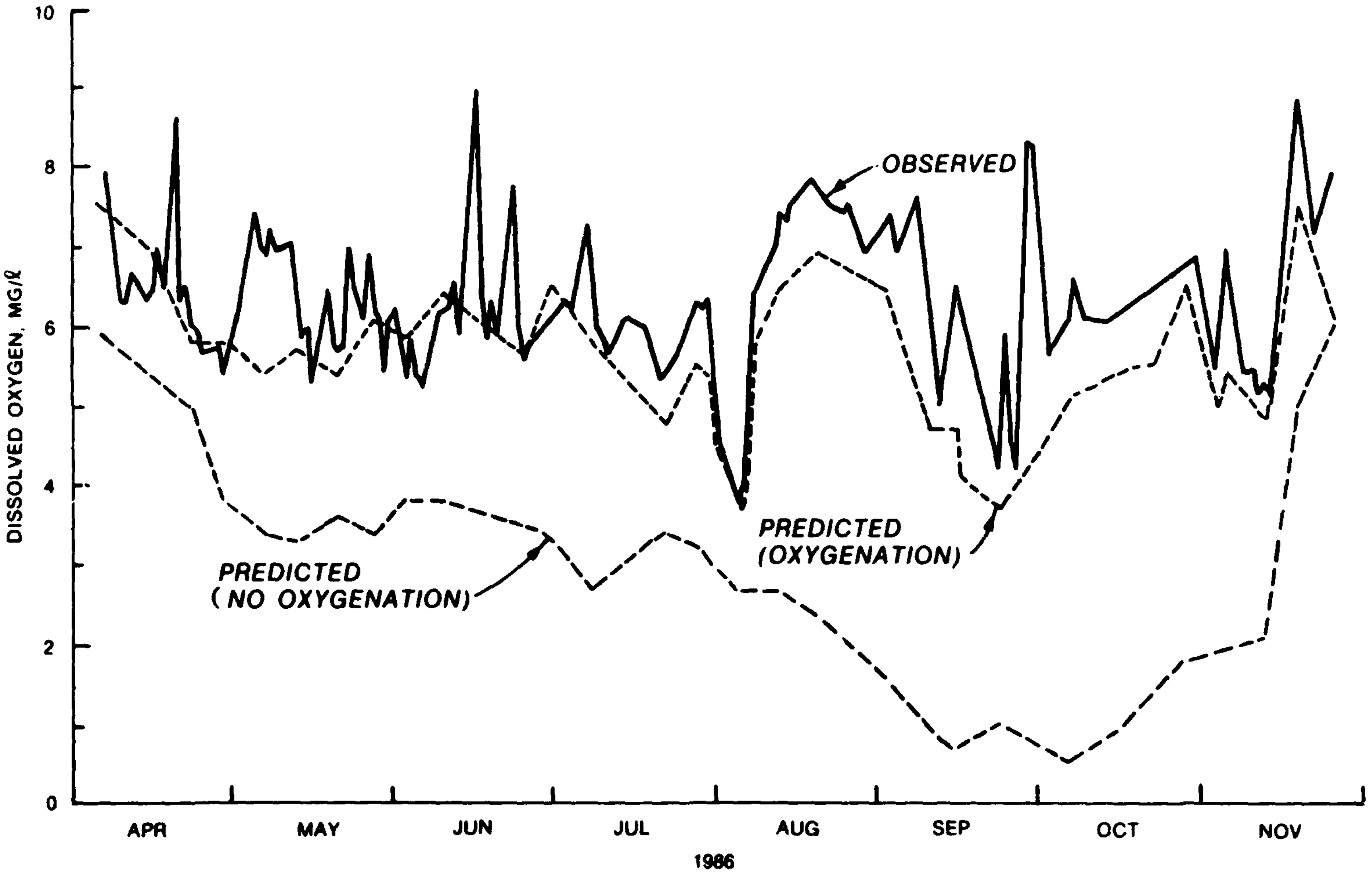

Figure 32. SELECT predictions of dissolved oxygen concentrations versus observed concentrations in the Richard B. Russell Dam releases

Phytopigment Distributions

65. Primary productivity, a contributor of organic carbon to Hartwell, Richard B. Russell, and J. Strom Thurmond Lakes, displayed seasonal, spatial, and interlake differences that are important to an understanding of trophic dynamics. These differences were reflected by phytopigment concentrations, an indicator of phytoplankton standing crop (Figure 33). In 1984, the pattern of chlorophyll a concentrations in Richard B. Russell Lake indicated maximum

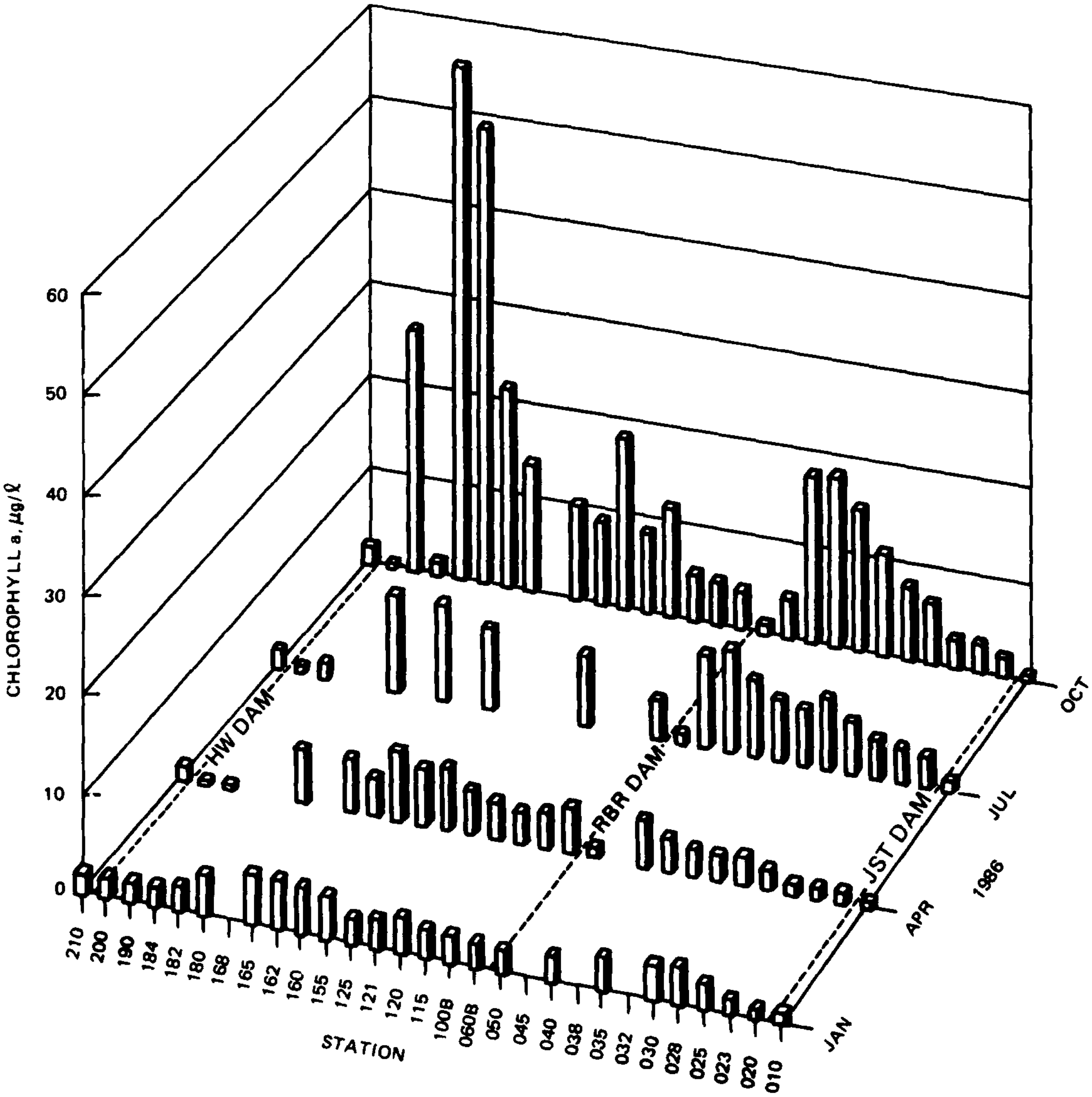

Figure 33. Patterns of distribution of chlorophyll a concentrations in Hartwell, Richard B. Russell, and J. Strom Thurmond Lakes for January, April, July, and October 1986

values of 10 to 14 μg/ℓ during July-August with peaks near sta 180 and 100. In 1984, chlorophyll a concentrations in J. Strom Thurmond Lake were maximal (14 μg/ℓ) during February-March with a peak near sta 30. In 1985, the maximum chlorophyll a concentrations (approximately 10 μg/ℓ) for Richard B. Russell Lake occurred during August and again during October-November near sta 180 and 160. Maximum chlorophyll a concentrations for 1985 in J. Strom Thurmond Lake (10 to 12 μg/ℓ) occurred near sta 40 in the influence of both Richard B. Russell Dam releases and inflows from Broad River. Most of J. Strom Thurmond Lake, however, had chlorophyll a concentrations <6 μg/ℓ, a concentration value 50 percent lower than that observed in 1984.

66. In 1986 (Figure 33), the pattern of chlorophyll a concentrations was similar to that for 1985. Winter (January) concentrations were low (<10 μg/ℓ) at all locations. The presence of chlorophyll a in the outflows was presumably due to downmixing of surface plankton. In April, concentrations had increased slightly in Richard B. Russell Lake, and outflows had very low concentrations of chlorophyll a. In July, chlorophyll a concentrations were greatest near the inflows where a gradual change from lotic-dominated processes to lentic-dominated processes occurred. However, even those concentrations rarely exceeded 10 μg/ℓ. By October, chlorophyll a concentrations in Hartwell Lake were approximately 2 μg/ℓ, little greater than in the outflow. Concentrations in Richard B. Russell Lake peaked near sta 180 (>40 μg/ℓ), rapidly decreased to approximately 15 μg/ℓ near sta 160, and maintained concentrations of nearly 8 μg/ℓ to the Richard B. Russell Lake forebay. Outflow concentrations to J. Strom Thurmond Lake were negligible. Chlorophyll a rapidly increased to nearly 20 μg/ℓ near the confluence of Broad River (sta 38) then gradually decreased in concentration to approximately 2 to 3 μg/ℓ in the J. Strom Thurmond Lake forebay.

67. In general, Richard B. Russell Lake is more productive than either Hartwell or J. Strom Thurmond Lakes. Although J. Strom Thurmond Lake is, at present, less productive than Richard B. Russell Lake, chlorophyll a concentrations during 1984-1986 were similar to concentrations observed during 1981 (Applied Biology, Inc. 1982) and 1973 (US Environmental Protection Agency 1978). In the third year of the impoundment of Richard B. Russell Lake, there were no observable changes of chlorophyll a concentrations in J. Strom Thurmond Lake. Instead, the spatial distribution of chlorophyll a in J. Strom Thurmond Lake has changed. Greater concentrations exist in upstream areas

associated with inflows, and concentrations less than those observed during pre-Richard B. Russell Lake studies exist at downstream locations on J. Strom Thurmond Lake.

Diel Studies

68. The frequency and times of generation determine many of the physical and chemical conditions of reservoir tailwaters. Because a diel pattern of operation was maintained at Richard B. Russell Dam, two diel studies were performed to identify diel variations, if any, in J. Strom Thurmond Lake water quality related to Richard B. Russell Dam releases. The first diel survey (22-25 June 1986) (US Army Engineer Waterways Experiment Station 1986) showed that both thermal and chemical characteristics for the upper 5 km of J. Strom Thurmond Lake were dominated by releases from Richard B. Russell Dam (Figure 34). Within an hour after the start of generation, the Richard B. Russell Dam release dominated the upper 2 km of J. Strom Thurmond Lake, and in 5 hr a plunge line had developed 4 km downstream from Richard B. Russell Dam (Figure 35). This pattern persisted up to 2 hr after generation ceased. However, within 8 hr after the end of generation, the pre-generation thermal structure was reestablished throughout the tailwater area (Figure 36).

69. A similar survey during 2-4 November 1986 was less able to identify diel trends of water quality due to near isothermal conditions in Richard B. Russell Lake and the similarity of temperatures between the Richard B. Russell Dam release and J. Strom Thurmond Lake surface water (US Army Engineer Waterways Experiment Station 1987). By that time, drought conditions had caused the J. Strom Thurmond Lake surface to reach abnormally low elevations. For this reason, extensive areas of the lake bed in the headwater region of J. Strom Thurmond Lake were exposed, creating difficulty for sampling. Indeed, normal flow patterns were altered, and some sampling locations were dry. Therefore, comparisons between surveys are difficult.

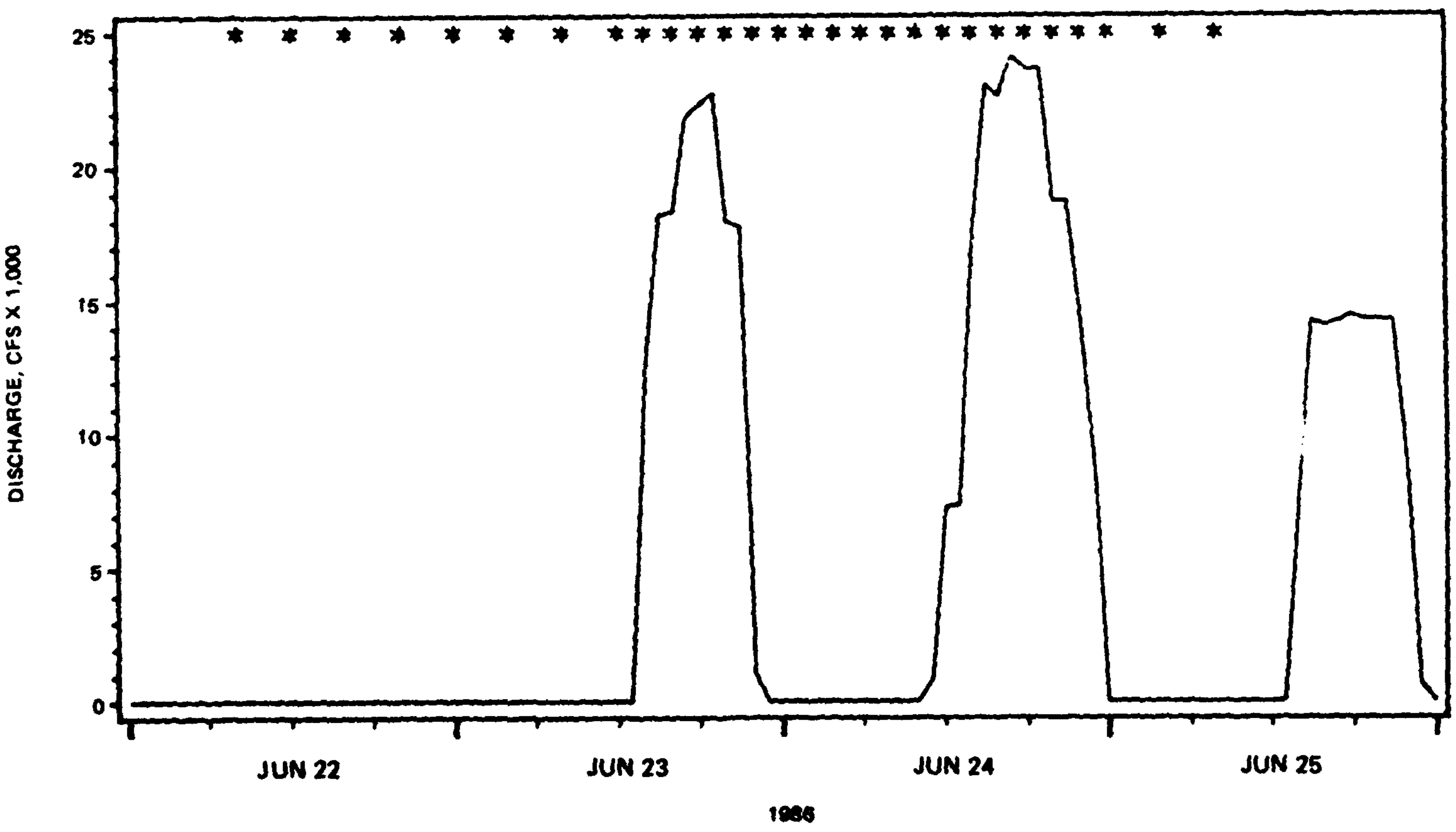

Figure 34. Discharges from the Richard B. Russell Dam during the diel study in J. Strom Thurmond Lake. (Asterisks indicate sampling times)

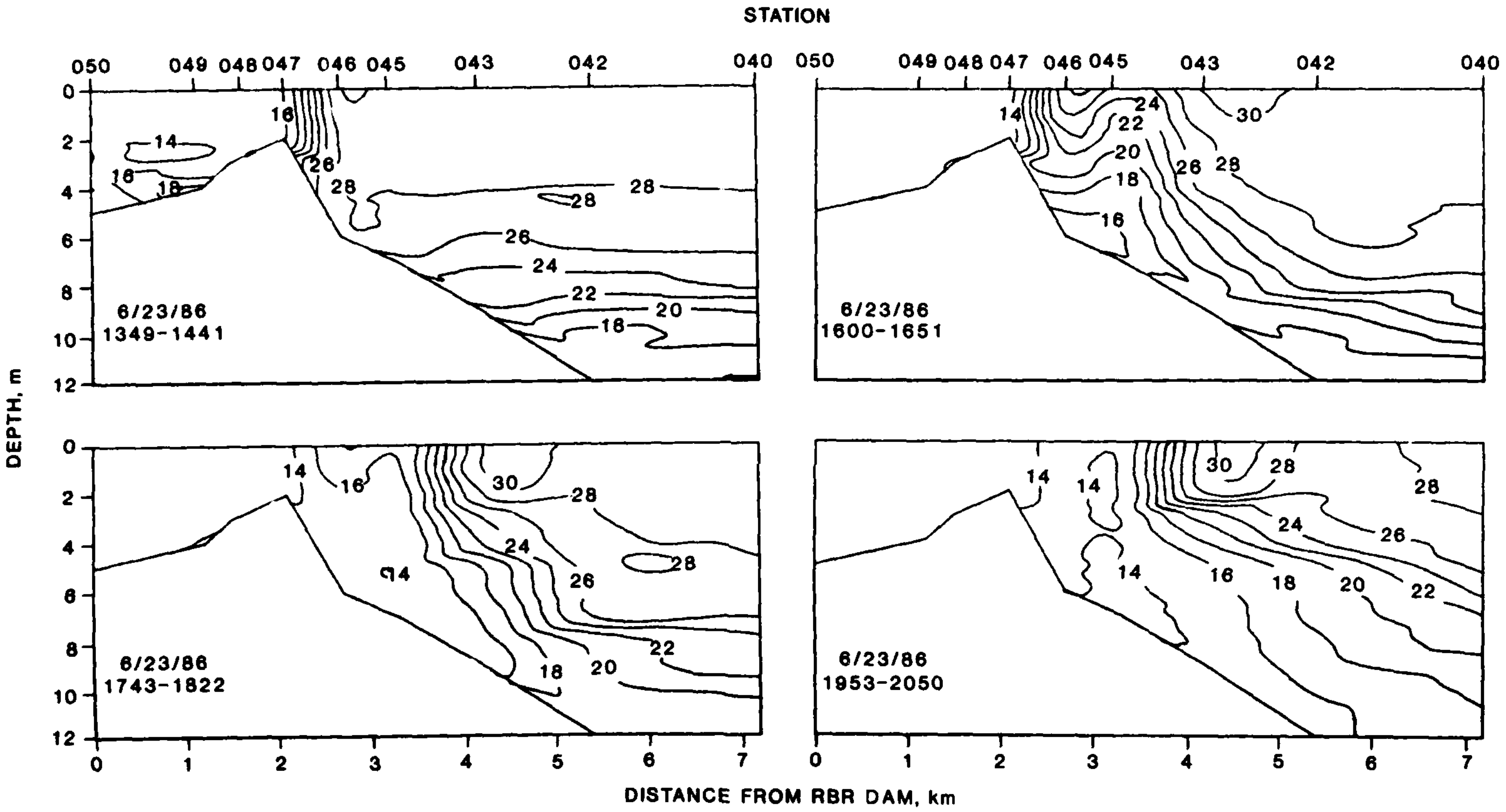

Figure 35. Longitudinal and vertical changes in temperature in the headwater region of J. Strom Thurmond Lake during generation from Richard B. Russell Dam

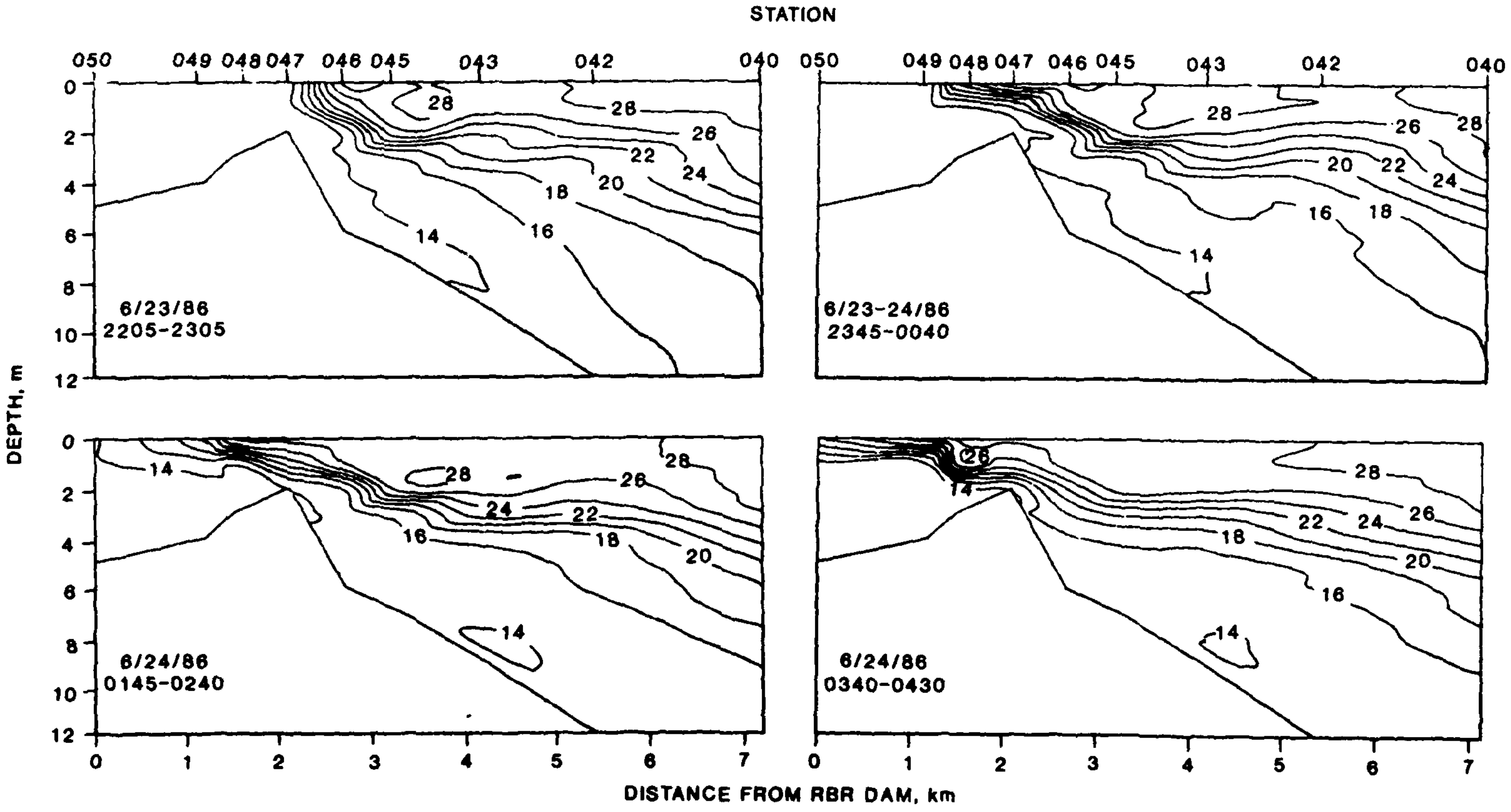

Figure 36. Longitudinal and vertical changes in temperature in the headwater region of J. Strom Thurmond Lake following generation from Richard B. Russel Dam

PART V: DISCUSSION

70\. Although the region suffered drought conditions for much of 1986, several water quality characteristics for Hartwell, Richard B. Russell, and J. Strom Thurmond Lakes were similar to those observed in 1984 and 1985. Of these, pH displayed no unexpected trends. Values for pH varied near pH 6 to 7.5 for the three lakes at all depths and times. At most locations in Hartwell, Richard B. Russell, and J. Strom Thurmond Lakes, conductivities ranged from 20 to 50 μS. However, during stratification and oxygen depletion in hypolimnia, complex oxidation-reduction reactions often resulted in conductivity values up to approximately 100 μS. The effects of such redox conditions are first manifested in the tributary arms of Richard B. Russell Lake. Conditions were most severe during 1984 when much of the volume of Richard B. Russell Lake was anoxic. Since then, maxima in conductivity values have progressively declined as oxygen depletion has become less severe.

71\. Oxidation-reduction potential is an electrochemical measurement which approximates electron activity in aqueous solutions and is an indication of oxidizing or reducing environments. Although reducing conditions will continue to exist in the anaerobic hypolimnia of these lakes in the future, declining maxima in conductivity values in Richard B. Russell Lake are an indication that these conditions have decreased in severity in much of the lake.

72\. Sulfide concentrations in the Richard B. Russell Lake mainstem declined to <1 mg/ℓ in 1985 and to approximately 0.5 mg/ℓ in 1986. Current concentrations of sulfide in Hartwell and J. Strom Thurmond Lakes are mostly unmeasurable (<0.1 mg/ℓ). Since reducing conditions are expected to continue to decline, Richard B. Russell Lake will likely approach these conditions in the future.

73\. The dynamics of phosphorus and nitrogen are important water quality considerations because they enable phytoplankton growth and directly influence organic production throughout lake food webs. Concentrations of these nutrients in Hartwell, Richard B. Russell, and J. Strom Thurmond Lakes were low during 1984-1986. Total phosphorus often occurred in concentrations lower than detection limit (0.005 mg/ℓ) and will likely continue to be the limiting nutrient as it has been in the past (US Environmental Protection Agency, 1978). Total nitrogen occurred in greater concentrations. Although total nitrogen concentrations ranged from 0.6 to 1.0 mg/ℓ in the hypolimnion, epilimnetic concentrations were much less.

74. Prior to construction of Richard B. Russell Dam, the National Eutrophication Survey (NES) (US Environmental Protection Agency 1978) demonstrated that for the year 1973, two loading sources, the Savannah and Broad Rivers, contributed >58 percent of total phosphorus and nearly 75 percent of total nitrogen to J. Strom Thurmond Lake. Applying the simplified technique FLUX (Walker 1987) to river and outflow chemistry data, total phosphorus loading for the Savannah River was calculated for the years 1975-1979 and 1985-1986 (Table 9). These calculations suggest that loading of total phosphorus has changed. Historically (1975-1979), average total phosphorus loading to J. Strom Thurmond Lake by the Savannah River has ranged from 71,913 to 141,982 kg P/year. This agrees generally with loadings calculated by NES for 1973 (149,184 kg P/year). Comparable figures calculated for 1985 and 1986 are significantly less (48 and 74 percent, respectively) than preimpoundment conditions. On the assumption that loading from the Broad River has not changed (data were unavailable after 1979), this indicates that the major source of total phosphorus to J. Strom Thurmond Lake is now the Broad River instead of the Savannah River. Calculations for the Broad River for the years 1973 and 1975-1979 showed total phosphorus loading of 73,543 to 126,299 kg P/year. These figures were biased toward low flow conditions which means that true loading may have been even greater. Although not conclusive, the reduction of particulate inputs and overall quantities of phosphorus to J. Strom Thurmond Lake by Richard B. Russell Lake is potentially an important long-term change, which may affect productivity throughout the J. Strom Thurmond Lake food web.

75. Although many water quality changes were observed between 1984 and 1985, similarities between 1985 and 1986 were apparent for temperature (Figures 37-41) and dissolved oxygen (Figures 42-46). The seasonal thermal structures of each lake are well established; however, seasonal trends in dissolved oxygen continue to remain dynamic. Changes in dissolved oxygen concentrations are related to the rapid decomposition of submerged organic materials and the rapid development of biotic communities in the new reservoir. Although major changes in dissolved oxygen concentrations in Richard B. Russell Lake occurred during the first summer of impoundment, less pronounced changes continue in both lakes.

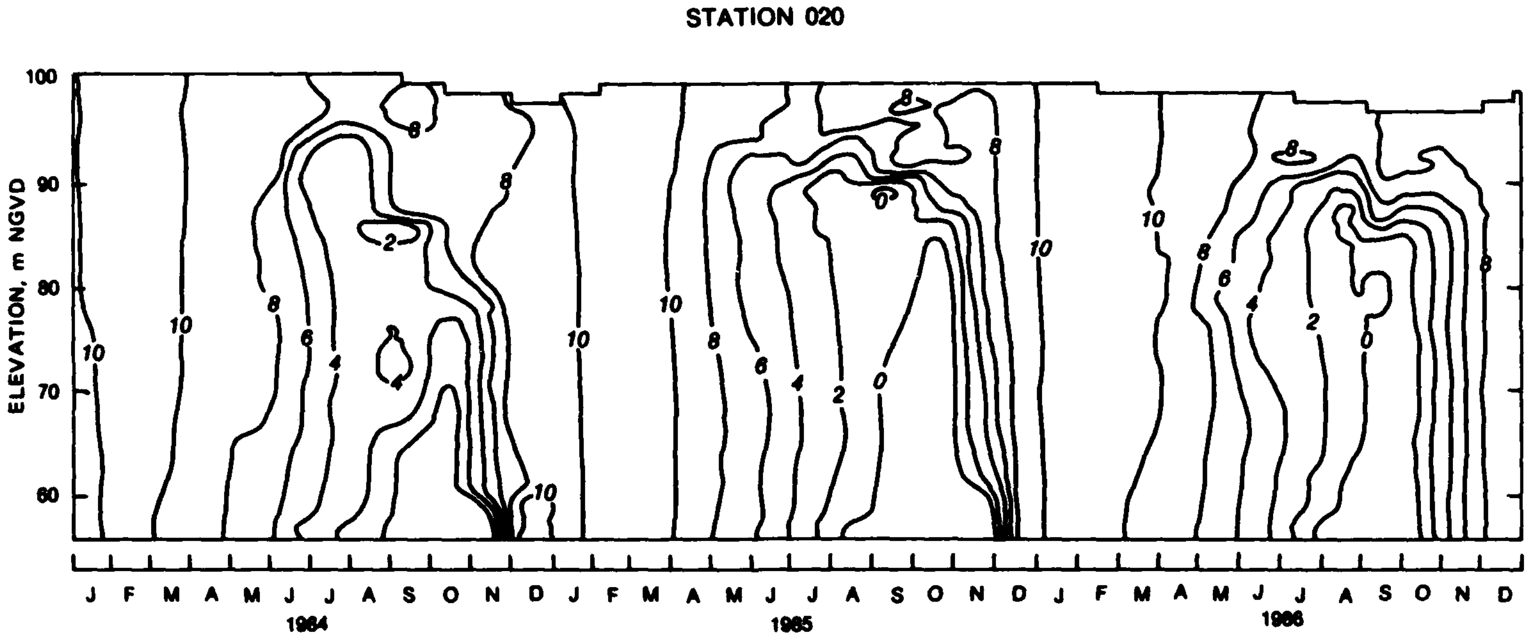
STATION 020

Figure 37. Temporal and vertical patterns in temperature for sta 020, J. Strom Thurmond Lake, 1984-1986

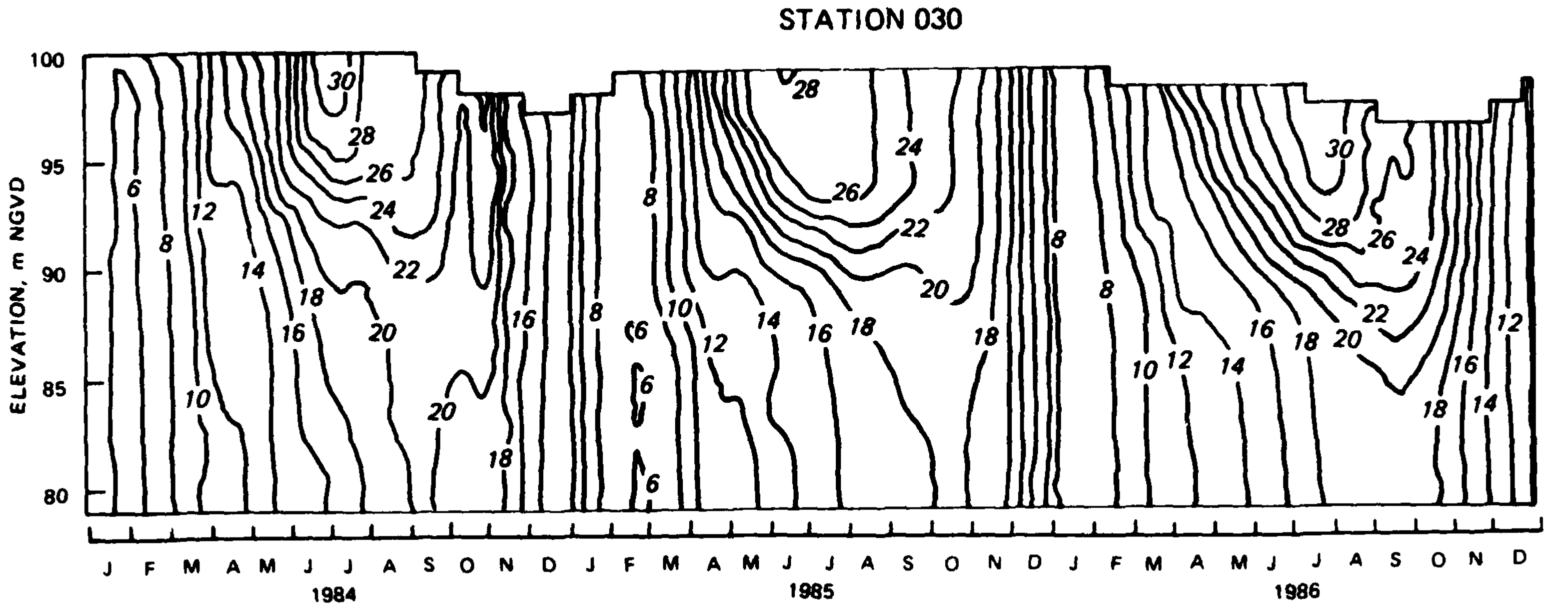

Figure 38. Temporal and vertical patterns in temperature for sta 030, J. Strom Thurmond Lake, 1984-1986

STATION 120

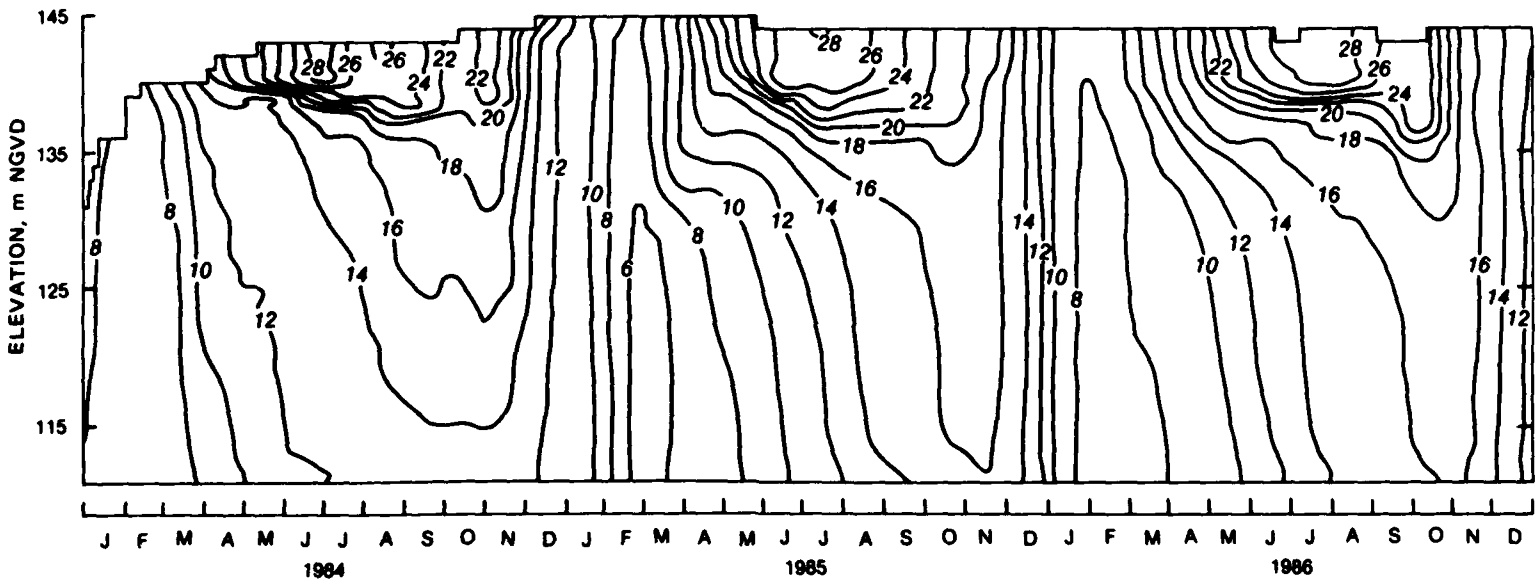

Figure 39. Temporal and vertical patterns in temperature for sta 120, Richard B. Russell Lake, 1984-1986

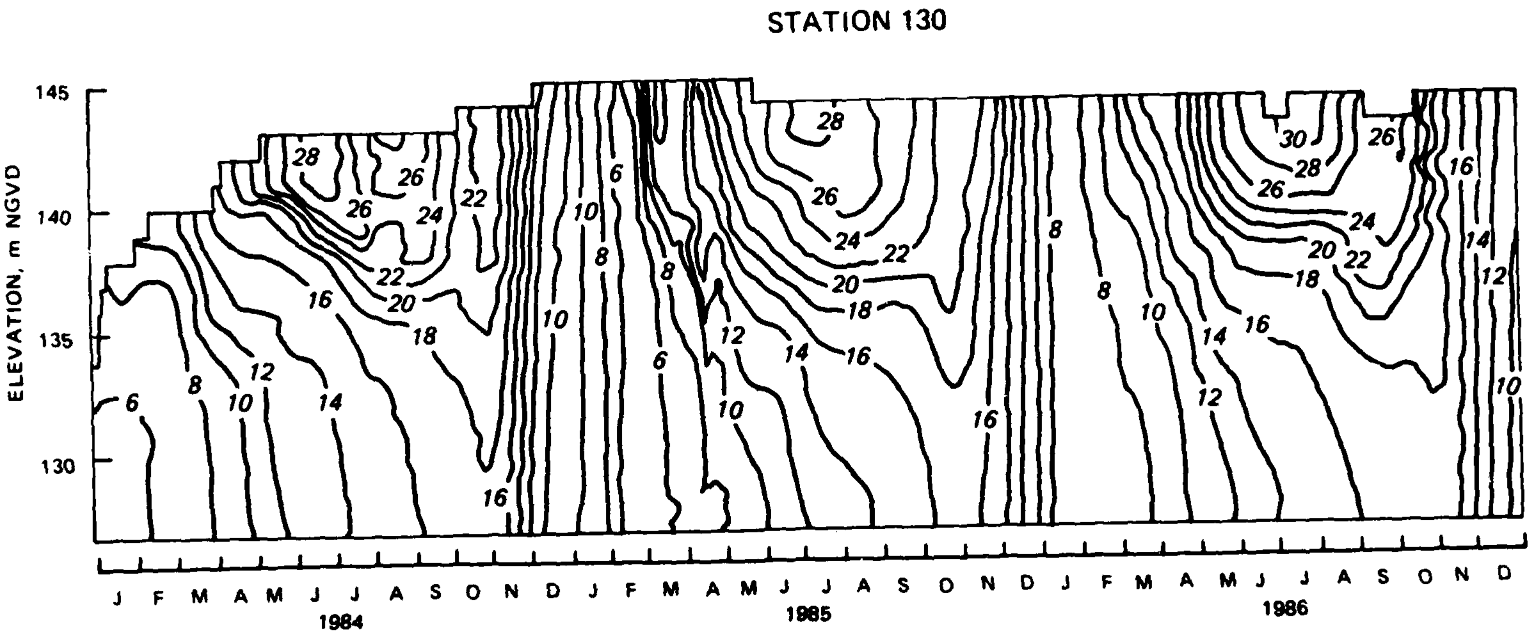

Figure 40. Temporal and vertical patterns in temperature for sta 130, Richard B. Russell Lake, 1984-1986

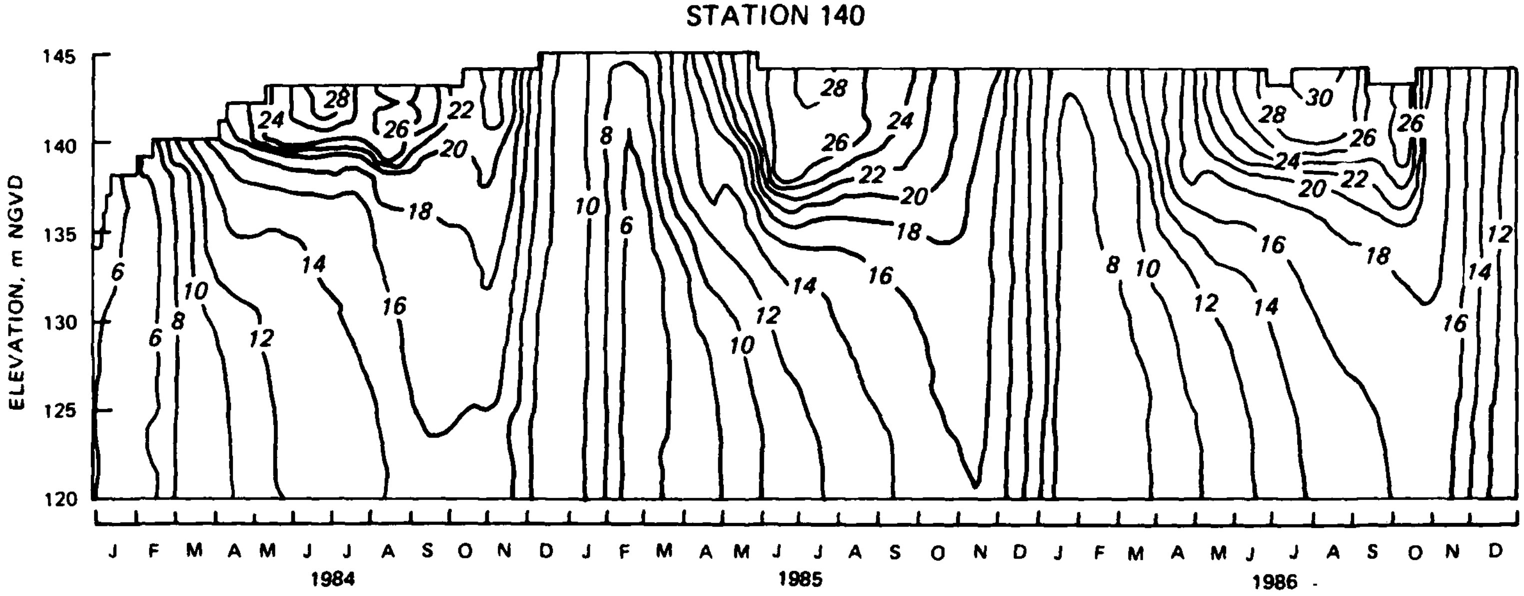

Figure 41. Temporal and vertical patterns in temperature for sta 140, Richard B. Russell Lake, 1984-1986

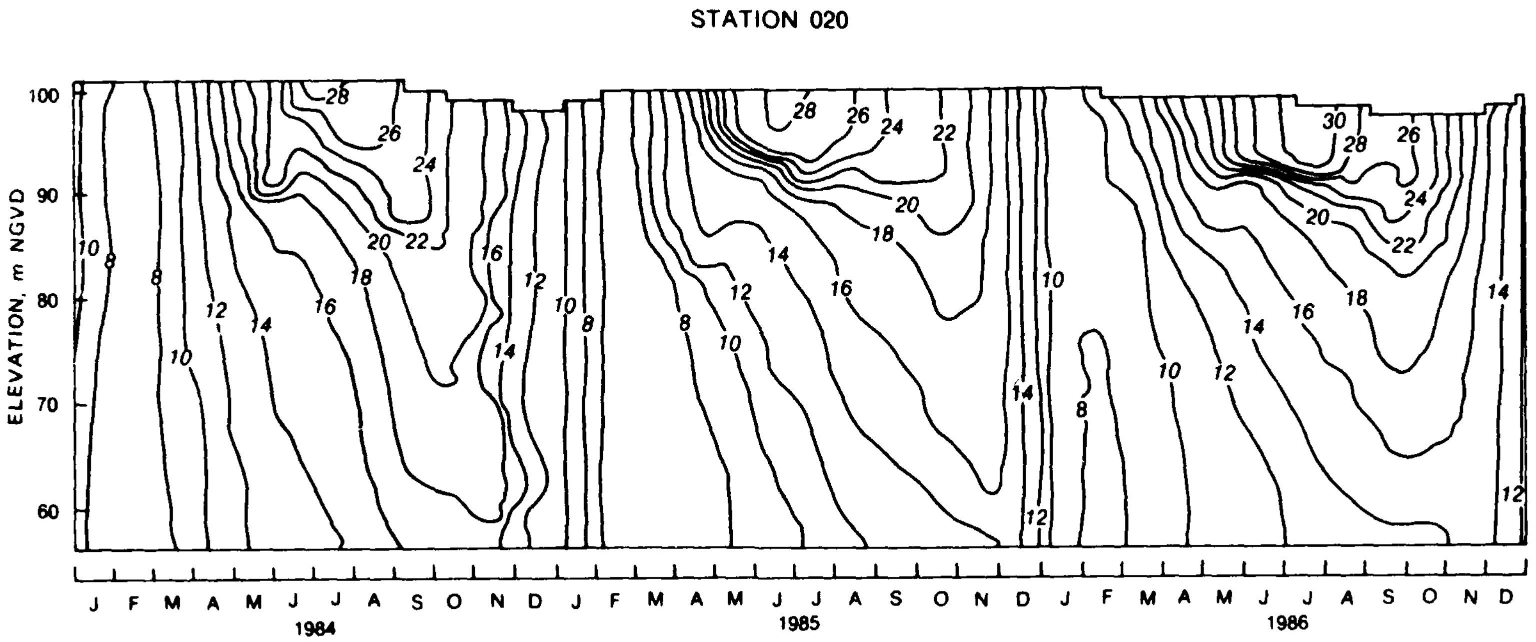

Figure 42. Temporal and vertical patterns in dissolved oxygen for sta 020, J. Strom Thurmond Lake, 1984-1986

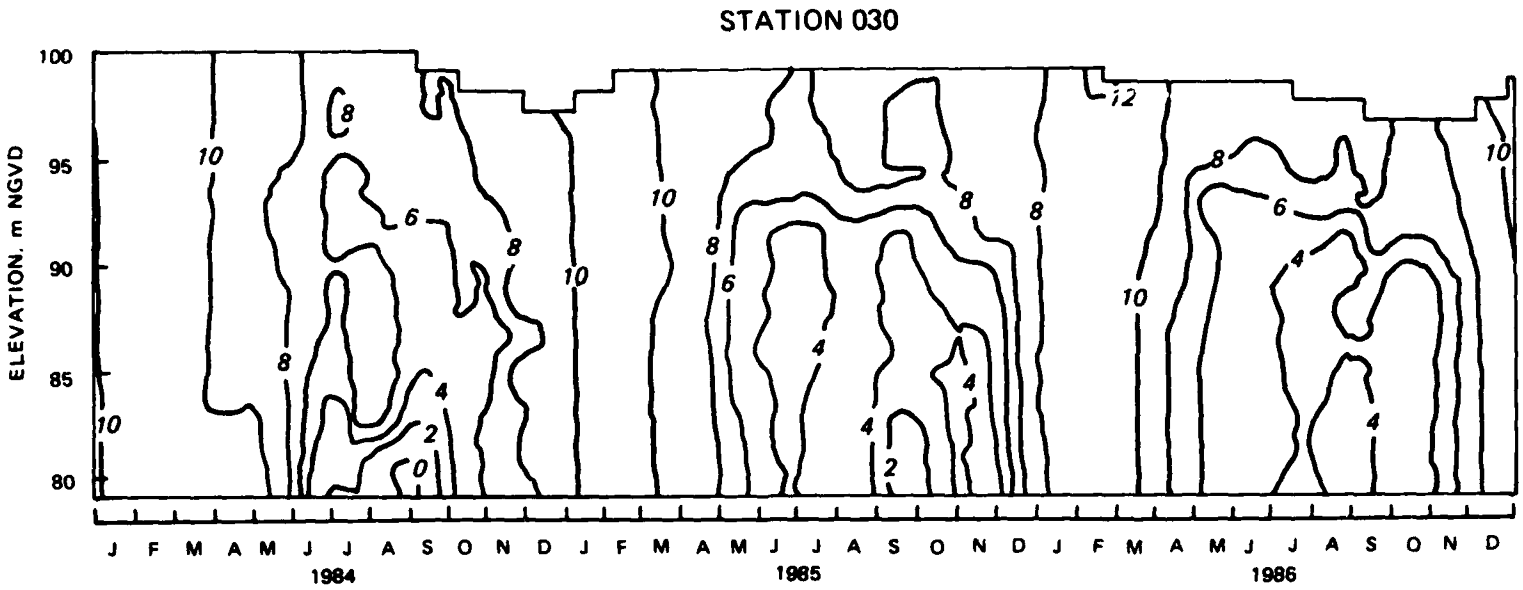

Figure 43. Temporal and vertical patterns in dissolved oxygen for sta 030, J. Strom Thurmond Lake, 1984-1986

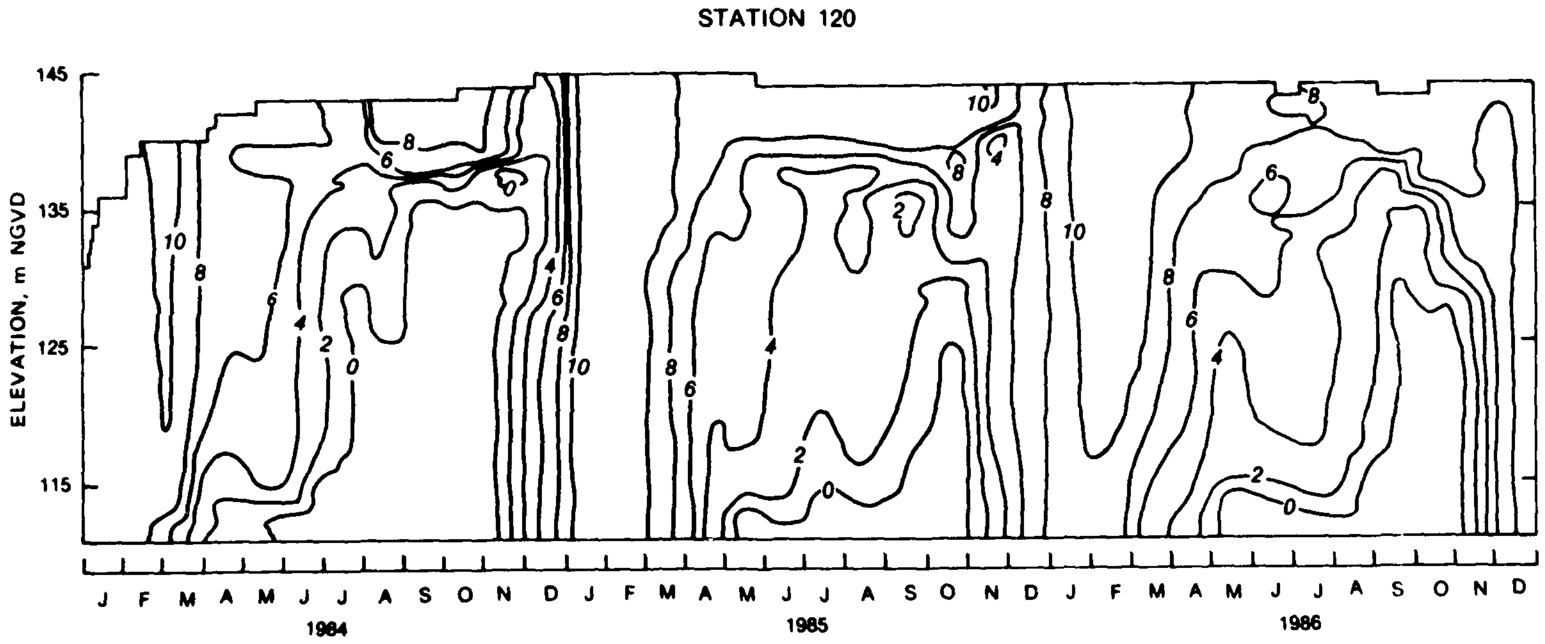

Figure 44. Temporal and vertical patterns in dissolved oxygen for sta 120, Richard B. Russell Lake, 1984-1986

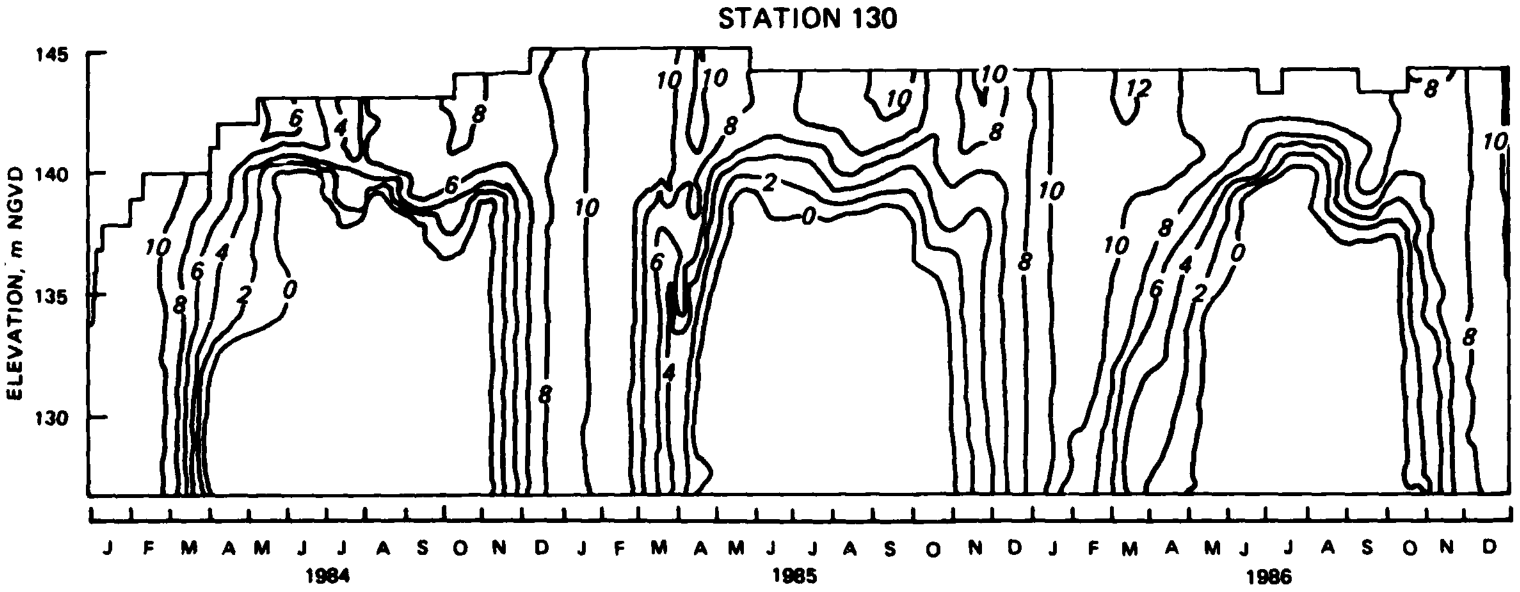

Figure 45. Temporal and vertical patterns in dissolved oxygen for sta 130, Richard B. Russell Lake, 1984-1986

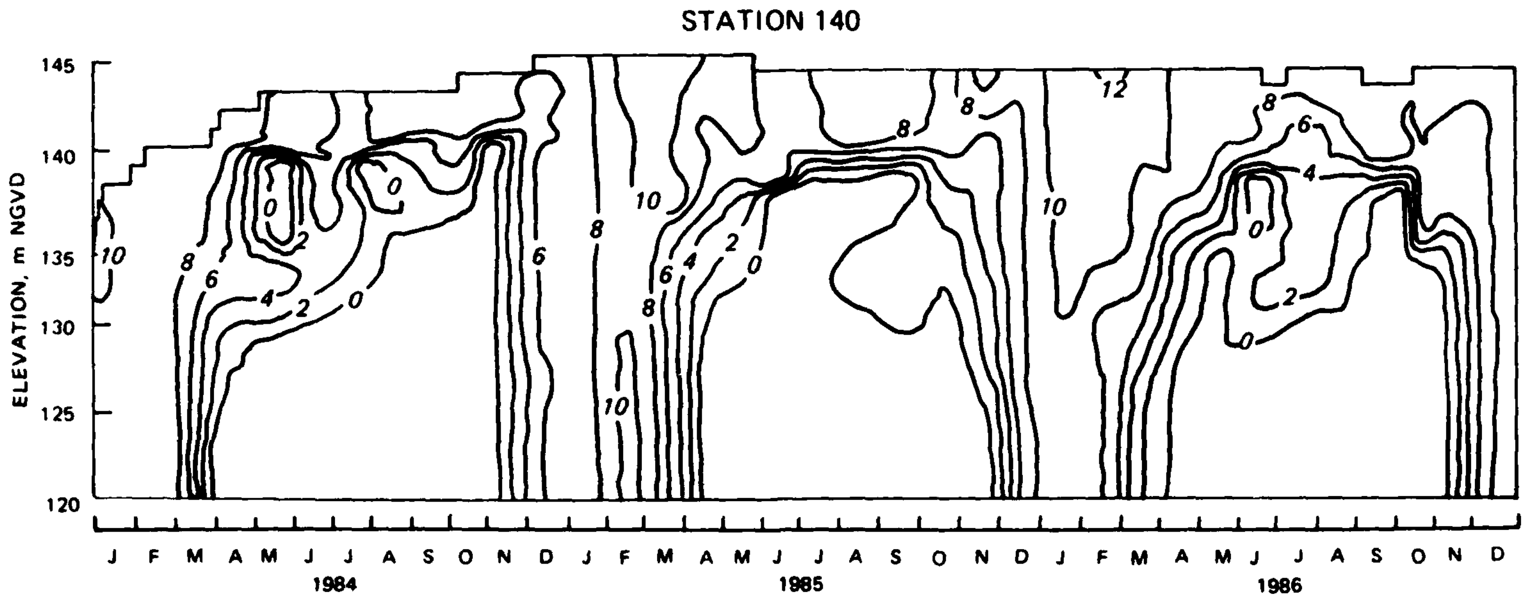

Figure 46. Temporal and vertical patterns in dissolved oxygen for sta 140, Richard B. Russell Lake, 1984-1986

76. The most important water quality trends observed during 1986 were related to the effects of impoundment of Richard B. Russell Lake on J. Strom Thurmond Lake and to the operation of the oxygen-diffuser system. While the effects of impoundment on J. Strom Thurmond Lake are not easily discernible, the importance of the oxygenation system to the release waters from Richard B. Russell Dam is clear. However, the effects of the oxygenation system on the cycling of metals and nutrients in the Richard B. Russell Lake forebay require further evaluation.

77. The pulse-oxygenation system successfully increased oxygen concentrations in the Richard B. Russell Dam release to approximately 6 mg/ℓ. Failure to operate the pulse-oxygenation system for approximately 1 week during midsummer allowed the effects of the presence and absence of the system to be compared during summer anoxic conditions. This comparison indicated that at a capacity of 80 tons of oxygen per day, the pulse-oxygenation system could increase oxygen concentrations in the release by 2 to 3 mg/ℓ. Analysis of emerging bubble-plume gases indicated highly variable diffusion efficiencies, 30 to 90 percent for the pulse system and 50 to 80 percent (measured for 1985) for the continuous system. Maintenance of acceptable dissolved oxygen concentrations in Richard B. Russell Dam releases would not be possible without the system.

78. Of the parameters monitored in situ, dissolved oxygen is the most chemically and biologically important. The magnitude of dissolved oxygen concentrations determines habitat limits for obligate aerobes from bacteria to fish. The presence of dissolved oxygen also influences and, in turn, is influenced by many chemical reactions in water. For example, the solubility (and the availability) of many substances in water is often influenced by the oxidation state of the substance.

79. Dissolved oxygen concentrations in temperate lakes and reservoirs follow a pattern of distribution that is influenced primarily by seasonal changes in water temperature. The reservoirs of the Savannah River follow the pattern characterized for warm, monomictic, temperate lakes. In such lakes, dissolved oxygen typically approaches saturation during the winter mixing period only to be highly influenced by internal biological and chemical processes during stratification. The stratified period, then, is the time of greatest interest for water quality managers because this is when the

reservoirs are often depleted of dissolved oxygen in the deeper waters of their hypolimnia.

80. In many respects, dissolved oxygen concentrations in Hartwell, Richard B. Russell, and J. Strom Thurmond Lakes for 1986 were similar to those observed in 1985. The most important change was observed for Richard B. Russell Lake which had lower oxygen depletion rates in 1986 than in 1985. This observation was important because less oxygen was necessary to meet the release criterion, and the trend was due, in part, to the decreased intensity of aquatic processes (e.g., decomposition) which deplete oxygen.

81. The simplified water quality modeling technique, PROFILE, was used to summarize the large data base of spatially and temporally varying dissolved oxygen concentrations in Richard B. Russell and J. Strom Thurmond Lakes. Such a summary for the mainstem of Richard B. Russell Lake (sta 120) indicated that the volumetric oxygen-depletion rate for the metalimnion was less than that for the hypolimnion. Moreover, the 1986 volumetric oxygen-depletion rates for the hypolimnion were reduced 50 percent from 1984 levels, and the 1986 rates for the metalimnion were reduced by approximately 30 percent from 1984. Because the changes from 1985 to 1986 were still greater than from 1984 to 1985, additional reductions of dissolved oxygen demand in Richard B. Russell Lake are expected in the future.

82. Volumetric oxygen-depletion rates for mainstem locations in the J. Strom Thurmond Lake forebay (sta 20) in 1986 were greater than comparable rates for the Richard B. Russell Lake mainstem (sta 120) (Table 10). Indeed, volumetric oxygen demand in the J. Strom Thurmond Lake forebay increased for 1985 and 1986 compared to 1984 or 1981 (historical data). The subjectivity of depth and time-interval selection for the use of PROFILE caused relatively small variations of the estimates. The agreement between 1981 and 1984 and between 1985 and 1986 suggested that observed differences are real; however, data limitations make it difficult to separate year-to-year random variation from potential pregeneration and postgeneration influences. Therefore, careful monitoring of trends in demand in J. Strom Thurmond Lake should continue.

83. Results from the mid-lake region of J. Strom Thurmond Lake (sta 30) indicated a general decrease of volumetric oxygen demand in 1985 and a modest increase in 1986. The high oxygen demand in 1984 may have been due to rapid decomposition of labile organic material in the newly inundated soil, litter,

and standing timber in Richard B. Russell Lake (James et al. 1985). Anoxia in Richard B. Russell Lake indicated that the rate of oxygen consumption exceeded supply. Under these conditions in 1984, organic carbon concentrations in Richard B. Russell Lake exceeded 2 mg/ℓ at the surface during late summer and exceeded 6 mg/ℓ in the hypolimnion. Most of this carbon was dissolved and, therefore, easily transported to J. Strom Thurmond Lake where its further decomposition may have affected an increase in oxygen demand in J. Strom Thurmond Lake.

84. Results of 3 years of study suggest two possible impacts of the impoundment of Richard B. Russell Lake on trends of dissolved oxygen in J. Strom Thurmond Lake. First, the observed increases in volumetric depletion rates in J. Strom Thurmond Lake may be a general long-term trend due to the presence of Richard B. Russell Lake. Second, the impact may be a transient effect of the short-term (i.e., 1984) release of dissolved organic material to J. Strom Thurmond Lake. In 1986, organic carbon concentrations in Richard B. Russell lake were 50 percent of the 1984 concentrations and showed no remarkable spatial or temporal trends. Similar reductions in organic carbon released to J. Strom Thurmond Lake were also observed.

85. Outflows to subsequent reservoirs affect other important materials such as iron and manganese as well. Under the reducing conditions found in anaerobic hypolimnia, these metals become soluble and occur in greater concentrations than in surface waters. This process occurred in Hartwell, Richard B. Russell, and J. Strom Thurmond Lakes in 1986 as well as in previous years. Quantitative estimates of the magnitude of iron and manganese transport from Hartwell to Richard B. Russell and from Richard B. Russell to J. Strom Thurmond Lake are still not well defined.

86. Metal concentrations in releases from Hartwell, Richard B. Russell, and J. Strom Thurmond Dams in 1986 were similar with respect to ratios of total to dissolved fractions. The Hartwell Lake forebay maintained an oxidizing environment well into the summer while in Richard B. Russell Lake the oxygenation system accomplished much the same result. Concentrations of iron and manganese released from Hartwell Lake were less than for Richard B. Russell Lake, but both releases contained iron predominantly in the particulate (oxidized) form and manganese in the dissolved (reduced) form. Moreover, manganese occurred in the dissolved form throughout the J. Strom Thurmond Lake mainstem.

87. Manganese oxidation proceeds at a sufficiently slow rate to allow the reduced form of this metal to be transported through the three-reservoir system (Hsiung 1987). Such transport from upstream reservoirs along with additional releases from the sediments could result in greater downstream concentrations of reduced manganese.

PART VI: CONCLUSIONS

88. In the third year of impoundment of Richard B. Russell Lake, evidence from field studies indicates that limnological characteristics of the new reservoir have changed markedly. This trend was more pronounced for physical characteristics of the new lake than for chemical characteristics (such as those controlling distributions of iron and manganese). Although evidence at present does not allow complete assessment of longer term effects on J. Strom Thurmond Lake water quality, it does suggest that such effects are possible with respect to dissolved oxygen concentrations; loading of the major limiting nutrient, phosphorus; and loading and processing of iron and manganese.

89. Late summer dissolved oxygen concentrations in the releases from Richard B. Russell Lake (approximately 6 mg/ℓ) were higher than from Hartwell Lake (approximately 2 to 4 mg/ℓ) due to the successful operation of the pulse-oxygenation system. Observations indicated that the pulse-oxygenation system added 2 to 3 mg/ℓ to Richard B. Russell Lake releases during mid to late summer. During this time, iron and manganese were released from both Hartwell and Richard B. Russell Lakes in similar forms; manganese was released primarily in the dissolved form while iron was released primarily as particulates. In these respects, the similarity of Richard B. Russell and Hartwell Lake releases was made possible by the continuous operation of the pulse-oxygenation system.

90. Winter conditions for Hartwell, Richard B. Russell, and J. Strom Thurmond Lakes were similar in all respects. Internal demands for dissolved oxygen in Richard B. Russell Lake still exceed those in J. Strom Thurmond Lake but have decreased during the first 3 years of impoundment. Additional, but smaller, decreases in oxygen demand in Richard B. Russell Lake are likely in the future. Oxygen demand in J. Strom Thurmond Lake has increased and should be monitored in the future to determine if this is a long-term trend.

91. Impoundment of Richard B. Russell Lake has altered the quantity and quality of materials transported via the Savannah River to J. Strom Thurmond Lake. Phosphorus transport to J. Strom Thurmond Lake may be less than what it was prior to the impoundment of Richard B. Russell Lake. Materials such as carbon, manganese, and inorganic nutrients enter the J. Strom Thurmond

headwater region in predominately dissolved rather than particulate forms since the impoundment of Richard B. Russell Lake.

92. Future improvements in water quality are likely for Richard B. Russell Lake due to decreased internal oxygen demands and chemically reducing conditions which facilitate the release of dissolved metals and other materials from lake sediments and inundated soils. While the periods of operation of the oxygenation systems may be decreased, the need for their operation remains for the foreseeable future. During that time, the operation of the oxygenation system will maintain acceptable water quality conditions.

PART VII: RECOMMENDATIONS

93. The maturation of Richard B. Russell Lake will continue to be a major factor in the water quality of both Richard B. Russell and J. Strom Thurmond Lakes. Continued monitoring of physical and chemical variables in tributary embayments and the mainstem of Richard B. Russell Lake will allow further assessment of the maturation of Richard B. Russell Lake.

94. Water quality sampling should continue to address the dynamics of iron and manganese in the vicinity of the oxygenation system. Additionally, the impacts of metals exportation on each lake and of nutrient loading to J. Strom Thurmond Lake require further evaluation.

95. The importance of the oxygenation system to the water quality of the Richard B. Russell Lake forebay and release waters indicates that monitoring efforts in this vicinity should continue. Data from previous years, with varied operation of the system, suggest that the operation of the pulse system may have dissimilar effects than the operation of the continuous system. Further evaluation of the operation of the system is necessary and should be aimed at optimization of system operation.

96. Continued evaluation of hypolimnetic oxygenation demand in both lakes will provide increased information in the assessment of impacts of impoundment on J. Strom Thurmond Lake and the magnitude of these impacts in subsequent years.

97. Continued monitoring of phytoplankton dynamics in J. Strom Thurmond and Richard B. Russell Lakes will allow increased understanding of changes in water quality on the biota of the lakes.

98. Finally, as mentioned in James et al. (1986), efforts should be made to ensure that ongoing water quality studies provide the necessary information for evaluating the impacts of pumped-storage operation on the water quality of Richard B. Russell and J. Strom Thurmond Lakes and to support on-going fishery studies in J. Strom Thurmond Lake.

REFERENCES

American Public Health Association. 1980. Standard Methods for the Analysis of Water and Wastewater, 15th Edition, Washington, DC.

Applied Biology, Incorporated. 1982. "Clarks Hill Lake Water Quality Study," Decatur, GA.

Davis, J. E., Holland, J. P., Schneider, M. L., and Wilhelms, S. C. 1987. "SELECT: A Numerical, One Dimensional Model For Selective Withdrawal," Instruction Report E-87-2, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Hach Chemical Co. 1978. DR-EL/2 Methods Manual, Hach Chemical Company. Ames, IA.

Hains, J. J. 1985. "Practical Considerations for Routine Chlorophyll Measurements: Precautions and Comparison of Extraction Methods," Journal of Freshwater Ecology, Vol 3, pp 175-179.

Hsiung, Tung-Ming. 1987. "Manganese Dynamics in the Richard B. Russell Impoundment," M.S. Thesis, Clemson University, Clemson, SC.

Hydrolab Corp. 1984. Operation and Maintenance Manual for Hydrolab Surveyor II, Hydrolab Corporation, Austin, TX.

James, W. F., Gunkel, R. C., Jr., Carroll, J. H., Kennedy, R. H., Schreiner, S. P., Ashby, S., and Hains, J. 1986. "Water Quality Studies: Richard B. Russell and Clarks Hill Lakes; Second Annual Interim Report," Miscellaneous Paper EL-86-12, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

James, W. F., Kennedy, R. H., Schreiner, S. P., Ashby, S., and Carroll, J. H. 1985. "Water Quality Studies: Richard B. Russell and Clarks Hill Lakes; First Annual Interim Report," Miscellaneous Paper EL-85-9, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Raveh, A., and Avnimelech, Y. 1979. "Total Nitrogen Analysis in Water, Soil, and Plant Material with Persulfate Oxidation," Water Research, Vol 13 pp 911-912.

South Carolina Department of Health and Environmental Control. 1985. News release, 2 December 1985, Columbia, SC.

Speziale, B. J., Schreiner, S. P., Giammatteo, P. A., and Schindler, J. E. 1984. "Comparison of N, N-dimethylformamide Dimethyl Sulfoxide, and Acetone for Extraction of Phytoplankton Chlorophyll," Canadian Journal of Fisheries and Aquatic Sciences, Vol 41, pp 1519-1522.

US Army Engineer District, Savannah. 1974. "Design Memorandum No. 8; Geology," Savannah, GA.

US Army Engineer Waterways Experiment Station. 1986. "Richard B. Russell Lake Water Quality Studies; Quarterly Summary of Field Activities; Summary No. 23," Vicksburg, MS.

__________. 1987. "Richard B. Russell Lake Water Quality Studies; Quarterly Summary of Field Activities; Summary No. 25," Vicksburg, MS.

US Environmental Protection Agency. 1978. "A Compendium of Lake and Reservoir Data Collected by the National Eutrophication Survey in Eastern North-central and Southeastern United States." Working Paper No. 475, Corvallis, OR.

__________. 1979. *Manual of Methods for Chemical Analysis of Water and Wastewater,* National Environmental Research Center, Cincinnati, OH.

Walker, W. W. 1987. "Empirical Methods for Predicting Eutrophication in Impoundments; Report 4, Phase III: Applications Manual," Technical Report EL-81-9, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Table 1

Physical Characteristics for J. Strom Thurmond, Richard B. Russell, and Hartwell Lakes

Characteristics	J. Strom Thurmond Lake	Richard B. Russell Lake	Hartwell Lake
Maximum power pool elevation, m NGVD	100.6	144.8	201.2
Minimum power 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 River 79 Seneca River 72
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, days*	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

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* At maximum power pool elevation.

** Mean discharge for the period 1925-1973.

† Mean river discharge for 31 years.

Table 2

Sampling Schedule

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

Table 3

List of Variables

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

Table 4

Average Volumetric Depletion Rates (mg/ℓ/day) for Richard B. Russell Lake Based on PROFILE Calculations

	1984		1985		1986	
Station	Depletion Rate	MLz*	Depletion Rate	MLz	Depletion Rate	MLz
060B	0.066	135	0.057	135	0.077	135
120	0.068	135	0.056	135	0.039	135
130	0.134	138	0.124	138	0.093	138
140	0.117	138	0.108	140	0.085	140

* MLz = Pool elevation (m, NGVD) at bottom of mixed layer.

Table 5

Average Areal Depletion Rates ($mg/m^2/day$) for Richard B. Russell Lake Based on PROFILE Calculations

	1984		1985		1986	
Station	Depletion Rate	MLz*	Depletion Rate	MLz	Depletion Rate	MLz
060B	716	135	613	135	825	135
120	593	135	469	135	321	135
130	657	138	606	138	456	138
140	873	138	873	140	685	140

* MLz = Pool elevation (m, NGVD) at bottom of mixed layer.

Table 6

Average Areal Depletion Rates (mg/m^2/day) for J. Strom Thurmond Lake Based on PROFILE Calculations

Station	1981	1984	1985	1986
020	512	548	726	793
030	NA*	861	548	444
040	NA	196	425	463

Note: Values computed for hypolimnion plus metalimnion, up to elevation 90 m (295 ft), NGVD.

* NA = not available. Insufficient data for calculations.

Table 7

Average Volumetric Depletion Rates (mg/ℓ/day) for J. Strom Thurmond Lake Based on PROFILE Calculations

Station	1981	1984	1985	1986
020	0.04	0.04	0.06	0.06
030	NA*	0.07	0.04	0.04
040	NA	0.02	0.03	0.04

Note: Values computed for hypolimnion plus metalimnion, up to elevation 90 m (295 ft), NGVD.

* NA = not available. Insufficient data for calculations.

Table 8

Oxygen-Injection System Off-Gas Analysis Results

15 July 1986			21 August 1986			1 October 1986		
Sample*	% Transferred	% O_2 loss	Sample	% Transferred	% O_2 loss	Sample	% Transferred	% O_2 loss
1 a	29.0	70.5	1	43.3	54.2	1	55.4	50.0
2 a	32.8	69.0	2	26.9	73.3	2	42.9	59.5
3 a	32.3	69.1	3	37.3	65.0	3	37.3	63.2
4 a	29.0	73.1	4	43.3	59.2	4	56.3	48.5
5 a	36.3	63.4	5	61.8	38.8	5	64.3	42.8
6 a	33.0	66.9	6	50.7	53.7	6	72.7	36.0
7 a	32.7	72.7	7	43.9	55.0	7	77.3	35.5
8 a	27.8	64.7	8	44.8	57.5	8	52.2	56.0
9 a	26.8	62.8	9	40.3	65.0	9	31.7	67.0
10 a	25.3	65.5	10**	94.0	26.3	10	41.9	59.5
1 b	30.7	68.0	11	47.8	61.7	11	59.1	48.2
2 b	37.9	73.7	12**	89.6	30.0	12	39.5	61.0
3 b	36.2	71.1	13**	81.2	27.2	13**	90.4	28.0
4 b	45.3	70.3	14**	84.2	30.0	14	41.0	65.5
5 b	31.5	61.9	15**	86.6	32.0	15	57.8	55.5
6 b	34.5	62.6	16	71.6	33.8	16**	84.8	36.5
7 b	31.8	64.6	17	52.2	42.5	17	49.4	64.5
8 b	28.4	64.6	18	71.6	32.5	18	34.5	70.5
9 b	23.9	67.8	19	66.6	39.7	19	27.0	70.0
10 b	22.8	71.6				20	37.3	62.5
						21	37.3	62.5
						22	33.5	65.5
						23	36.3	62.7
						24	30.2	68.0
						25	35.4	64.0

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* a = pregeneration samples, 0930 hr; b = samples during generation, 1500 hr.

** Contaminated samples.

Table 9

Total Phosphorus (TP) Load to J. Strom Thurmond Lake from the Savannah River

Year	Mean Flow	TP Load, kg/year	Data Source
1973	175.3	149,184	USEPA, NES
1975	209.6	78,998-155,974	FLUX **
1976	197.1	74,298-146,695	
1977	172.7	65,105-128,544	
1978	152.0	57,320-113,154	
1979	222.4	83,846-165,546	
1985	*	41,911	WES, FLUX
1986	*	32,981	WES, FLUX

* Flows recorded by powerhouse operation.
** FLUX was applied to historic data taken at Highway 72.

Table 10

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
020	Metalimnion	0.042	0.040	0.064	0.064
020	Hypolimnion	0.039	0.047	0.064	0.062
030	Metalimnion	NA*	0.056	0.030-0.031	0.035-0.046
030	Hypolimnion	NA	0.082	0.027-0.028	0.035-0.045
120	Metalimnion	NA	0.062-0.07	0.052-0.053	0.034-0.040
120	Hypolimnion	NA	0.070	0.063-0.067	0.031-0.036
130	Metalimnion	NA	0.088-0.22	0.102-0.18	0.073-0.090
130	Hypolimnion	NA	0.197-0.29	0.184-0.20	0.117
140	Metalimnion	NA	0.070-0.20	0.073-0.16	0.072-0.115
140	Hypolimnion	NA	0.221-0.59	0.217-0.18	0.125-0.137

Note: A range of values indicates variation of the estimate due to subjective variation of choice of depths, dates, or both.
* NA = Not available. Insufficient data for calculations.

APPENDIX A: ANALYTICAL PROCEDURES

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) have been calculated for each variable for each replicate, and then a mean of the CV's has been 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 which had values above the detection limit, and mean CV's were calculated for each variable (Table A1).

3. The accuracy or description of how closely analyzed values are to the actual values was evaluated by the analysis of spiked samples prepared in the laboratory. Laboratory values were compared to 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

Variable	Replicate Samples	Split Samples
Turbidity	6.1	0.6
Total alkalinity	2.0	3.0
Chloride	1.0	1.0
Sulfate	7.7	3.5
Total organic carbon	7.1	4.6
Dissolved organic carbon	7.0	3.6
Total phosphorus	7.7	10.8
Total soluble phosphorus	14.5	10.7
Soluble reactive phosphorus	6.0	5.0
Total nitrogen	5.8	7.0
Total dissolved nitrogen	11.4	10.3
Ammonia nitrogen	7.2	1.8
Nitrate-nitrite nitrogen	5.5	2.6
Total iron	11.0	5.1
Dissolved iron	8.4	0.4
Total manganese	11.5	2.5
Dissolved manganese	5.9	0.7
Total sodium	4.2	6.3
Total potassium	5.2	5.5
Total calcium	7.4	2.2
Total magnesium	1.1	1.5

Table A2

Mean Percent Recovery for Laboratory Spiked Samples

Variable	Percent Recovery
Total alkalinity	93.6 ± 11.5
Chloride	98.5 ± 30.9
Sulfate	90.2 ± 18.0
Total organic carbon	94.5 ± 17.1
Total phosphorus	94.3 ± 27.0
Total soluble phosphorus	109.3 ± 12.2
Soluble reactive phosphorus	89.8 ± 30.8
Total nitrogen	101.6 ± 24.2
Total dissolved nitrogen	99.6 ± 16.6
Ammonia nitrogen	95.8 ± 13.5
Nitrate-nitrite nitrogen	90.6 ± 11.8
Total iron	100.1 ± 14.5
Dissolved iron	106.6 ± 19.0
Total manganese	102.7 ± 21.8
Dissolved manganese	103.5 ± 12.5
Total sodium	97.2 ± 4.4
Total magnesium	96.3 ± 2.2
Total calcium	70.8 ± 2.9
Total potassium	85.8 ± 5.4

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 Corp. 1984.

Specific Conductance*

Method: Electrometric.
Detection Limit: 1 μS/cm.
Calibration: Conductivity standard solutions.
Reference: Hydrolab Corp. 1984.
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 Corp. 1984.

Oxidation-Reduction Potential*

Method: Electrometric.
Calibration: Ferric/ferrous iron solution standardized to 475 mv.
Reference: Hydrolab Corp. 1984.

Alkalinity

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

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* In-situ measurements made with Hydrolab Surveyor II.

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 Limits: 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 0.45μ, membrane filter; automated ascorbic acid colorimetric method.

C. Soluble Reactive Phosphorus (SRP)

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

Detection Limits: 0.005 mg P/ℓ (dependent upon range used in analyses).
Calibration: Standard curves at beginning and end of each batch of samples.
Equipment: Auto analyzers, (Technicon Auto Analyzer II, Technicon Instruments Corp., 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 (NO^3/NO^2-N)

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

Detection Limits: 0.02 mg/N/ℓ for TN, TSN, and NH4-N, 0.04 mg N/ℓ for NO^3/NO^2-N (dependent upon range used in analysis).

Calibration: Standard curves at beginning and end of each batch of samples.
Equipment: Auto analyzers (Technicon Auto Analyzer II, Technicon Instrument Corp., 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. NH4-N and NO^3/NO^2-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 samples 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 Co. 1978.

Metals

A. Total Iron and Manganese (TFe, TMn)

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

B. Dissolved Iron and Manganese (DFe, DMn)

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

Detection Limits: 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 2 years of this study, samples for analysis of chlorophyll *a* were taken as integrated depth samples at depths equivalent to twice the secchi depth. Chlorophyll *a* and other phytopigments were extracted using a modified procedure which 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.