Miscellaneous Paper W-98-1
April 1998

US Army Corps of Engineers
Waterways Experiment Station

Water Quality Research Program

Determination of Richard B. Russell Dissolved Oxygen Injection System Efficiency Utilizing Automated Remote Monitoring Technologies

by John W. Lemons, Michael C. Vorwerk, DynTel Corporation
Joe H. Carroll, WES

Approved For Public Release; Distribution Is Unlimited

Prepared for Headquarters, U.S. Army Corps of Engineers

The contents of this report are not to be used for advertising, publication, or promotional purposes. Citation of trade names does not constitute an official endorsement or approval of the use of such commercial products.

The findings of this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

PRINTED ON RECYCLED PAPER

Water Quality
Research Program

Miscellaneous Paper W-98-1
April 1998

Determination of Richard B. Russell Dissolved Oxygen Injection System Efficiency Utilizing Automated Remote Monitoring Technologies

by John W. Lemons, Michael C. Vorwerk

DynTel Corporation
3530 Manor Drive
Vicksburg, MS 39180

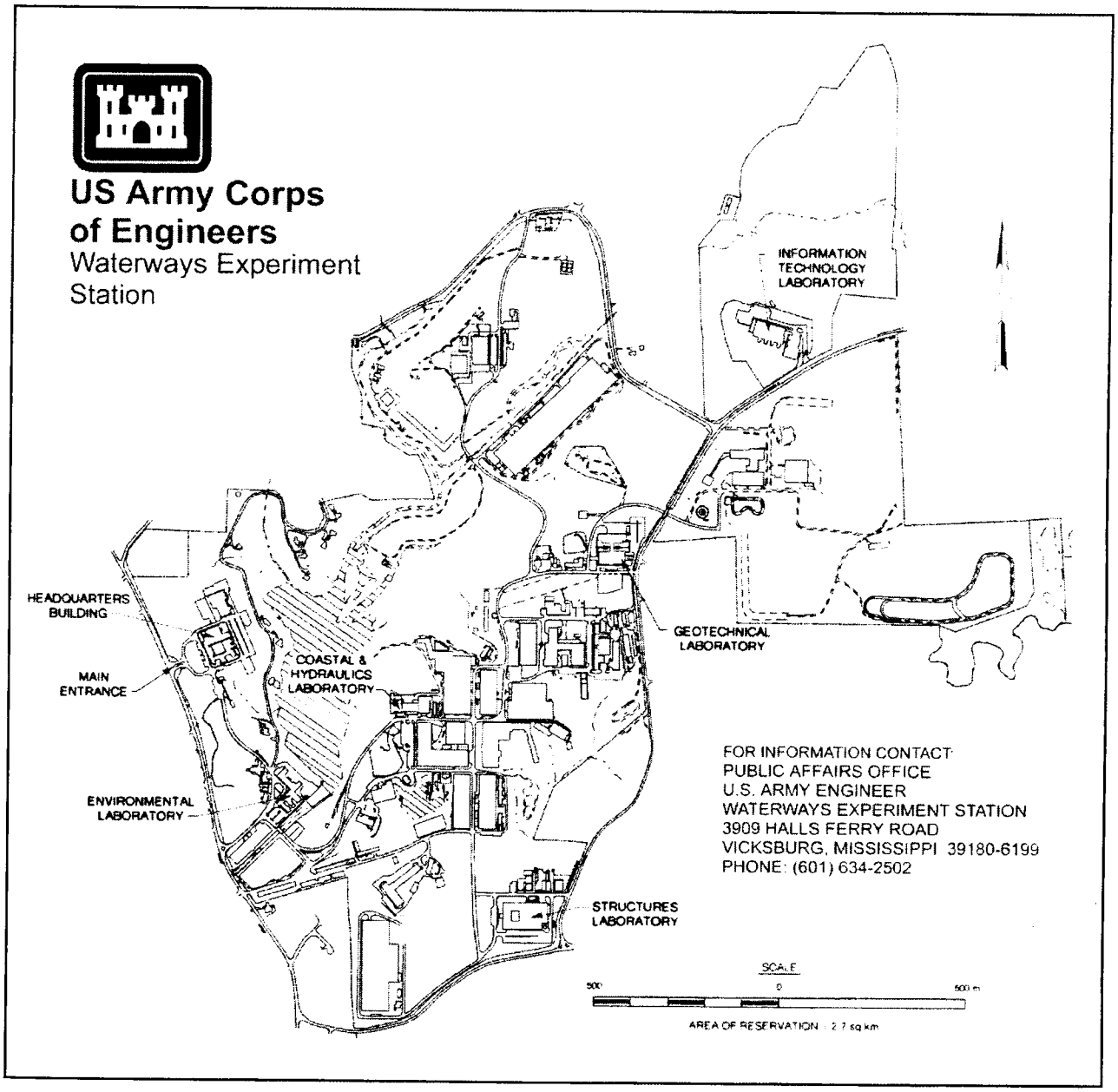
Joe H. Carroll

U.S. Army Corps of Engineers
Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Final report

Approved for public release; distribution is unlimited

Prepared for U.S. Army Corps of Engineers
Washington, DC 20314-1000



Waterways Experiment Station Cataloging-in-Publication Data

Lemons, John W.

Determination of Richard B. Russell dissolved oxygen injection system efficiency utilizing automated remote monitoring technologies / by John W. Lemons, Michael C. Vorwerk, Joe H. Carroll ; prepared for U.S. Army Corps of Engineers.

71 p. : ill. ; 28 cm. — (Miscellaneous paper ; W-98-1)

Includes bibliographic references.

1. Water — Dissolved oxygen — Testing. 2. Tailwater ecology. 3. Biochemical oxygen demand. 4. Richard B. Russell Lake (Ga. and S.C.) I. Vorwerk, Michael C. II. Carroll, Joe H. III. United States. Army. Corps of Engineers. IV. U.S. Amy Engineer Waterways Experiment Station. V. Water Quality Research Program (U.S.) VI. Title. VII. Miscellaneous paper (U.S. Army Engineer Waterways Experiment Station) ; W-98-1.

TA7 W34m no.W-98-1

Contents

Preface vii

Summary viii

1—Introduction 1

2—Background 6

3—Methods 11

Water Quality 16
Velocity 18
Data Compilation 20

4—Results and Discussion 23

Velocity 23
Water Quality 34
Injection Efficiency 39

5—Conclusions 49

References 54

Appendix A: BASIC Program for Time Lagging Water Quality Data Sets A1

SF 298

List of Figures

Figure 1. Savannah River vicinity map 1

Figure 2. Richard B. Russell forebay continuous oxygen injection system 2

Figure 3. 1995 release dissolved oxygen concentrations for Richard B. Russell, Hartwell, and J. Strom Thurmond dams 3

Figure 4. Temperature profile for Richard B. Russell forebay Station 112B displaying respective layers of a stratified water column 7

Figure 5. Cross-sectional view of Richard B. Russell Dam 7

Figure 6. Schematic diagram of continuous component of Richard B. Russell oxygen injection system 8

Figure 7. "Black box" representation of Richard B. Russell forebay 10

Figure 8. Lateral dissolved oxygen concentrations collected on 11 October 1995 via towed Datasonde 3 11

Figure 9. Hypothetical movement of water parcels from Richard B. Russell Station 112B (upstream) to 100B (downstream) 12

Figure 10. Vertical plane of hypolimnion 13

Figure 11. Primary deployment locations 13

Figure 12. Sample calibration log sheet 14

Figure 13. Schematic diagram of water quality instrument deployments 15

Figure 14. Schematic diagram of velocity meter deployments 15

Figure 15. Schematic diagram of velocity meter deployment during pumped storage testing 15

Figure 16. Uncorrected and calibration-corrected dissolved oxygen concentration data for Station 112B 17

Figure 17. Uncorrected and calibration-corrected dissolved oxygen concentration data for Station 112B at 20 m off lake bottom 18

Figure 18. Representative depth regions utilized for dissolved oxygen weighting 20

Figure 19. Representative depth regions utilized in column-averaged velocity computations 20

Figure 20. Velocity versus depth versus time for Richard B. Russell Station 090B for period beginning 11 September and ending 21 September 1995 24

Figure 21. Column-averaged velocities for Station 090B plotted against Richard B. Russell Dam conventional generation levels 25

Figure 22. Column-averaged velocities for Station 090B plotted against Richard B. Russell Dam pumped storage operation levels 26

Figure 23. Station 090B velocity profiles averaged by Richard B. Russell Dam operation levels 26

Figure 24. Two-dimensional representation of Richard B. Russell forebay water velocities collected between 11 and 21 September 1995 27

Figure 25. Richard B. Russell forebay flow vectors separated by dam operation levels measured 5 m above lake bottom . . 28

Figure 26. Richard B. Russell forebay flow vectors separated by dam operation levels measured 15 m above lake bottom . 29

Figure 27. Richard B. Russell forebay flow vectors separated by dam operation levels measured 20 m above lake bottom . 29

Figure 28. Richard B. Russell forebay flow vectors separated by dam operation levels measured 25 m above lake bottom . 30

Figure 29. Richard B. Russell forebay flow vectors separated by dam operation levels measured 35 m above lake bottom . 30

Figure 30. Richard B. Russell hourly mean water column velocity magnitudes separated by dam operation levels 31

Figure 31. Averaged velocity profile from Richard B. Russell forebay collected via acoustic doppler current profiler . . 32

Figure 32. Richard B. Russell forebay dissolved oxygen profiles collected 21 June 1995 33

Figure 33. Richard B. Russell forebay dissolved oxygen profiles collected 28 June 1995 33

Figure 34. Richard B. Russell forebay dissolved oxygen profiles collected 5 July 1995 33

Figure 35. Richard B. Russell forebay temperature profiles collected 21 June 1995 33

Figure 36. Richard B. Russell forebay temperature profiles collected 28 June 1995 34

Figure 37. Richard B. Russell forebay temperature profiles collected 5 July 1995 34

Figure 38. Overlay of dissolved oxygen concentrations measured via automated and grab sampling techniques at Richard B. Russell Station 100B between 21 June and 10 July 1995 35

Figure 39. Temperature data for Richard B. Russell Stations 100B and 112B for period from 21 June to 10 July 1995 36

Figure 40. Difference in dissolved oxygen concentrations measured 0.5 m off lake bottom at Richard B. Russell Stations 100B and 112B between 21 June and 10 July 1995 37

Figure 41. Difference in dissolved oxygen concentrations measured 10 m off lake bottom at Richard B. Russell Stations 100B and 112B between 21 June and 10 July 1995 37

Figure 42. Difference in dissolved oxygen concentrations measured 20 m off lake bottom at Richard B. Russell Stations 100B and 112B between 21 June and 10 July 1995 38

Figure 43. Difference in dissolved oxygen concentrations measured 30 m off lake bottom at Richard B. Russell Stations 100B and 112B between 21 June and 10 July 1995 38

Figure 44. Travel times for water parcels from Station 112B to oxygen injection system to Station 100B 40

Figure 45. Oxygen uptake efficiencies and Richard B. Russell Dam operations for period from 23 June to 11 July 1995 41

Figure 46. Oxygen uptake efficiency and Richard B. Russell Dam operations plotted against hour of day for period from 23 June to 11 July 1995 42

Figure 47. Richard B. Russell Station 100B dissolved oxygen concentrations plotted against time of travel from oxygen injection system to 100B 45

Figure 48. Spectral density plot of oxygen uptake efficiency 46

Figure 49. Dissolved oxygen concentrations for Stations 100B, 112B, and oxygen injection system for period from 23 June to 10 July 1995 47

Figure 50. Hourly averaged 100B and 112B dissolved oxygen concentrations and oxygen uptake efficiencies for period from 23 June to 10 July 1995 47

Preface

The work reported herein was conducted as part of the Water Quality Research Program (WQRP), Work Unit 32809. The WQRP is sponsored by the Headquarters, U.S. Army Corps of Engineers (HQUSACE), and is assigned to the U.S. Army Engineer Waterways Experiment Station (WES) under the purview of the Environmental Laboratory (EL). Funding was provided under Department of the Army Appropriation No. 96X3121, General Investigation. Dr. John W. Barko was Program Manager for the WQRP. Mr. Robert C. Gunkel, Jr., was Assistant Manager for the WQRP. Program Monitor during this study was Mr. Frederick B. Juhle, HQUSACE.

The report was prepared by Mr. John W. Lemons and Dr. Michael C. Vorwerk, DynTel Corporation, Vicksburg, MS, and Mr. Joe H. Carroll, Environmental Processes and Effects Division (EPED), EL, WES. The authors gratefully acknowledge the support and assistance of personnel associated with WES's Trotters Shoals Limnological Research Facility, Calhoun Falls, SC. Special appreciation is extended to Dr. Karin Vorwerk for her assistance with data analysis.

The work was performed under the general supervision of Dr. Robert Kennedy, Acting Branch Chief, Ecosystem Processes and Effects Branch, EPED; Dr. Richard Price, Chief, EPED; and Dr. John Harrison, Director, EL.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Robin R. Cababa, EN.

This report should be cited as follows:

> Lemons, J. W., Vorwerk, M. C., and Carroll, J. H. (1998). "Determination of Richard B. Russell dissolved oxygen injection system efficiency utilizing automated remote monitoring technologies," Miscellaneous Paper W-98-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

The contents of this report are not to be used for advertising, publication, or promotional purposes. Citation of trade names does not constitute an official endorsement or approval of the use of such commercial products.

Summary

During the summer of 1995, an array of water quality instruments were deployed at the U.S. Army Corps of Engineers' Richard B. Russell reservoir located on the Georgia-South Carolina border. These instruments were deployed as part of a study designed to measure the effectiveness and efficiency of an oxygen injection system installed to ameliorate the detrimental effects of hydropower operation during summer months when release dissolved oxygen concentrations would have otherwise been anoxic.

Instruments were deployed at two locations (one upstream and one downstream) of the injection system to measure the dissolved oxygen concentrations before and after oxygen injection. These data were incorporated with water velocity data, Richard B. Russell Dam operations data, and oxygen system injection rates for the period of study. Analyses were conducted to quantify oxygen injection efficiencies under varying dam and injection system operational scenarios.

Automated sampling yielded continuous water quality data sets that could not have been obtained via alternate techniques, such as grab sampling. Data demonstrated that oxygen was stored during periods of no operation by Russell Dam. Efficiencies were dependent on the previous week's dam and injection system operation with a trend of increasing efficiency as the operational week progressed. The implication was that higher oxygen levels following extended nonoperation periods (typically weekends) led to relatively low efficiencies since the water column was closer to saturation levels. As the stored oxygen was depleted during weekly operation, oxygen was more readily absorbed and efficiencies were greater.

Dissolved oxygen concentrations measured at the downstream station were dependent on the water's time of exposure to the oxygen injection system. This implied that during periods of high dam operation levels, exposure times would not be of sufficient duration to allow absorption of all injected oxygen.

This study demonstrated that methods developed for measuring primary production levels in flowing streams could be successfully adapted to reservoirs. By incorporating data collected through

close-interval sampling over a period of weeks, it was possible to draw conclusions concerning the injection system's operation under varying operational scenarios. Self-contained, water quality data loggers made it possible to collect the data needed to successfully identify patterns associated with oxygen injection and dam operation. Additionally, their use simplified data analysis and collection since biological and chemical oxygen demands and oxygen-deficit curves did not have to be directly measured.

1 Introduction

The impoundment of rivers to create reservoirs for anthropomorphic uses such as power production, storage, flood control, and recreation often has detrimental consequences for the existing riverine ecosystem. Construction of dams and their resultant pools constricts rivers such that the projects often become point source polluters by introducing water that contains less oxygen, cooler temperatures, and/or higher concentrations of ferric and sulfuric compounds than would normally be present in the downstream habitat. Pollution in this manner can lead to serious, widespread consequences to the riverine ecosystem that have been, until recently, largely ignored.

The purpose of this report is to document a study conducted to quantify the effectiveness of an oxygen injection system in Richard B. Russell Lake on the Savannah River. Richard B. Russell (RBR) Dam is a U.S. Army Corps of Engineers (COE) owned and operated hydropower project located on the Savannah River between South Carolina and Georgia (Figure 1). It impounds an area that covers 107.9 km^2 between the COE impoundments of Hartwell (upstream) and J. S. Thurmond (downstream) dams. RBR Lake is characterized by a primarily granitic basin, poorly drained watershed, and surface waters that are low in dissolved solids, total alkalinity, and buffering capacity (Ashby et al. 1994).

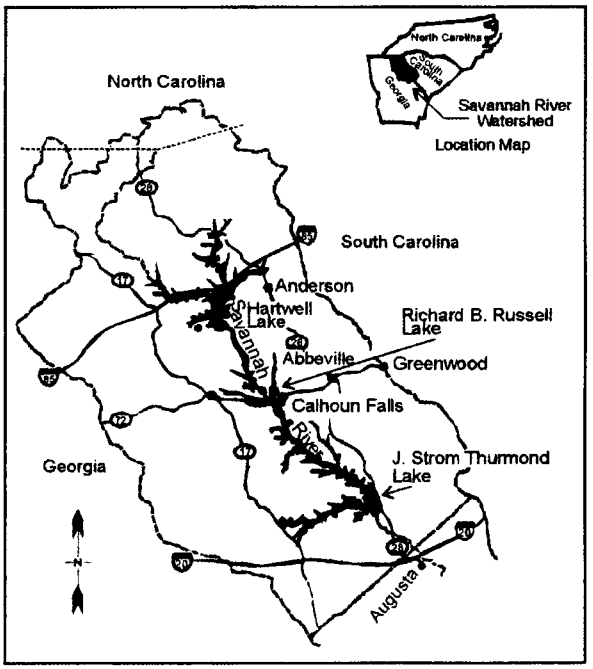


Figure 1. Savannah River vicinity map

The RBR project was originally approved by the "Flood Control Act of 1966" as Trotters Shoals Dam (Public Law 89-789, Eighty-Ninth Congress HR 18233) to provide power generation, flood control, recreation, fish and wildlife habitat, streamflow regulation, and water

supply (Ashby et al. 1994). During the initial planning stages for the RBR project, questions were raised by the State resource agencies of Georgia and South Carolina concerning possible deleterious effects on downstream water quality and aquatic habitat resulting from hydropower operation. Subsequently, the COE agreed to maintain a minimum release dissolved oxygen (DO) concentration of 6.0 $mg \cdot L^{-1}$ and were granted permission to proceed with the project.

Many techniques for increasing hydropower release DO concentrations, such as weirs, turbine venting, surface aerators, diffuser systems, draft tube aeration, selective withdrawal, and reservoir destratification have been utilized in reservoirs with varying performance records (Aquatic Systems Engineering 1990). Each reservoir's hydrological, morphological, chemical, and biological characteristics interact to influence the performance of these systems such that different techniques or combinations of techniques may be necessary to achieve the desired results.

To meet the 6.0-$mg \cdot L^{-1}$ minimum release DO concentration requirement at RBR, the COE installed an oxygen injection (O_2) system in RBR forebay to add oxygen during stratified periods, typically early summer to early fall, when the hypolimnetic DO concentration approached anoxia. The oxygen injection system at RBR consisted of two components: (a) a pulse injection system attached to the upstream face of the dam and (b) a continuous injection system located on the lake bottom approximately 1.6 km upstream of the dam (Figure 2). During maximum operation,

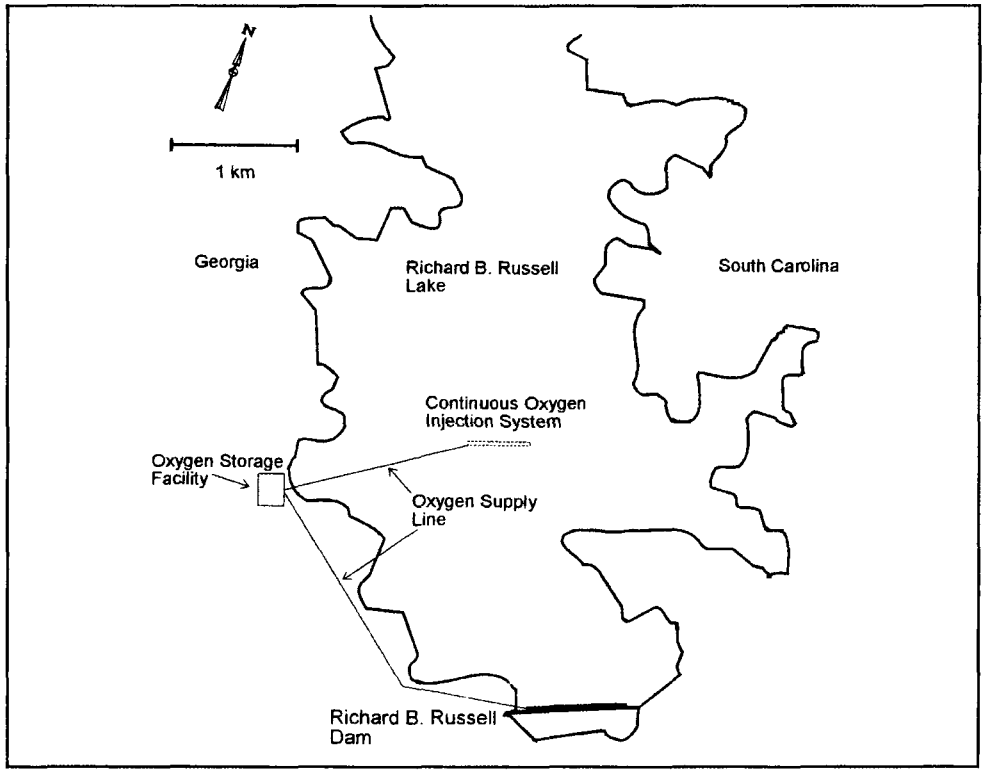


Figure 2. Richard B. Russell forebay continuous oxygen injection system

these systems introduce as much as 100 tons of oxygen per day into RBR forebay to overcome an estimated 4- to 5-mg·L^{-1} DO deficit. Neighboring Hartwell (HW) and J. S. Thurmond (JST) reservoirs, which have no oxygen remediation systems, experience release DO concentrations of approximately 1 to 2 mg·L^{-1} during late summer (Figure 3).

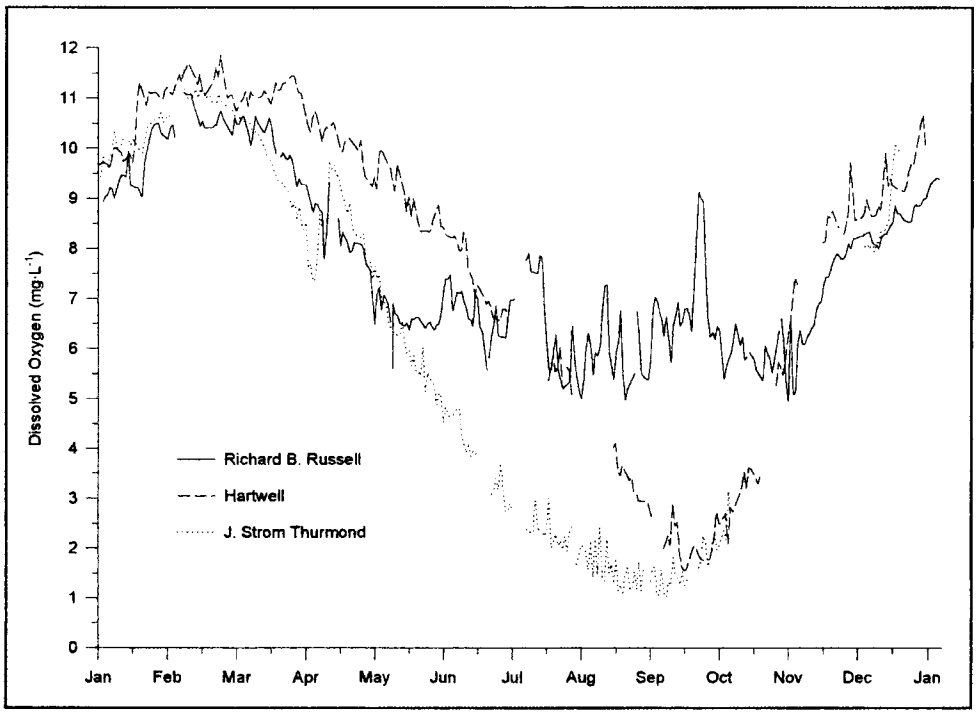


Figure 3. 1995 release dissolved oxygen concentrations for Richard B. Russell, Hartwell, and J. Strom Thurmond dams

Hypolimnion aeration via pure oxygen injection seeks to take advantage of the increased hydrostatic pressure at depth to improve gas transfer efficiencies. The injection of pure oxygen is preferred over air injection, as the latter has the potential for supersaturation of gaseous nitrogen, which is detrimental to fish and other wildlife (American Public Health Association 1992; Aquatic Systems Engineering 1990; Bouk 1980). The volume of the hypolimnion allows for storage of dissolved oxygen that may then be released during power generation. This principle was an additional justification for the RBR continuous injection system.

The original plan of operation for O_2 injection was that the continuous component would be routinely used to increase the release DO concentrations with the pulse component serving in a supplemental capacity during critical periods of limited DO concentrations. Gaseous oxygen was supplied to the system from a liquid oxygen facility located on the Georgia shore (Figure 2). This report will discuss the findings of a study focused on the continuous component of the RBR oxygen injection system.

The primary approach for estimating injection efficiencies for the RBR O_2 system has been gas analyses of individual bubbles conducted via laboratory tank tests. Based on these studies, the gas transfer efficiency of the diffusers was between 25 and 96 percent, with efficiencies for the smaller bubbles averaging about 70 percent (Gallagher and Mauldin 1987). Subsequent conclusions concerning the operation of the system have been based on in situ forebay profiles, oxygen injection rates, dam operation schedules, and continuous records from the RBR release water quality monitor.

None of the aforementioned approaches for quantifying the effectiveness of the RBR O_2 injection system address the short-term oxygen and hydrologic dynamics inherent to RBR forebay and, as a result, have been inadequate for day-to-day operational decision making. Laboratory gas analyses ignore potential biological and chemical influences altogether. Estimates based on the DO concentrations of RBR Dam's release waters include potential biological and chemical influences as water traverses the 1.6-km distance between the continuous injection system and RBR Dam. Efficiency determinations conducted in either fashion would unfairly include or exclude photosynthesis and respiration influences on DO dynamics that could potentially increase or decrease the actual system efficiency. The system presently consists of a combination of ceramic and rubber diffusers. To date, efficiency calculations based on type have not acknowledged performance variations between the respective types. Furthermore, previous interpretations of injection system efficiency had been based on water quality records collected by the original downstream release monitoring system. Subsequent studies had determined data collected by that system to be suspect (Vorwerk and Carroll 1995); thus, efficiencies based on those data may have been in error.

In his seminal work on primary production in flowing waters, Howard T. Odum discussed the "upstream-downstream" approach as the "chief method available for the study of metabolism of flowing water communities" (Odum 1956). Odum applied this method to measure the primary production attributable to a marine turtle-grass (*Thalassia*) community. The study was conducted by measuring the stream DO concentration above and below a *Thalassia* community. An analysis of diurnal curves for oxygen and carbon dioxide allowed an estimation of the primary production of the community by calculating the difference between the upstream and downstream DO concentrations (Odum 1957).

This study sought to modify Odum's methods such that they could be applied to a reservoir. RBR forebay was treated as the stream with the O_2 system serving as the algal community. Sample locations were positioned nearer to the system than previous studies, thus, removing extraneous biological and chemical influences occurring within the 1.6-km distance between the injection system and RBR Dam. Biological and chemical influences occurring within the boundaries of the O_2 system were included through in situ data collection, unlike previous laboratory analyses. For the purposes of this report, efficiency is defined as the increase

in the hypolimnetic DO concentration per amount of DO added by the O_2 system (also expressed as a concentration).

Specific hypotheses tested by this study included the following:

a. Dissolved oxygen accumulates in RBR forebay during periods when RBR Dam is not generating (especially weekends).

b. Oxygen distributions and dynamics vary accordingly in response to dam operation, especially pumped-storage operation.

c. Grab sampling is inadequate for identifying short-term patterns with respect to temperature and DO fluctuations and is therefore inadequate for determining the efficiency of the O_2 system.

Of particular interest to the project managers at RBR were changes in the efficiency (the increase in the hypolimnetic DO concentration per unit O_2 added) and effectiveness (the ability of the system to maintain desired release DO concentration of 6.0 $mg \cdot L^{-1}$) of the forebay continuous O_2 system. While historical "grab" data afforded some record of the system's performance over long periods, they yielded little insight into the short-term influences resulting from day-to-day project operations. Close-interval sampling allowed for increased temporal resolution enabling these trends to be captured so relationships with RBR Dam could be explored.

Furthering understanding of water movement through RBR forebay was an additional focus of this study. Describing the hydrological processes within RBR forebay was crucial for drawing conclusions with respect to mass transport within the system. While studies addressing pumped- storage influences had been conducted, no study to date had sufficiently described flow fields and patterns within RBR forebay during generation periods.

2 Background

The physical, chemical, and biological processes occurring within reservoirs are subjected to both natural and anthropogenic forces. Describing the RBR system requires an understanding of both the natural driving forces controlling DO concentrations and the anthropogenic impacts resulting from hydopower production. Natural oxygen inputs come from the atmosphere and photosynthetic activity. Algal photosynthetic activity produces oxygen and consumes carbon dioxide in the presence of sufficient light of the proper wavelengths to drive the reactions. The wavelengths necessary to stimulate photosynthesis range from 400 to 700 nm, referred to as photosynthetically active radiation (PAR). Respiration, like photosynthesis, also results from biotic activity; however, respiration results in a net decrease in the dissolved oxygen concentration and occurs irrespective of light presence. The reactions for photosynthesis and respiration are typically depicted together as

$$nCO_2 + H_2O \leftrightarrow (CH_2O)n + O_2$$

where n is usually 3, 6, or 12 depending on the stage of photosynthesis/respiration that is occurring (Cole 1983; Horne and Goldman 1994).

The amount of dissolved oxygen that water may hold depends on the gas's solubility and partial pressure which, in turn, depend on the ambient hyperbaric pressure and temperature. Temperature influences the ability of water to hold oxygen and, as a rule, colder water can contain more oxygen than warmer water. The solute and sediment content of water also have an inverse relationship with the ability of water to take up and hold oxygen by occupying space between water molecules that may otherwise be occupied by oxygen (Cole 1983; Horne and Goldman 1994).

As temperate lakes and reservoirs undergo seasonal warming, the water column stratifies into three layers: the epilimnion, the metalimnion, and the hypolimnion (Figure 4). The epilimnion consists of the warmer surface water and is the least dense layer. The metalimnion is comprised of the transitional zone between the epilimnion and the hypolimnion. The hypolimnion consists of the bottom waters and is the coldest, most dense

layer of the water column. In the southeastern United States, thermal stratification may result in a difference of more than 20 °C between the epilimnion and the hypolimnion. Because of the density differences between the three layers, materials are not easily exchanged between them. Thus, the hypolimnion is isolated from the infusion of atmospheric oxygen that replenishs the DO concentration of the epilimnion. The lack of light penetration by PAR wavelengths into the hypolimnion precludes photosynthesis but does not affect respiration, leading to a reduction in the hypolimnetic DO concentration. Chemical reactions in the reservoir's sediments are stimulated in an oxygen-free environment, and these reactions act to further deplete the hypolimnetic DO concentration.

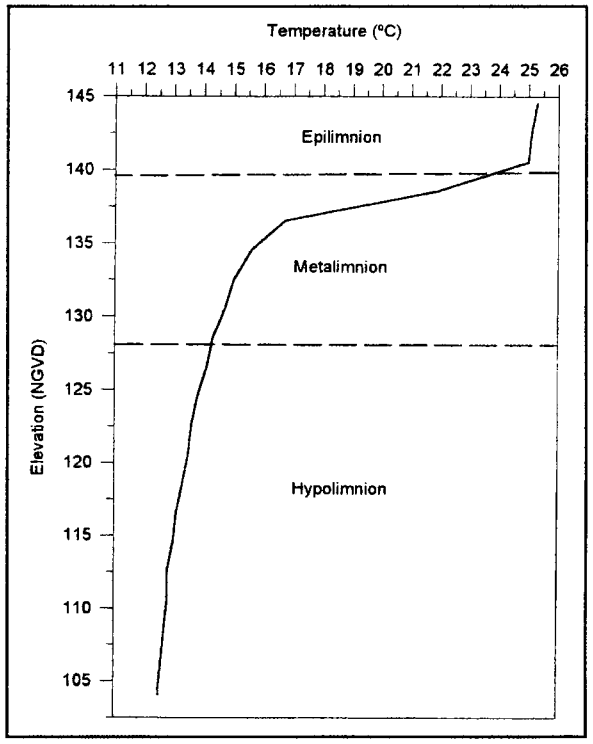


Figure 4. Temperature profile for Richard B. Russell forebay Station 112B displaying respective layers of a stratified water column

In hydropower dams, penstock openings (the inlets for water passage from the forebay into the dam) are typically located deep within the water column (Figure 5). As a result, cold, oxygen-poor water is released through the dam into a tailwater that is, by contrast, warm, shallow, and well oxygenated. Thus, the ability to artificially increase hypolimnetic DO concentrations is an important tool for reservoir managers in that these methods can lessen the impacts of hydroelectric dams to the surrounding upstream and downstream ecosystems.

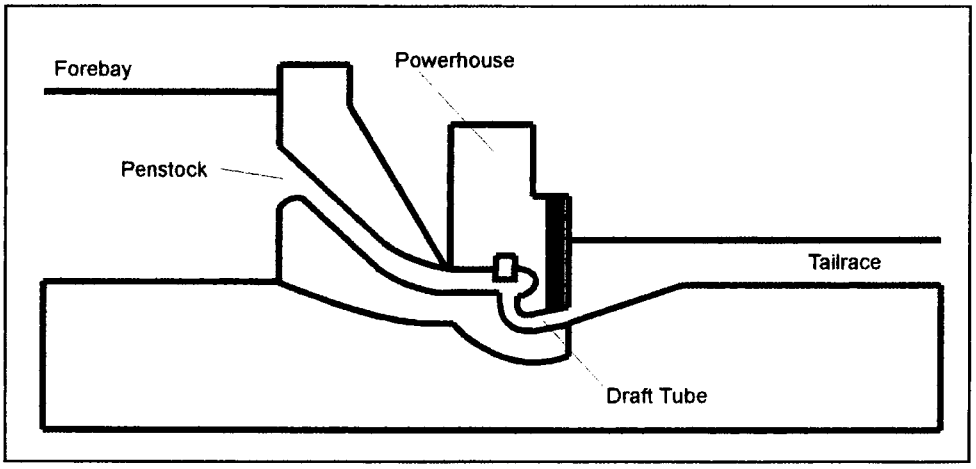


Figure 5. Cross-sectional view of Richard B. Russell Dam (not to scale)

Richard B. Russell Dam is a peaking hydropower facility, i.e., generation cycles vary with daily and seasonal power demands. There is typically no generation on weekends except during high flow periods for flood control purposes. Additionally, RBR Dam is a pumped-storage project with four of its eight turbines capable of reversing flows to move water from downstream to the forebay. This ability benefits project managers by increasing the dam's available pool for power production, but confounds hydrologists attempting to describe the flow patterns within RBR forebay.

The continuous component of the O_2 system consists of two 490-m-long, 20-cm-ID reinforced plastic pipes spaced about 30 m apart. The diffusers are approximately 18 cm in diameter and spaced about 30 cm apart along each pipe. The diffuser lines are supplied with oxygen from the storage facility via a distribution pipe (Figure 6). The original diffusers were composed of silica glass; however, replacement diffusers were composed of rubber. The standard permeability of the original ceramic diffusers was 60 $cm \cdot min^{-1}$ (Gallagher and Mauldin 1987).

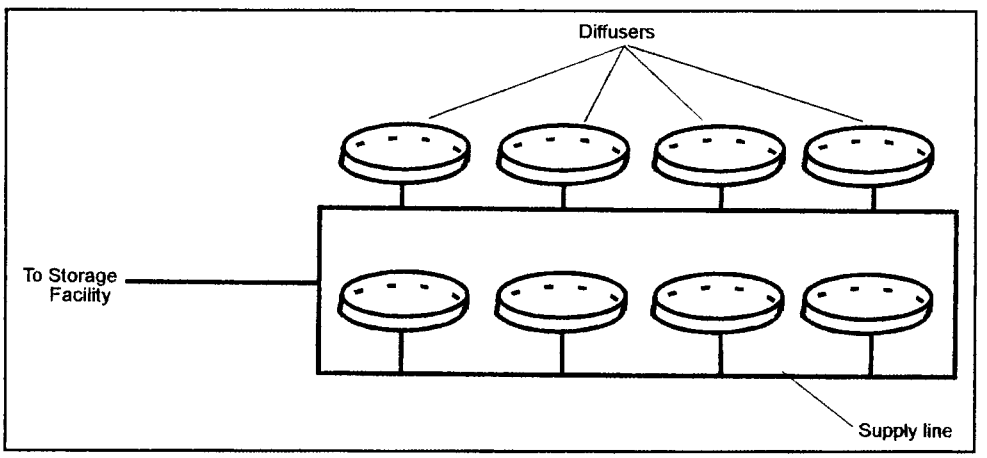


Figure 6. Schematic diagram (not to scale) of continuous component of Richard B. Russell oxygen injection system

The upstream-downstream approach sought to provide more representative estimates of the actual injection system efficiency than previous approaches. The efficiency of the oxygen injection system for the purpose of this study was defined as the effectiveness of the system as a whole at adding oxygen to RBR forebay. Longitudinal boundaries for the study were Station 112B (upstream) and Station 100B (downstream) because these stations were located closest to the injection system. Bounding the study in this manner allowed oxygen flux calculations to be localized to the immediate upstream and downstream region surrounding the system. This was imperative for meeting the study's goal of determining the effectiveness of the system at increasing the mass of O_2 in the forebay. In this manner, the study's goal was narrowed to address system efficiency with respect to increases in the O_2 mass in RBR forebay and not to the O_2 mass exiting RBR Dam.

Odum established the following criteria for utilizing the upstream-downstream approach to assess primary productivity (Odum 1957):

a. Presence of sufficient turbulence to allow point measurements to represent a region of the stream both laterally and vertically.

b. "Diurnal histories" of the water are the same for both the upstream and downstream locations.

c. Subtraction of diurnal respiratory fluctuations from measured DO concentrations yields the change attributable to primary production.

In turbulent streams, the assumption of vertical homogeneity is typically true; however, in most lakes and reservoirs, it is not. Furthermore, thermal stratification precludes material exchange between respective water layers. As a result of this isolation, single-point measurements were inadequate to spatially represent dissolved oxygen distributions.

Assumption two (common diurnal histories) should hold for the epilimnion due to the ambient energy inputs driving surface waters. The O_2 injection system could potentially invalidate this assumption with respect to the hypolimnion since the biological and chemical influences driving the deeper strata may react differently in oxygenated and oxygen-free environments. Because these influences were not measured for this study, the diurnal histories were assumed to be the same. Since the histories for the respective water layers were assumed to be identical, subtraction of the O_2 mass measured upstream from that measured downstream should yield the effective increase in oxygen attributable to the injection system. The change in O_2 mass divided by the mass of O_2 input via the injection system would represent the efficiency of the system.

Widely varying operation schedules led to widely fluctuating flows from day to day and hour to hour. As previously mentioned, there was typically no generation at the three Savannah River dams (HW, RBR, and JST dams) over weekends such that downstream water movement was effectively zero for 2 days per week. Pumped-storage operation at RBR Dam presented additional difficulties for describing the hydrology of RBR forebay in that the river's flow was reversed during pumped-storage events.

Developments in the technology of water quality instrumentation have greatly increased data-collection capabilities. Remote, automated equipment allowed close-interval sampling without the labor intensity required by "grab" sampling methodologies. Through continuous, close-interval sampling, this study sought to identify the dynamic nature of this system, yielding results that included the ongoing physico-chemical and biological processes without requiring direct measurement via classical approaches (e.g., biological, chemical, and sediment oxygen demands; phytoplankton counts; direct measurement of primary production and respiration). RBR forebay was, in effect, treated as a "black box" as

displayed in Figure 7. Material inputs and outputs were empirically measured, but processes occurring within the box, while not directly measured, were assumed to be occurring.

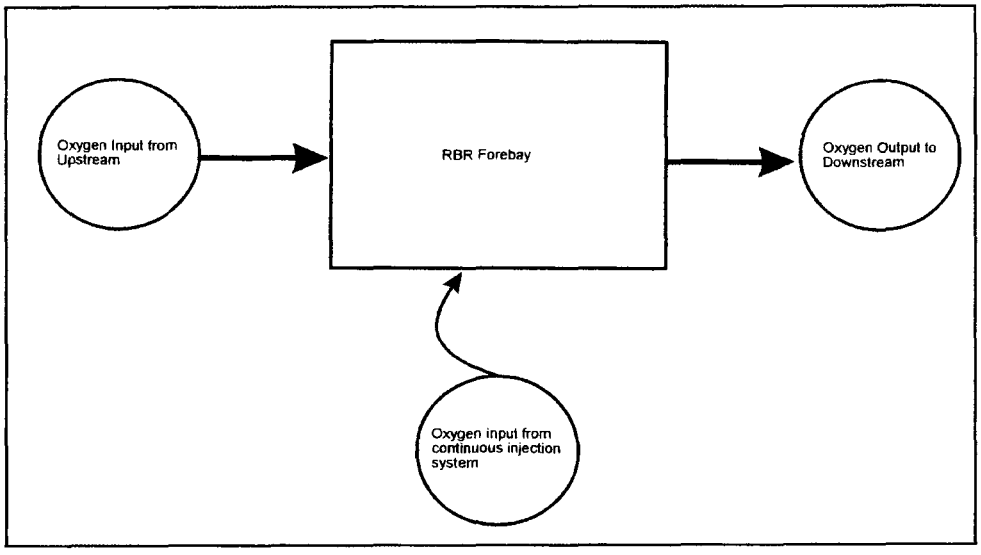


Figure 7. "Black Box" representation of Richard B. Russell forebay

3 Methods

This study sought to determine the efficiency of the system by calculating the mass of oxygen upstream and downstream of the system and the mass input by the oxygen injection system. Dividing the difference of the upstream and downstream concentrations by the mass input (expressed as a concentration) resulted in the system's efficiency. As previously discussed, Odum's approach could not be directly applied to RBR Lake. Instead of single-point measurements, multiple depths were sampled both upstream and downstream of the system. There was insufficient equipment to cover the entire forebay region; since vertical and longitudinal heterogeneities were thought to be greater than lateral variations (Figure 8), sample arrays focused on capturing the vertical, longitudinal, and temporal dynamics.

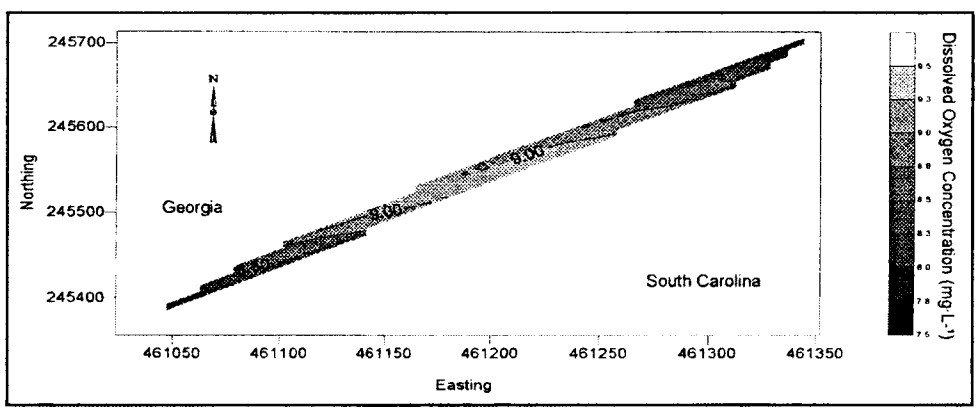


Figure 8. Lateral dissolved oxygen concentrations collected on 11 October 1995 via a towed Datasonde 3

Water was "followed" as it traveled from upstream to downstream of the system as is depicted in Figure 9. Downstream water quality measurements were time lagged before merging them with upstream measurements allowing direct comparisons of the same water parcels. Water velocity data were necessary for computing the travel times needed for time lagging. Equipment availability limited simultaneous velocity/water quality sampling to two locations; however, additional velocity recorders became available subsequent to the water quality study and were deployed

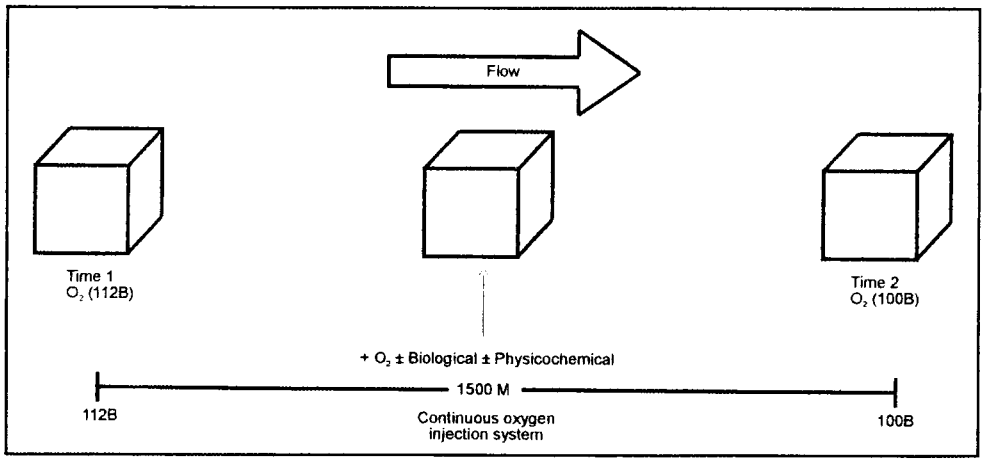


Figure 9. Hypothetical movement of water parcels from Richard B. Russell Station 112B (upstream) to Station 100B (downstream)

to supplement the two-point velocity measurements. Previous studies directed at pumped-storage operation at RBR had included the Acoustic Doppler Current Profiler (ADCP) velocity profiling, and these data were also utilized for describing flow-field dynamics.

The data-recording instruments utilized in this study included the following:

a. Hydrolab Recorders (DS3) equipped with sensors for temperature, DO, pH, specific conductance, and depth.

b. Endeco/YSI current meters equipped with sensors for velocity, direction, and temperature.

c. RD Instruments ADCP capable of utilizing sound signals to yield water column profiles for both velocity magnitude and direction.

All instruments were operated and maintained according to the manufacturers' specifications.

Water movement was assumed to be constrained laterally by the width of the thalweg (about 370 m) and vertically by the top of the hypolimnion (about 35 m off the lake bottom). The area of the vertical plane was thus calculated to be 12,950 m^2 (Figure 10). The depths for deployment were determined by examination of in situ water quality profiles from two forebay stations routinely sampled by the Trotters Shoals Limnological Research Facility (TSLRF), COE, U.S. Army Engineer District, Savannah. These determinations were crucial because the study was limited to a total of eight remote logging water quality instruments, which limited sampling to four upstream and four downstream locations. Deployments were concentrated at two thalweg stations (one upstream and one downstream) with four water quality instruments deployed vertically at each

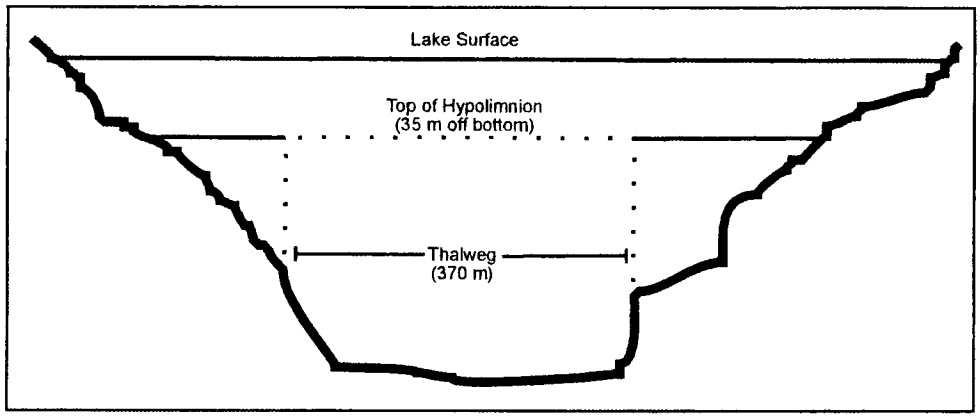


Figure 10. Vertical plane of hypolimnion (not to scale) (Dotted lines represent the dimensions used for calculation "area of influence" for concentration-to-mass conversions)

station. Velocity instruments were positioned at two depths at a station downstream of the water quality instruments.

The primary deployment locations for this study were Stations 090B, 100B, and 112B located in the thalweg of RBR forebay (Figure 11). Stations 100B and 112B were routinely monitored stations utilized by the TSLRF, while Station 090B was added specifically for this study. Station 112B was the upstream station closest to the O_2 injection system and measured the input DO concentration. Station 100B was the nearest downstream station to the O_2 injection system and measured the output DO concentration.

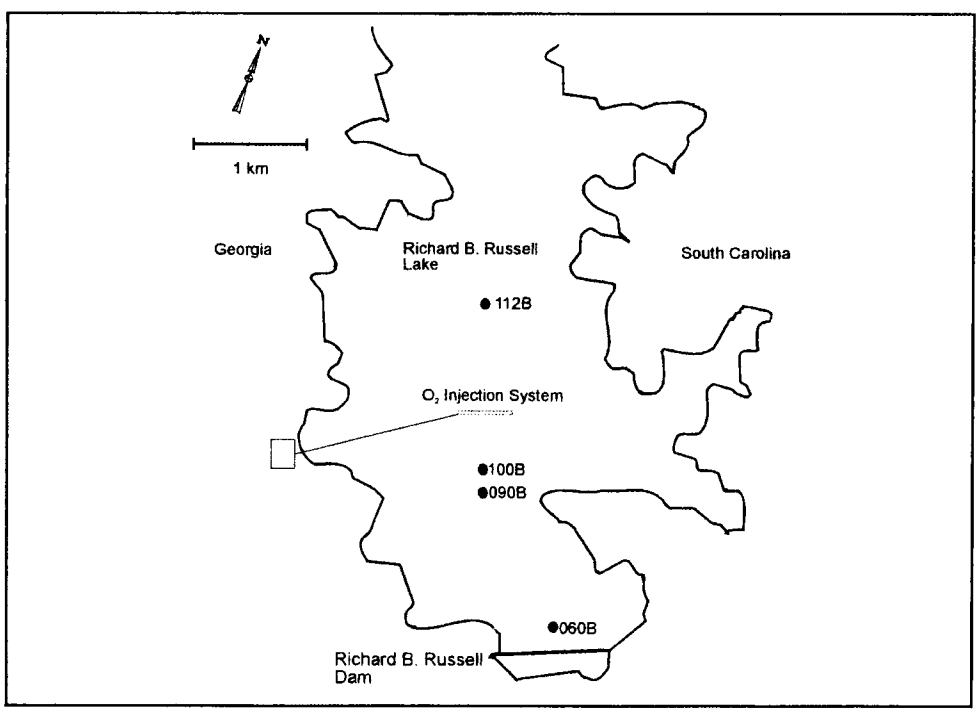


Figure 11. Primary deployment locations

Four DS3's equipped with internal battery packs and sensors for temperature, dissolved oxygen, specific conductance, pH, and depth were programmed to record at 30-min intervals and deployed on 21 June 1995. Specific conductance and pH sensors were calibrated to known standards and DO probes via air calibration following the manufacturer's guidelines. Figure 12 displays a calibration record sheet that is representative of the ones used for the study. Temperature sensors exhibit little drift and were factory calibrated such that follow-up calibrations were not required (Hydrolab Corporation 1991).

IN-LAKE MONITOR CALIBRATION LOG

DATE:
TIME:
INSTRUMENT ID:
DEPLOYMENT DEPTH:

PRE-CALIBRATION VALUES

TEMP: ____
pH: ____
SPCOND: ____
DO: ____

POST-CALIBRATION VALUES

TEMP: ____
pH: ____
SPCOND: ____
DO: ____

WINKLER VALUES

BOTTLE #	DS3 DO($mg \cdot L^{-1}$)	BEGINNING TITRANT	ENDING TITRANT	TOTAL	DIFFERENCE (DO CONC.)

Figure 12. Sample calibration log sheet

The water quality sondes were deployed on buoyed anchor lines consisting of 0.6-cm-diam aircraft cable at locations positioned 0.5, 10, 20, and 30 m off the lake bottom. The DS3 "string" was then attached to the permanent thalweg Stations 100B and 112B, which consisted of similar buoy/anchor configurations (Figure 13). The DS3s were downloaded and recalibrated on 28 June and again upon equipment retrieval on 15 July 1995.

Two velocity meters were deployed at Station 090B on a tethered buoy similar to those used for the DS3 deployments and positioned 10 and 20 m above the lake bottom (Figure 14). Each unit contained internal batteries and was programmed to record velocity, heading, and temperature data at 15-min intervals.

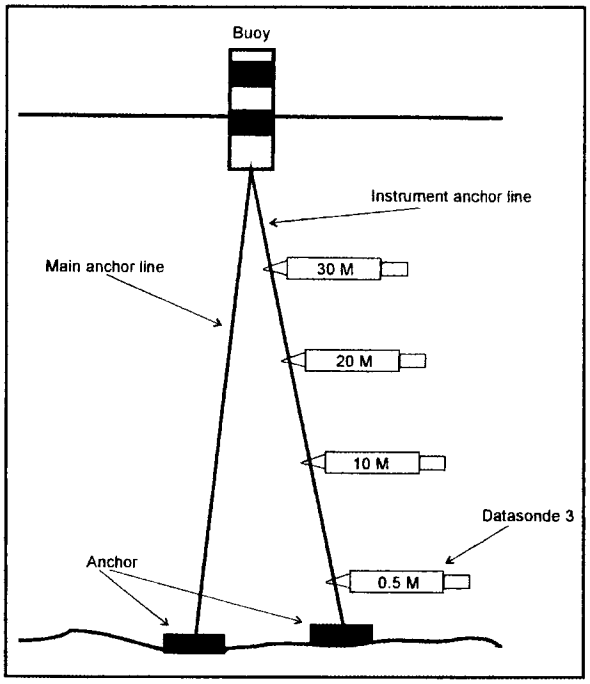


Figure 13. Schematic diagram (not to scale) of water quality instrument deployments

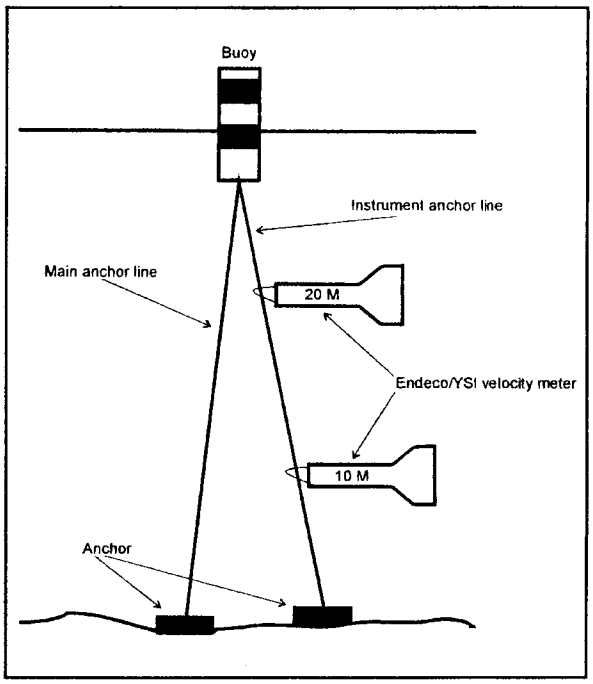


Figure 14. Schematic diagram (not to scale) of velocity meter deployments

Four additional velocity meters became available shortly after the completion of the original study. A total of six velocity meters were deployed in support of RBR Dam pumped-storage testing for a period of 1 week from 13 to 20 September 1995. Instruments were positioned at 5, 15, 20, 25, 30, and 35 m off the lake bottom (Figure 15).

The following data were available at completion of field work:

a. Simultaneous upstream and downstream measurements for temperature, DO, specific conductance, and pH.

b. Continuous velocity measurements for a single forebay station at two depths during the study and at four additional depths subsequent to the primary data collection.

c. Dam operation records for both conventional generation and pumped-storage operation.

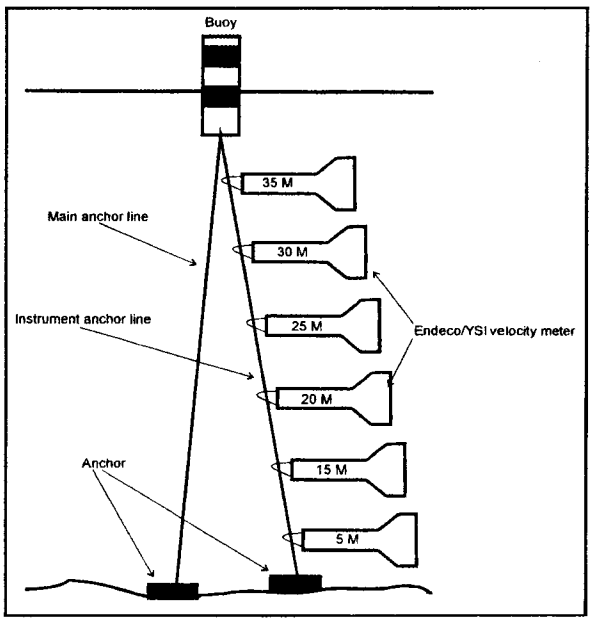


Figure 15. Schematic diagram (not to scale) of velocity meter deployment during pumped storage testing

d. Daily oxygen injection rates for the continuous and pulsed injection systems.

e. Continuous release water quality records for RBR Dam.

f. In situ water quality data for RBR Lake collected by the TSLRF.

Following equipment retrieval and downloading, data were edited to remove machine codes and nonrepresentative data that were recorded during field downloading and calibration periods when the sondes were out of the water. Data were then imported into scientific analysis software to facilitate merging with powerplant operation and oxygen injection records. The following sections outline the preliminary data filtering and assimilation processes conducted prior to the final analyses.

Water Quality

Precalibration and postcalibration data sets were incorporated with the DS3 data to allow calibration corrections based on the observed calibration drift. Correction was linear with respect to the time between precalibration and postcalibrations as

$$\frac{\Delta C}{\Delta T} \pm DO \tag{1}$$

where

ΔC = change in *DO* concentration between precalibrations and postcalibrations

ΔT = number of hours between calibrations

DO = *DO* concentration for each measurement between precalibrations and postcalibrations

This correction factor was adopted from similar corrections used for outflow DO concentrations for the three Savannah River dam automated monitors (Lemons et al. 1996). Figure 16 displays a plot of corrected and uncorrected water quality DO data recorded at Station 112B.

During the final week of the DS3 deployment, the DO membrane on the DS3 positioned 20 m off the bottom at Station 112B fouled. The membrane was replaced and calibrated during the 10 July 1995 calibration/download. New DO membranes require a "breaking in period" to allow the new membrane to relax to its final shape and, as a result, DO concentration measurements taken prior to the membrane reaching its final shape are subject to a high degree of variation and are unreliable (Hydrolab

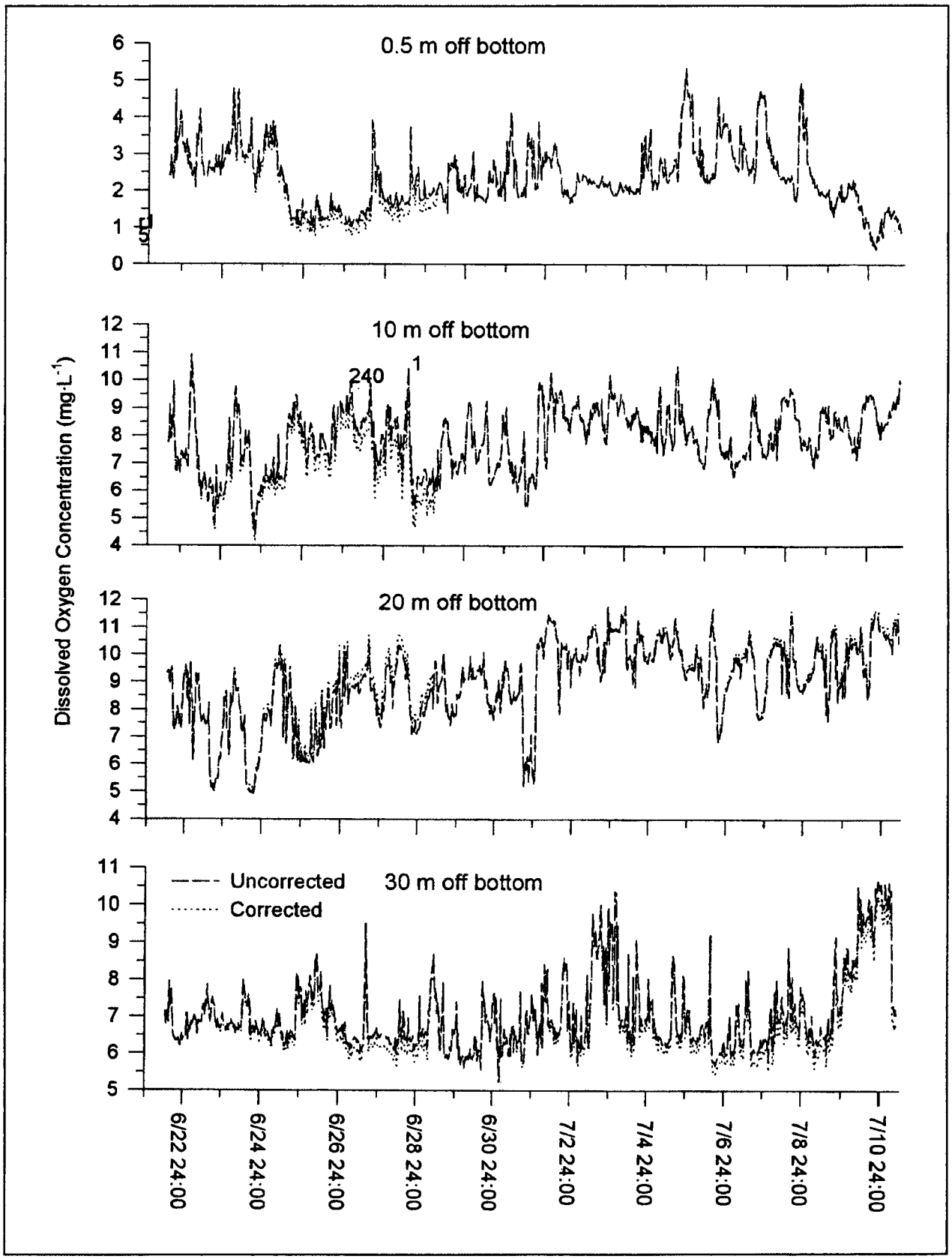


Figure 16. Uncorrected and calibration-corrected dissolved oxygen concentration data for Station 112B

Corporation 1991). For the data to be usable, some form of data correction was needed. Correction was achieved by comparing the automated readings with grab samples reported during the study period such that the rate of drift was approximated and the data corrected. The DO concentration data for the 20-m elevation exhibited an almost linear increase leading to stable readings that were nearly 10 $mg \cdot L^{-1}$ too high (Figure 17). "Correction" in this manner was undesirable, but preferable to the alternative, i.e., no DO concentration data for this elevation.

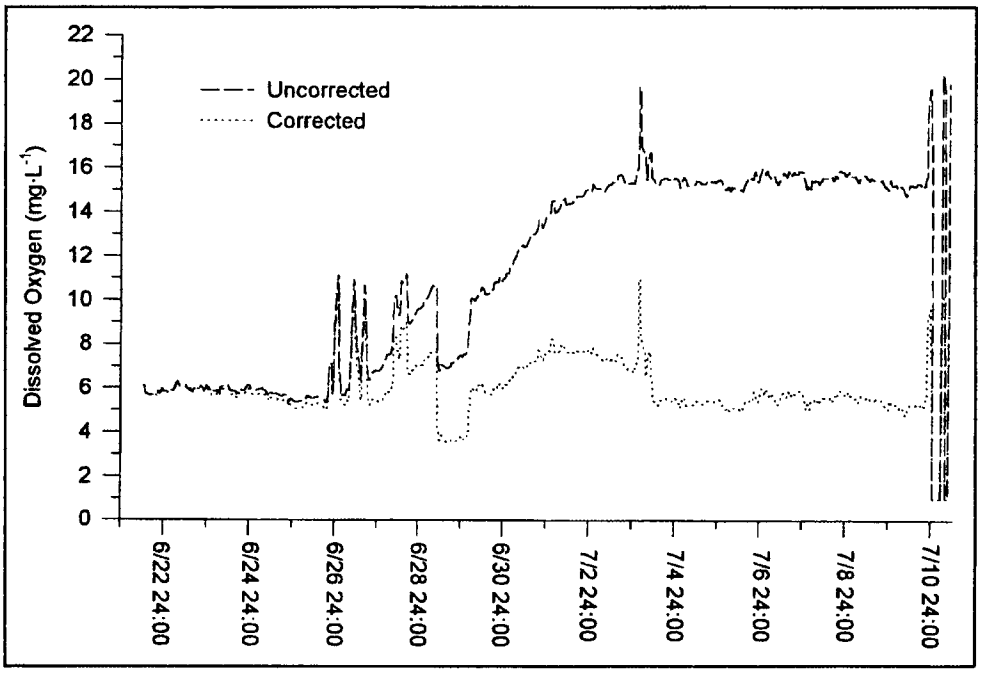


Figure 17. Uncorrected and calibration-corrected dissolved oxygen concentration data for Station 112B at 20 m off lake bottom

Velocity

The velocity instruments require factory calibrations; therefore, no calibration drift corrections were possible. The data were averaged every half hour to yield 30-min measurements for each elevation. Measurements that were recorded during periods when the instruments were out of the water during deployment and retrieval were removed and the subsequent edited data sets combined to provide a single, comprehensive velocity data set.

Measured velocities and directions were combined as follows:

$$a_x = a\cos\theta$$

$$a_y = a\sin\theta \qquad (2)$$

where

a = velocity

θ = compass direction

Conversion of velocity and directional data in this manner yielded the magnitude of the velocity with respect to both the x-axis and the y-axis in rectangular coordinates. Thus, plotting a_x as the "x" coordinate and a_y as the "y" coordinate resulted in a graphical presentation of both the water velocity and the direction of water movement.

After preliminary editing of the data sets, velocity data were merged with operational records from RBR Dam by time. RBR Dam operation data consisted of hourly averages of the previous hour's operation for each turbine in $ft^3 \cdot s^{-1}$, which was then converted to $m^3 \cdot s^{-1}$. Incorporating dam operation data with velocity analyses was necessary for determining potential relationships between generation, pumped storage, and water velocity.

Velocity data collected coincident to the water quality data collection proved insufficient to adequately represent the vertical heterogeneity exhibited by the vertical flow field. Knowledge of the vertical structure of the velocity field would be necessary for tracking water parcels for individual layers. Therefore, velocity and water quality data were depth-weighted and averaged to yield column averaged velocity and water quality measurements. Representative depth regions were demarcated as depicted in Figure 18 for DO and in Figure 19 for velocity. The calculation for depth weighting was

$$\textit{column average DO} = \frac{\sum_{i=0}^{n} DO_i \times \left(\frac{Z_{i+1} - Z_{i-1}}{2} \right)}{Z_{\max}} \tag{3}$$

where

Z = depth

Z_{max} = height of hypolimnion from lake bottom

Velocity values were depth weighted and averaged in the same manner by substituting velocity for DO.

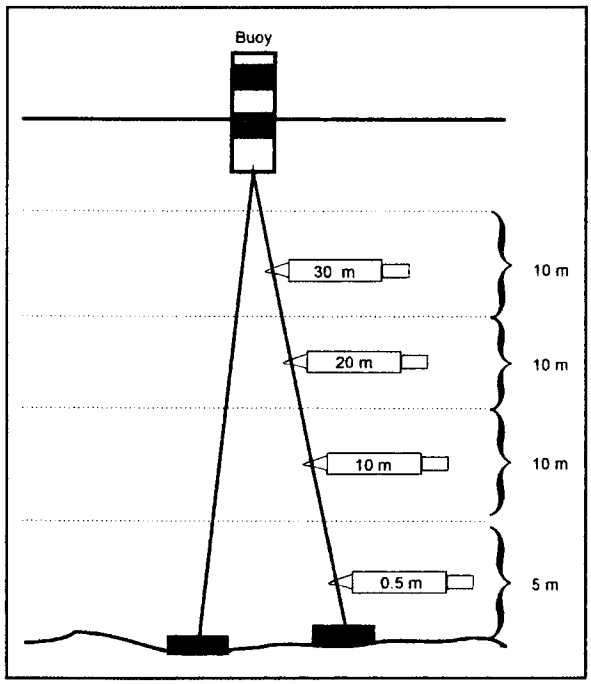


Figure 18. Representative depth regions utilized for dissolved oxygen weighting

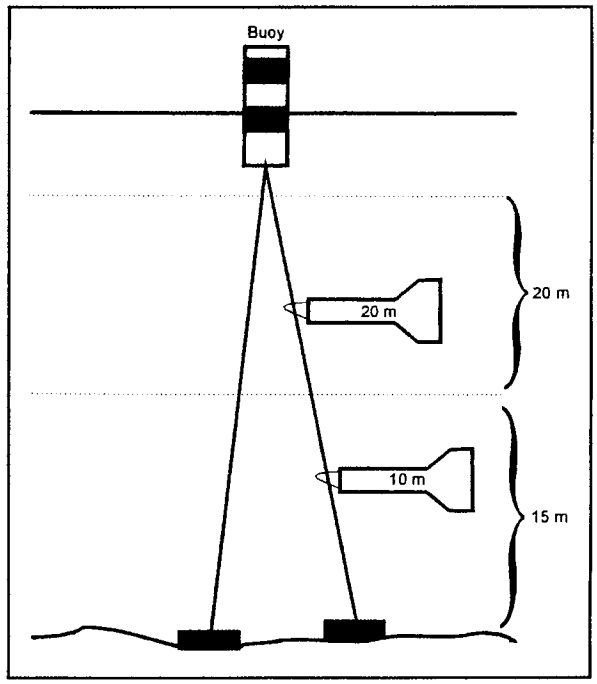


Figure 19. Representative depth regions utilized in column-averaged velocity computations

Data Compilation

Oxygen injection data were obtained from the Savannah District, reported as tons per day. To make inferences between these data, reported as a rate of injection, to the water quality data, reported as a concentration, conversions were conducted to yield injection system measurements as a concentration (milligrams per liter). First, injection rates were converted from tons per day to kilograms per second. Because oxygen was injected continuously, this was an acceptable conversion. To compute the volumetric component needed to yield an oxygen concentration, the rate was divided by the column-averaged velocity and then multiplied by the area previously described. The conversion may be depicted as

$$O_{2injected} = \frac{I}{A\left(\frac{V}{100}\right) \times 1000} \tag{4}$$

where

I = injection rate, kg·s^{-1}

V = water velocity, cm·s^{-1}

A = area of influence for O_2 system bounded by hypolimnion and thalweg, m^2

The denominator was multiplied by 1,000 to convert the volume from cubic meters to liters, and velocity was divided by 100 to convert from centimeters per second to meters per second.

To compare the O_2 masses at the upstream and downstream locations and the injection system, it was necessary to time lag measurements, thereby accounting for the travel time between the points to ensure that the same parcel of water was examined. Time lagging was performed by a BASIC computer program and based on the distance between Stations 112B and 100B (1,500 m) with the injection system located in the middle. Column-averaged velocities were used to represent the distance traveled by the water parcel for each sample interval as

$$v_1 t_1 + v_2 t_2 + v_3 t_3 + v_n t_n = d_1 + d_2 + d_3 + d_n \tag{5}$$

where

$v_n t_n$ = velocity at time n

d_n = distance traveled at time n

Because each time interval consisted of 30 min (the sample interval), this formula could be simplified as

$$v_1 + v_2 + v_3 + v_n = \frac{D_{total}}{30} \tag{6}$$

where D_{total} equals the total distance traveled for a given time period.

Equation 6 could be further simplified because the area was assumed to remain constant at 12,950 m^2 as previously described. Simplifying Equation 6 allowed the BASIC program to convert injection data from tons per day to milligrams per liter as

$$O_2\ injection\left(mg \cdot L^{-1}\right) = \frac{I \times 1000}{\frac{V}{100} \times A \times 1800s} \tag{7}$$

where

I = O_2 injection, kg·30 min^{-1}

V = water velocity, $cm \cdot s^{-1}$

A = area of influence of O_2 system, m^2

Since the area (A) was assumed to remain constant at 12,950 m^2, Equation 7 could be expressed as

$$O_2\ injection\left(mg \cdot L^{-1}\right) = 0.004290\left(\frac{I}{V}\right) \tag{8}$$

where

I = O_2 injection, kg·30 min^{-1}

V = water velocity, cm·s^{-1}

A permutation of Equation 6 was utilized by the BASIC program (Appendix A) to combine water quality records from Stations 112B, 100B, and the injection system such that like records were combined. Because the time lagged records represented the same parcel of water, the most basic computation for oxygen injection system efficiency was

$$Efficiency = \frac{O_{2out} - O_{2in}}{O_{2injected}} \tag{9}$$

where

O_{2out} = oxygen present at Station 100B, mg·L^{-1}

O_{2in} = oxygen present at Station 112B, mg·L^{-1}

$O_{2injected}$ = oxygen input by injection system, mg·L^{-1}

4 Results and Discussion

Velocity

Summary statistics for RBR Station 090B velocity data are presented in Table 1. These data were collected in support of pumped-storage testing for the period beginning 11 September and ending 21 September 1995.

Table 1
Summary Data for Richard B. Russell Station 090B Velocities (m·s-1)

Elevation off Bottom, m	Mean	Standard Deviation	Minimum	Maximum	RBR Dam Operation Scenario
5.0	0.00	0.01	0.00	0.02	Generation
15.0	0.02	0.01	0.00	0.05	Generation
20.0	0.03	0.02	0.00	0.07	Generation
25.0	0.03	0.02	0.00	0.08	Generation
35.0	0.01	0.01	0.00	0.04	Generation
5.0	0.00	0.00	0.00	0.03	No operation
15.0	0.01	0.01	0.00	0.05	No operation
20.0	0.01	0.02	0.00	0.08	No operation
25.0	0.01	0.01	0.00	0.08	No operation
35.0	0.01	0.02	0.00	0.13	No operation
5.0	0.00	0.01	0.00	0.02	Pumpback
15.0	0.01	0.02	0.00	0.05	Pumpback
20.0	0.02	0.02	0.00	0.06	Pumpback
25.0	0.01	0.02	0.00	0.06	Pumpback
35.0	0.04	0.05	0.00	0.16	Pumpback

Data were assigned an "operation level" based on RBR discharge ranging from -4 (representing pumped-storage operation > 495 $m^3 \cdot s^{-1}$) to 7 (representing conventional generation > 990 $m^3 \cdot s^{-1}$) in increments of 165 $m^3 \cdot s^{-1}$. Operation levels were chosen such that each was roughly equivalent to one turbine's operation (approximately 165 $m^3 \cdot s^{-1}$ or 5,800 cfs). That is, an operation level of "1" represented conventional generation with one unit; an operation level of "2" represented conventional generation with two units; an operation level of "-1" represented

pumped-storage operation with one unit, etc. An operation level of "0" signified no operation. The turbines at RBR Dam have historically been operated at full capacity; therefore, dividing release levels in this manner was appropriate.

Variabilities within the velocity data were extremely high, as would have been expected since operation at RBR Dam was thought to be the major factor controlling water movement within RBR forebay. The high degree of variability within individual operation levels, however, was unexpected. The variances ranged from a minimum of 0.109 $m \cdot s^{-1}$ (5.0 m off bottom with no dam operation) to 27.878 $m \cdot s^{-1}$ (35 m off bottom during pumped-storage operation). Figure 20 is a plot of velocity versus time by depth for Station 090B. While there is a high degree of variation between respective depths, there are distinct relationships between velocity and dam operation, the most notable being the highest velocities occurring at near-surface elevations during pumped-storage testing at RBR Dam.

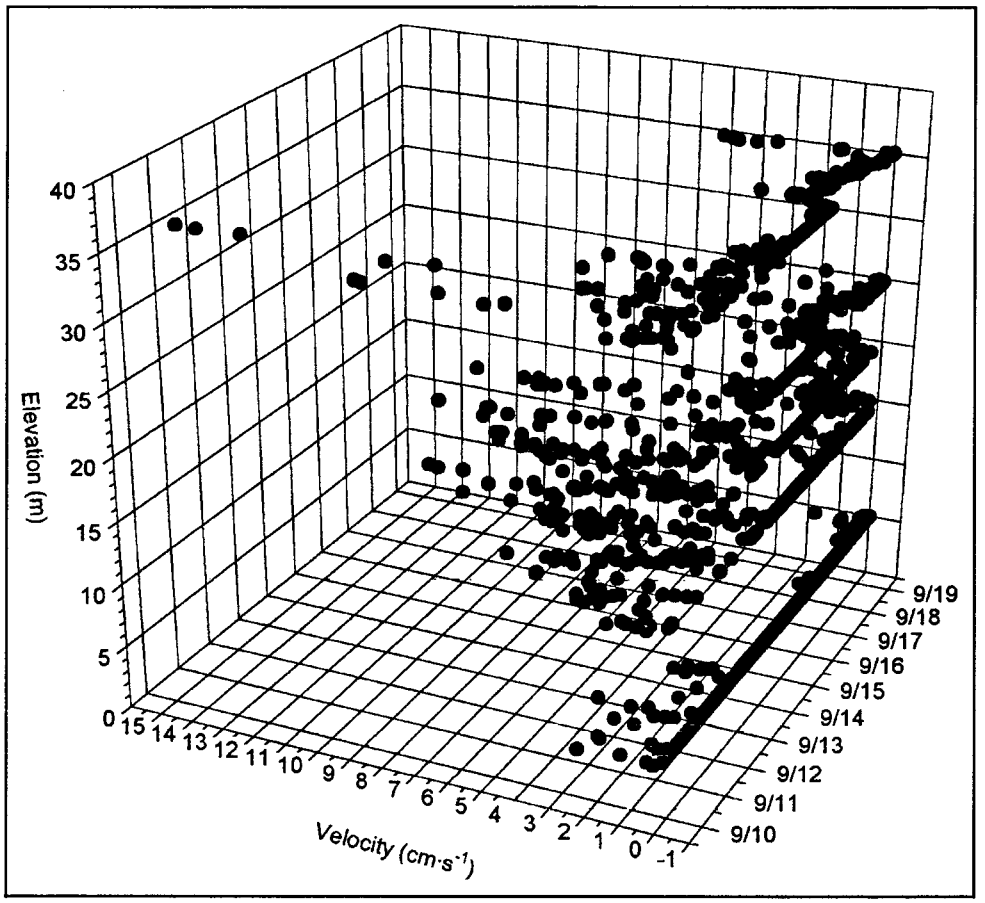


Figure 20. Velocity versus depth versus time for Richard B. Russell Station 090B for period beginning 11 September and ending 21 September 1995

Figure 21 depicts column-averaged velocities collected between 22 June and 6 July 1995 (coincident with water quality data collection) plotted against RBR Dam discharge during conventional generation cycles. The resultant linear relationship was described by the model

$$Column-averaged\ velocity\left(cm\cdot s^{-1}\right)$$

$$= 0.109572 + \left(RBR\ release\left(m^3\cdot s^{-1}\right)\times 0.004117\right)$$

$$r^2 = 0.6923$$

No clear relationship was discernible between the average 090B water velocity and RBR pumped-storage operation (Figure 22). This is most likely the result of concentrating data collection in the hypolimnion with velocity meters at elevations of 10 and 20 m off bottom. Since pumped-storage velocities were greatest at elevations greater than 25 m (Figure 23), pumpback events would not be reflected in the column-averaged velocities.

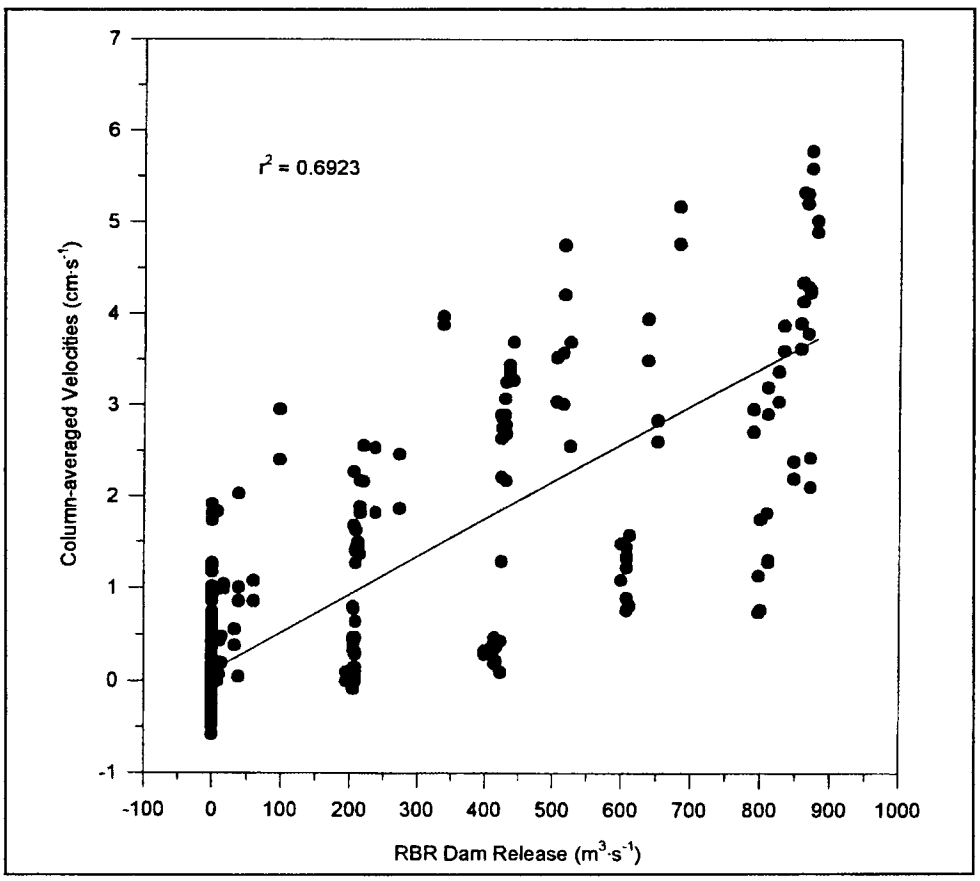


Figure 21. Column-averaged velocities for Station 090B plotted against Richard B. Russell Dam conventional generation levels

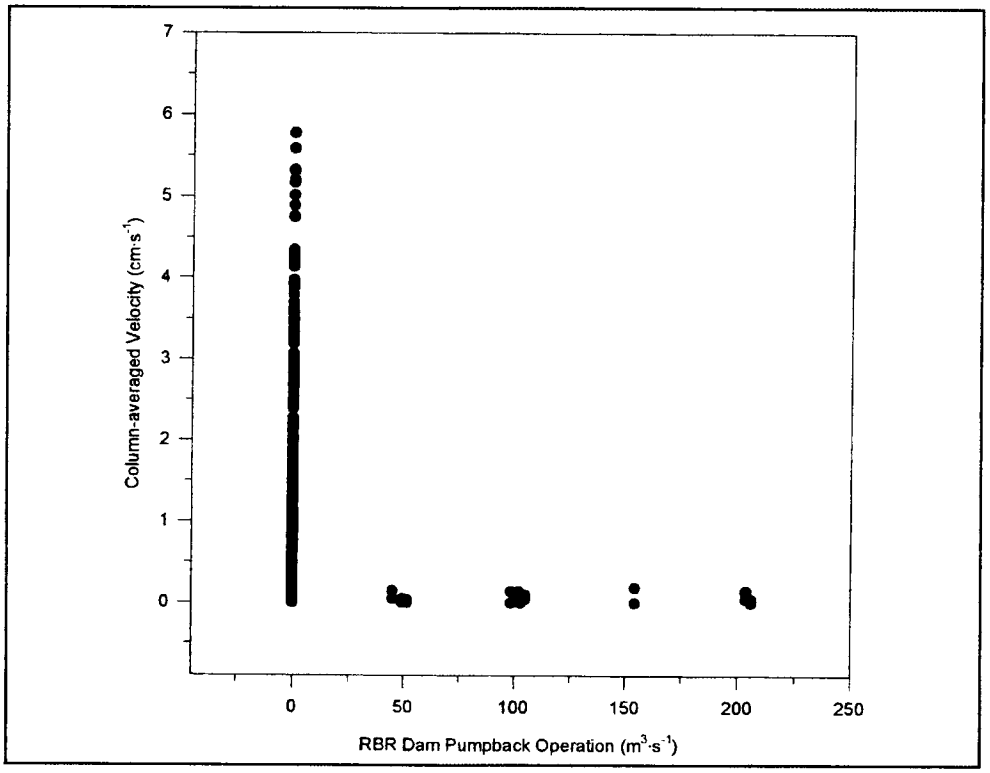


Figure 22. Column-averaged velocities for Station 090B plotted against Richard B. Russell Dam pumped storage operation levels

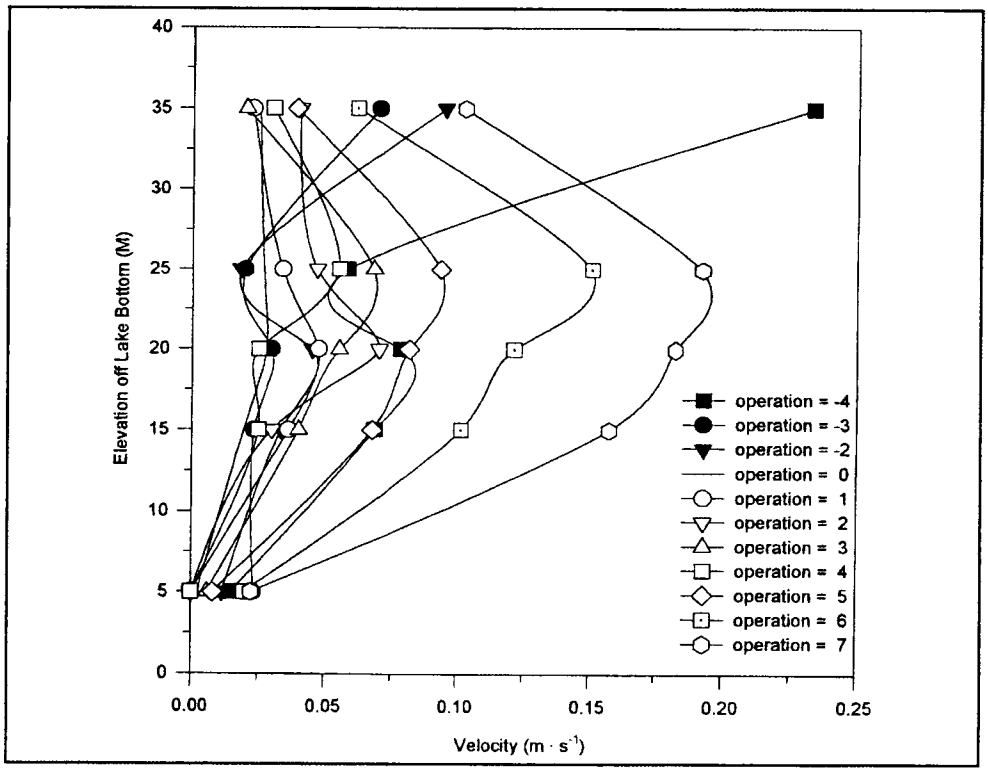


Figure 23. Station 090B velocity profiles averaged by Richard B. Russell Dam operation levels

Figure 24 provides another three-dimensional view of RBR flow patterns using the data collected during the special pumped-storage study (11 to 21 September 1995). Overlaying velocity measurements with flow directions emphasized the high degree of variability with respect to flow, particularly during periods when RBR Dam was not operating. Interpolations performed by the plotting software preclude an exact representation; however, the overall trends are real. The most notable pattern is concentrations of higher velocities related to RBR Dam operation periods. Because the velocity concentrations are not of consistent magnitude or duration for identical operation scenarios, one implication is that flows may not be constricted to the stringent boundaries used to define the area of influence for the concentration-to-mass conversions. The flow field may actually fluctuate in size in response to differing RBR operation scenarios.

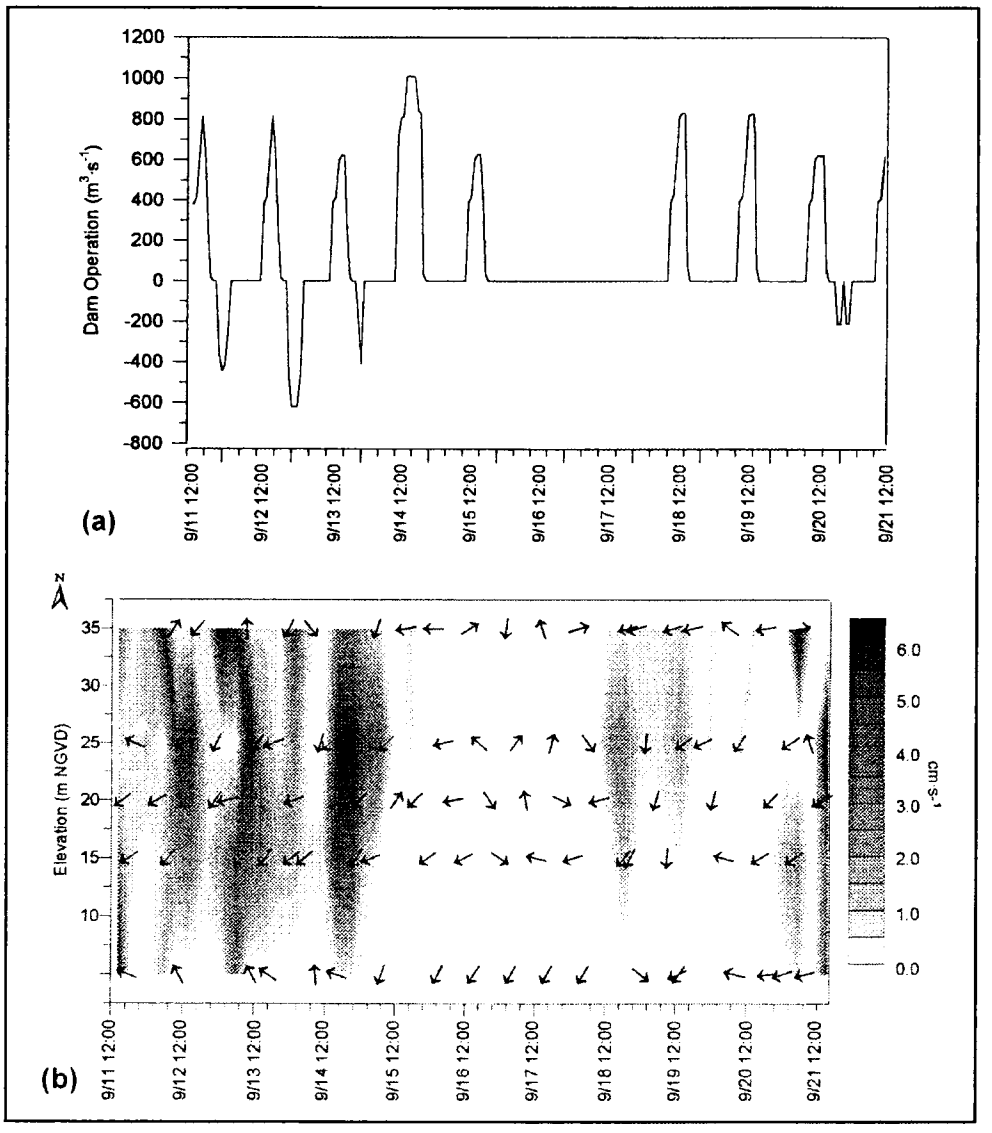


Figure 24. Two-dimensional representation of Richard B. Russell forebay water velocities collected between 11 and 21 September 1995 (Arrows signify flow direction)

Figures 25 to 29 display velocity magnitudes for the respective sample depths that were averaged by operation level as previously described. With the exception of the 5-m height, all demonstrate a noticeable relationship to dam operation with a net movement towards the dam during conventional generation. Pumped-storage operation affects velocity vectors at 25 and 30 m off the lake bottom reflected as movement in directions not directed at the dam. Elevations less than 25 m off lake bottom actually demonstrate water movement that is not discernible from generational flow patterns. This indicates that there is a recirculation current at these elevations during pumped-storage operation resulting in water movement towards the dam.

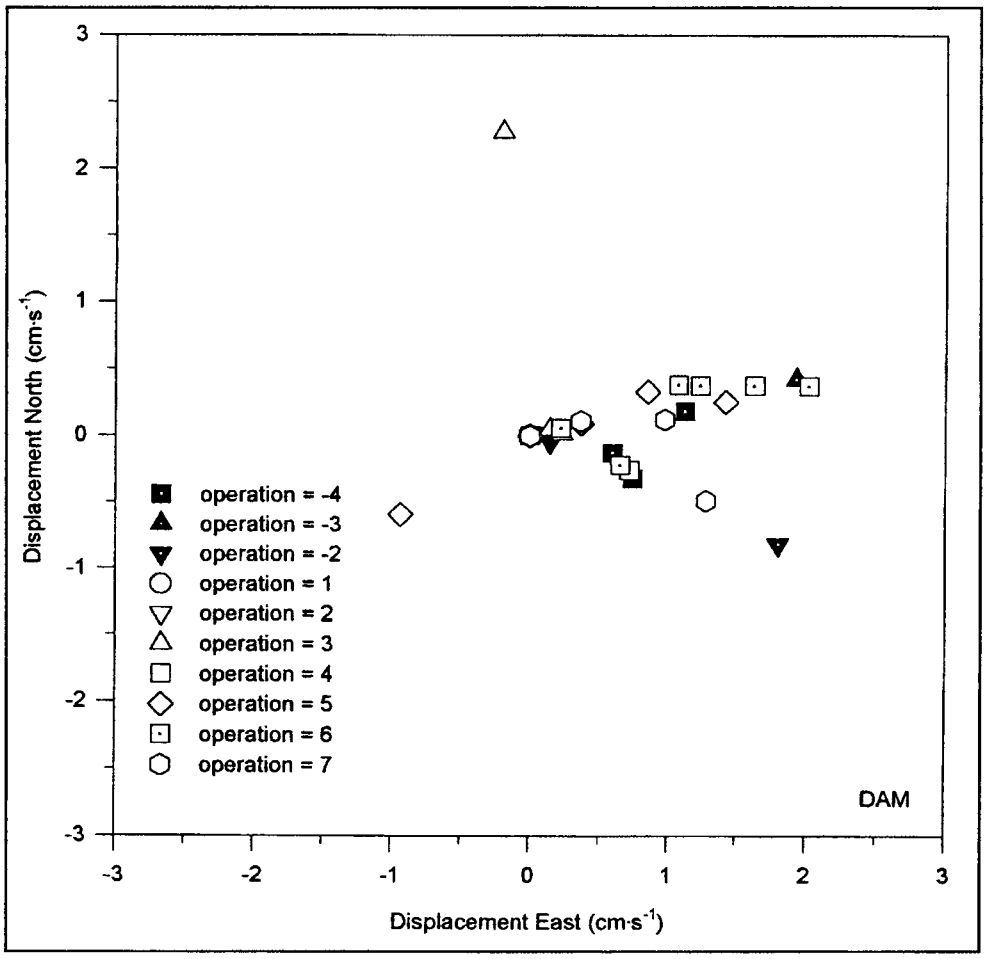


Figure 25. Richard B. Russell forebay flow vectors separated by dam operation levels measured 5 m above lake bottom

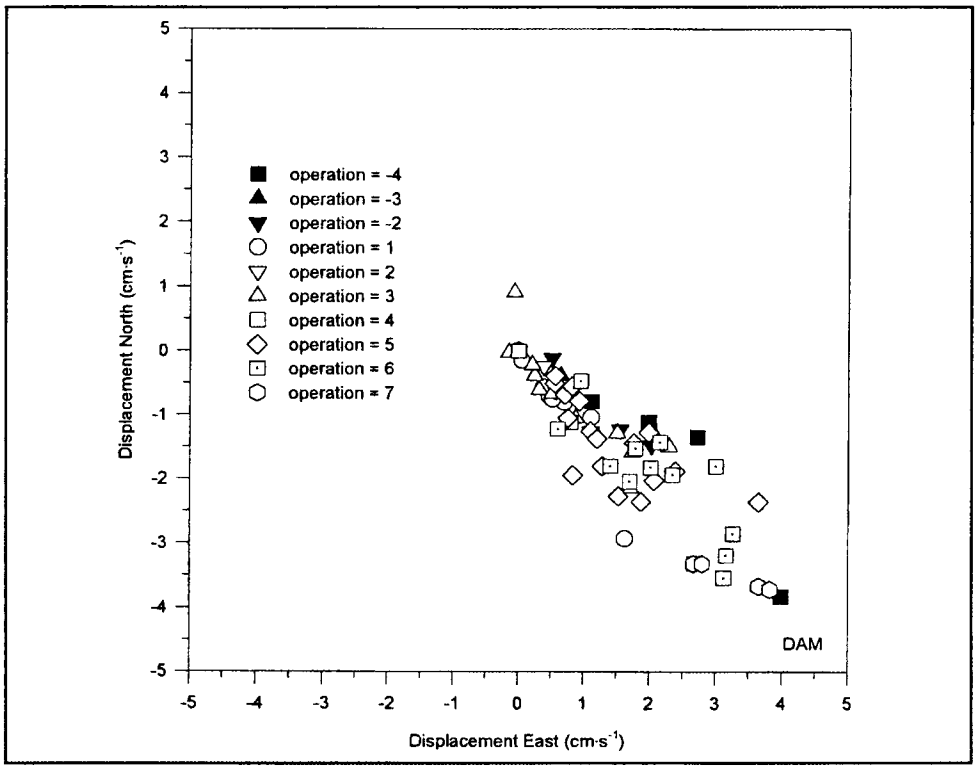


Figure 26. Richard B. Russell forebay flow vectors separated by dam operation levels measured 15 m above lake bottom

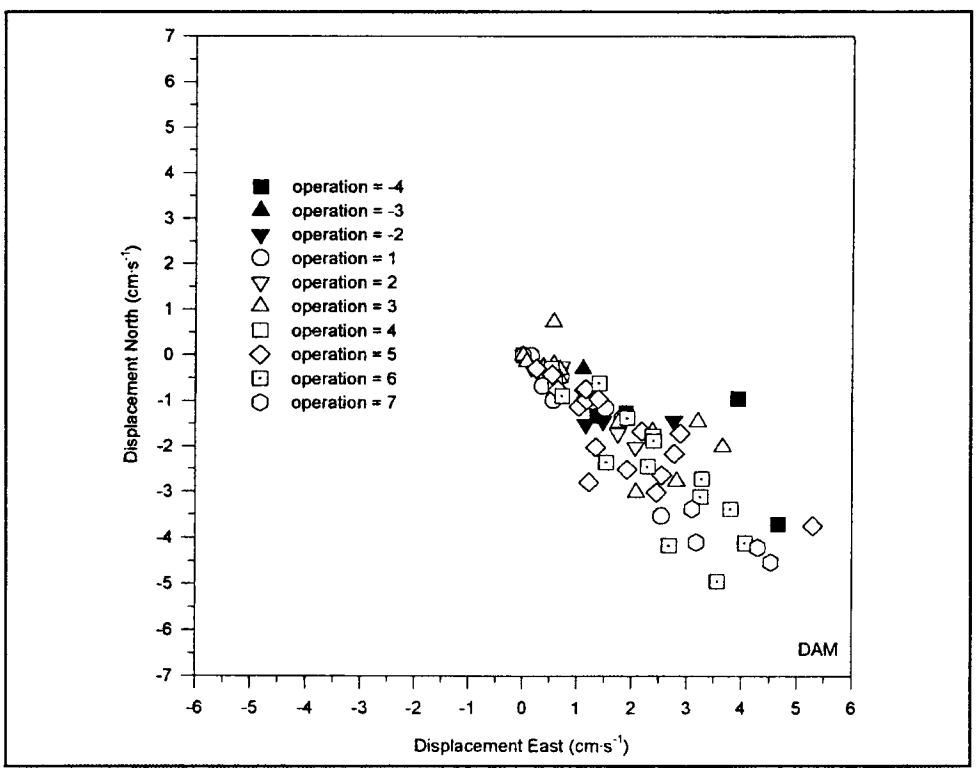


Figure 27. Richard B. Russell forebay flow vectors separated by dam operation levels measured 20 m above lake bottom

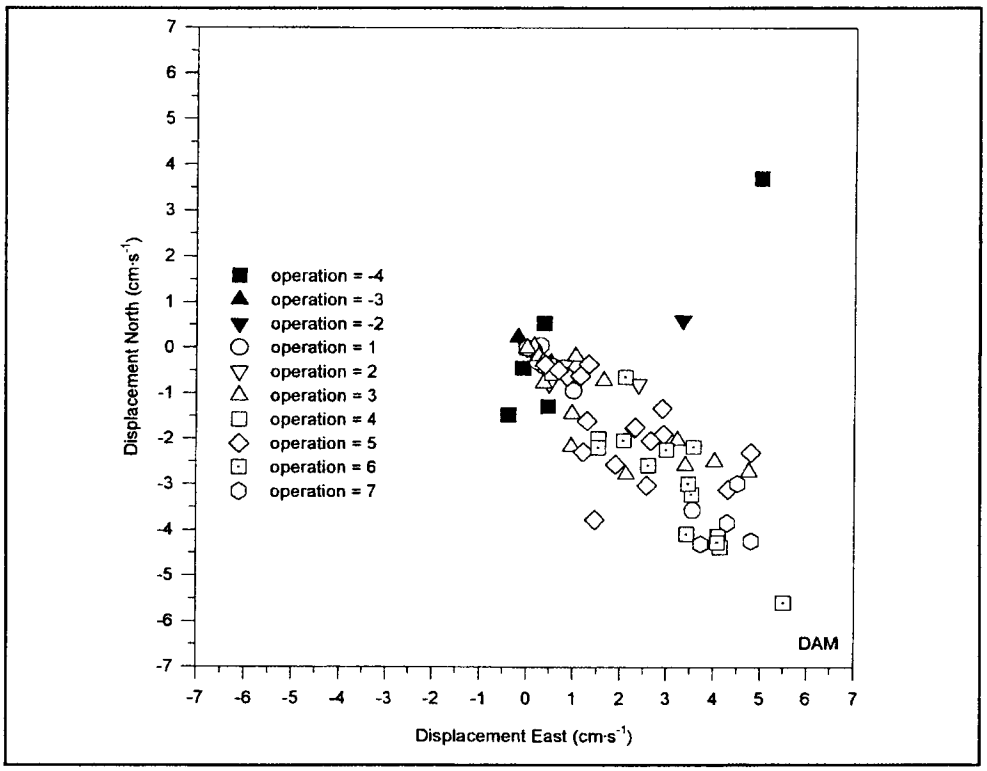


Figure 28. Richard B. Russell forebay flow vectors separated by dam operation levels measured 25 m above lake bottom

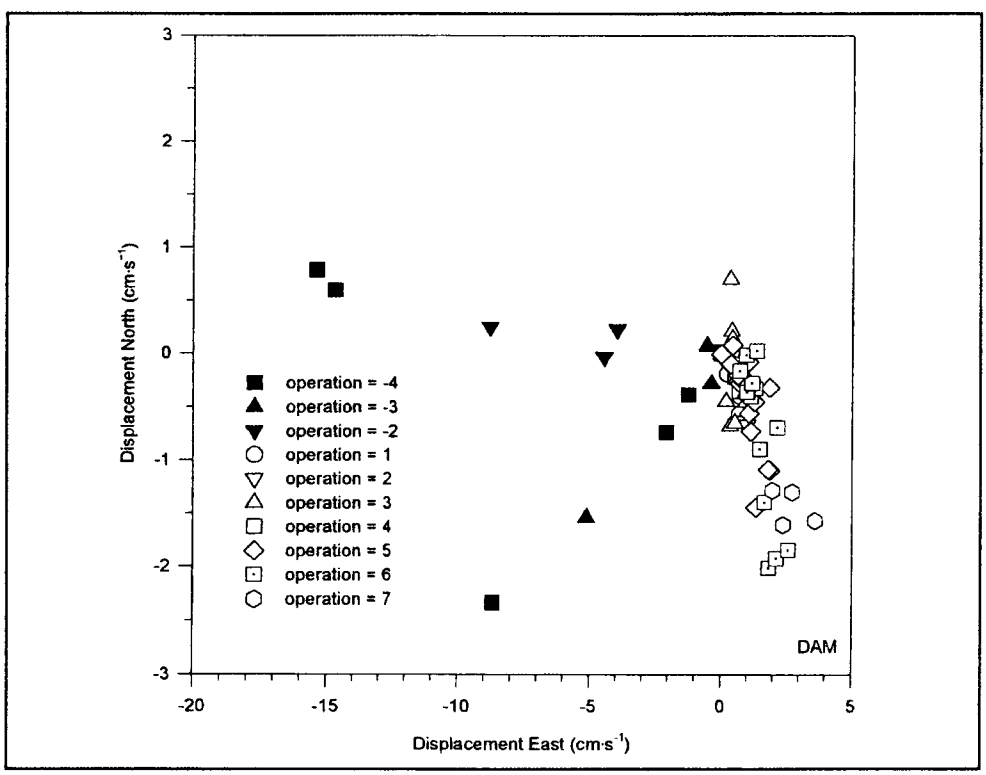


Figure 29. Richard B. Russell forebay flow vectors separated by dam operation levels measured 35 m above lake bottom

Plotting the column-averaged vectors (Figure 30) again demonstrates a net water movement towards the dam during conventional generation and a net movement away from the dam during pumped-storage operation. The velocity vectors at elevations of 25 and 35 m are of sufficient magnitude to overcome the recirculation at the lower elevations such that it is not seen in the column averages. Operation-averaged velocities plotted against depth (Figure 23) exhibited greatest velocities at elevations ranging from 20 to 30 m off the bottom during conventional generation and at 20 and 35 m off bottom during pumped storage. Water movement at 20 m off lake bottom was directed towards the dam during pumped storage, but those velocities represented about one-fifth of the velocities at the 35-m elevation. RBR forebay ADCP profiles (Figure 31) conducted during conventional generation with two units again demonstrated greatest velocities at 20 and 30 m off bottom during conventional generation. The spike apparent near the lake bottom resulted from the strong return signals emitted by the bottom and was not indicative of actual water velocities.[1]

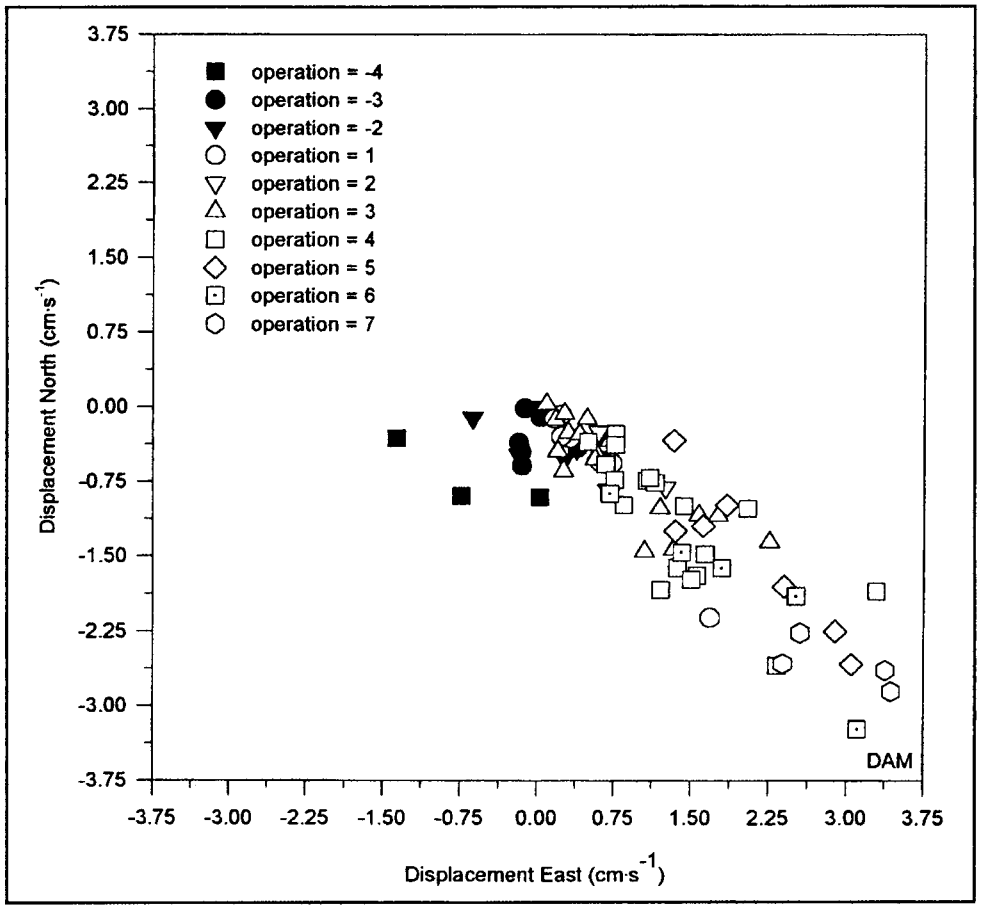


Figure 30. Richard B. Russell hourly mean water column velocity magnitudes separated by dam operation levels

[1] Personal Communication, December 18, 1996, Jon Knight, Limnologist, Duke Power Co., Huntersville, NC.

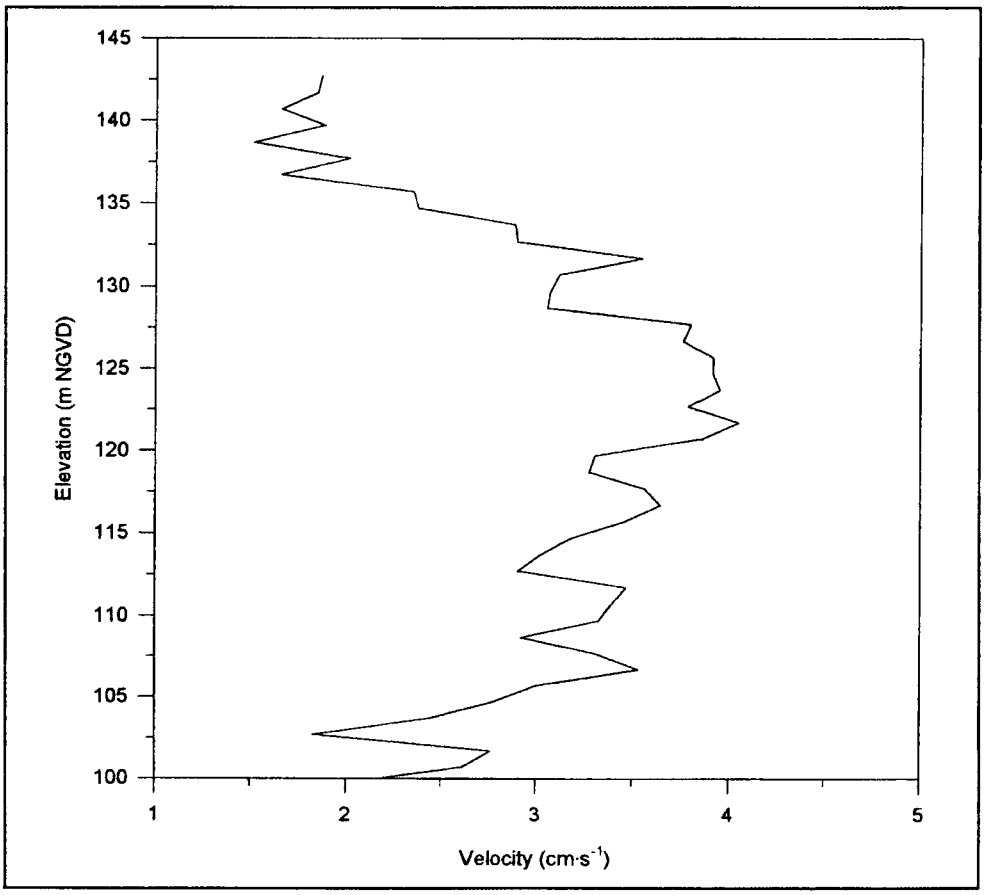


Figure 31. Averaged velocity profile from Richard B. Russell forebay collected via acoustic doppler current profiler (ADCP)

In situ profiles from RBR forebay demonstrated similar patterns with respect to DO manifested as a marked increase in DO concentrations for Station 100B between elevations of 10 and 20 m off the lake bottom (Figures 32 to 34). Profiles were taken prior to the inception of generation in each instance, but the residual plume of oxygen-rich water supported the assumption that these elevations exhibit a net movement of water downstream during conventional generation. There were no pumpback events prior to the in situ profiles, precluding conclusions about the potential short-term effects of pumped storage on the DO dynamics of RBR forebay.

The generation-affected elevations (15 to 25 m off lake bottom) lie within the withdrawal zone of RBR Dam as defined by the dimensions of the penstocks (10 to 33.2 m off lake bottom). This supports the assumption that RBR Dam is the major influence on water passage through the forebay. The velocity and temperature profiles also served to bound the vertical dimensions of the flow field. The presence of a strong thermocline at about 30 m off the bottom at Stations 112B, 100B, and 060B (located immediately upstream of RBR Dam) depicted in Figures 35 through 37 approximately corresponded to the top of the penstock openings. Dam withdrawal (and presumably dam-influenced water passage) would, therefore, be constrained to depths greater than 10 m.

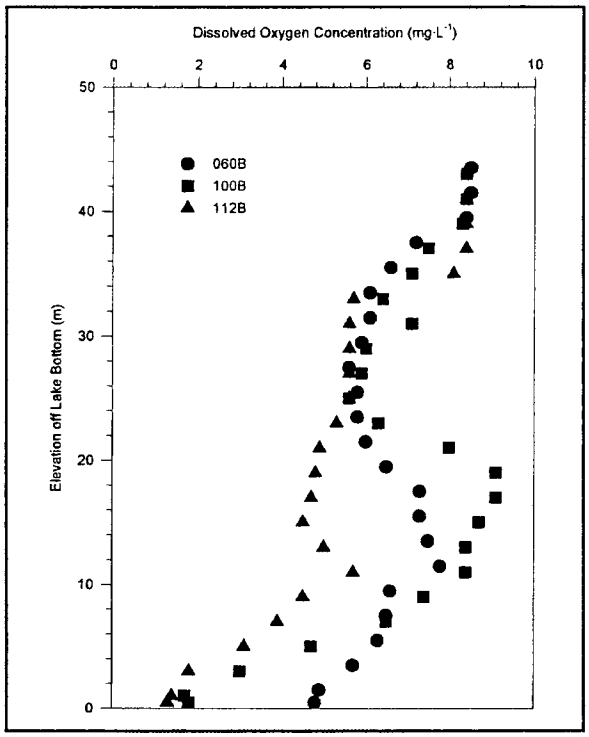


Figure 32. Richard B. Russell forebay dissolved oxygen profiles collected on 21 June 1995

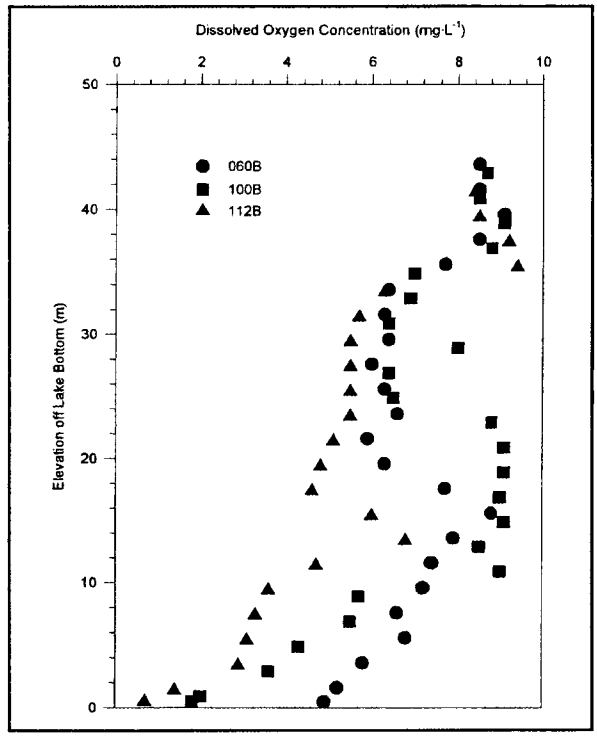


Figure 33. Richard B. Russell forebay dissolved oxygen profiles collected on 28 June 1995

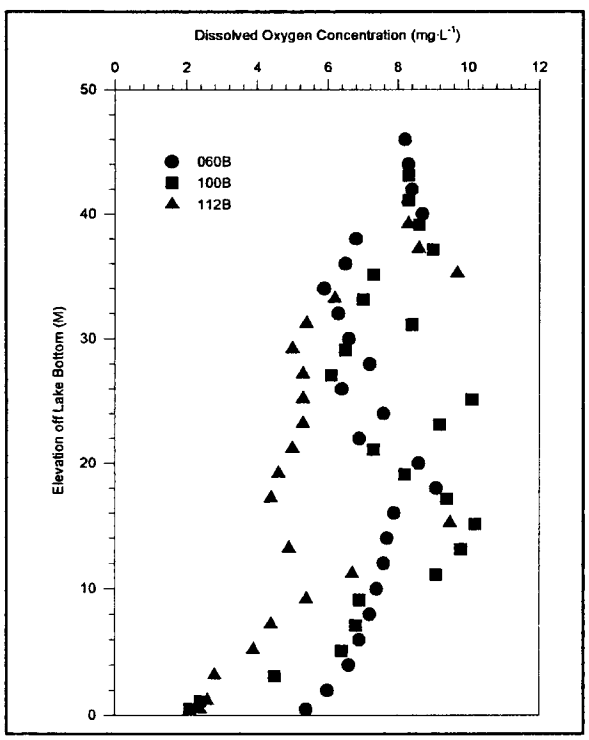


Figure 34. Richard B. Russell forebay dissolved oxygen profiles collected on 5 July 1995

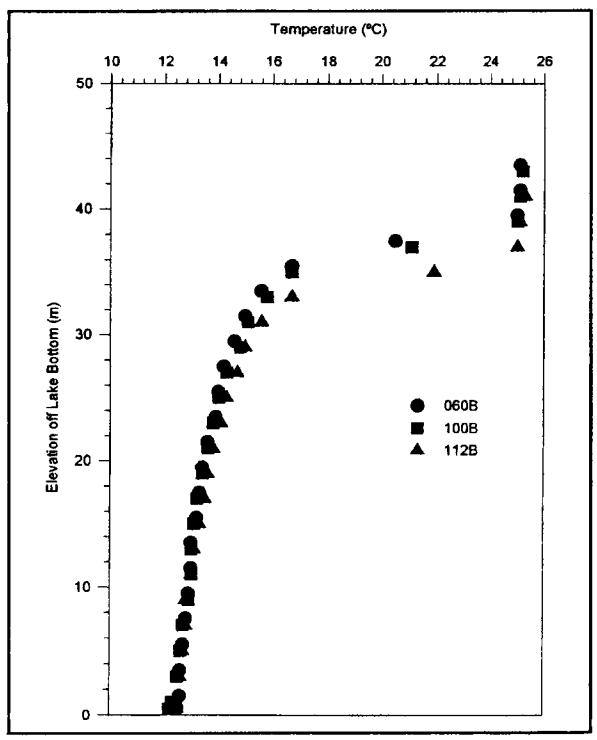


Figure 35. Richard B. Russell forebay temperature profiles collected on 21 June 1995

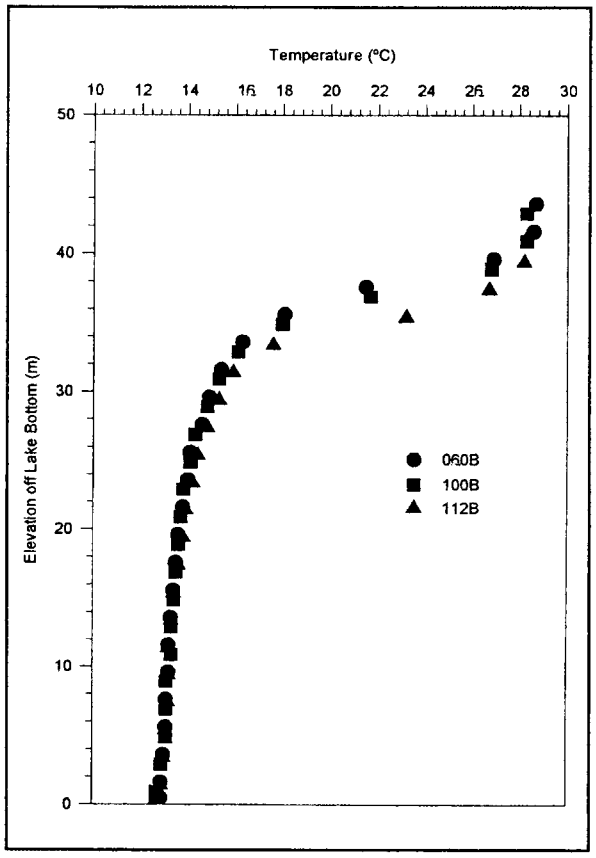


Figure 36. Richard B. Russell forebay temperature profiles collected on 28 June 1995

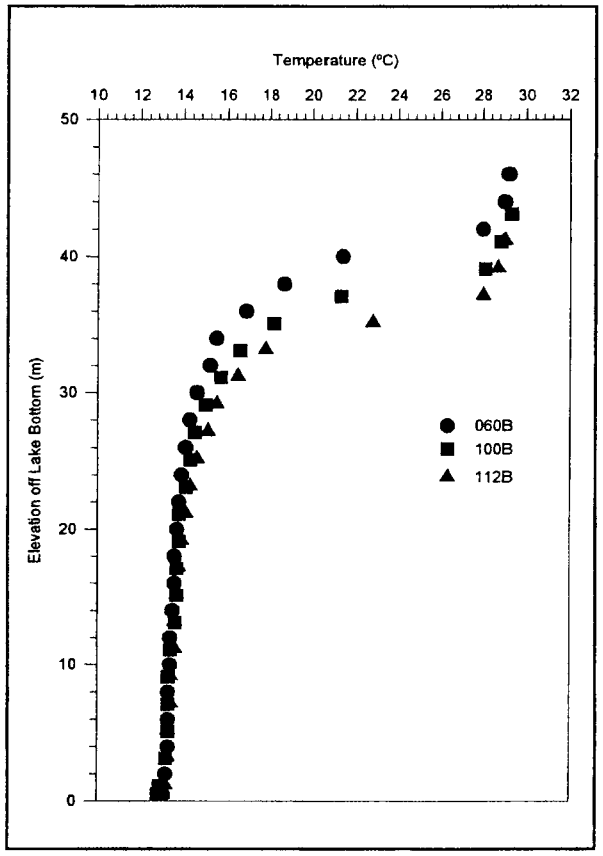


Figure 37. Richard B. Russell forebay temperature profiles collected on 5 July 1995

Water Quality

The primary benefit of automated data collection is that close-interval sampling often identifies short-term patterns that may be missed utilizing grab-sampling techniques. Dissolved oxygen concentrations measured at 35 m off the bottom via automated techniques are plotted versus time in Figure 38 with corresponding grab samples overlaid as symbols. Diel fluctuations are readily apparent in the automated data, but are not seen in the data collected by conventional grab sampling.

Temperature versus time for each depth are presented in Figure 39. The greatest fluctuation and difference between stations occurred at 30 m off bottom for both stations. This was not unexpected, as diel fluctuations dominated at this elevation, which was located above the thermocline and subject to earth warming phenomena. Temperatures recorded below the thermocline were much lower and exhibited little variation.

The differences in DO concentrations for Stations 112B and 100B (calculated as DO_{100B} - DO_{112B} with no lag factor) for each measured elevation versus time are presented in Figures 40 through 43. The greatest

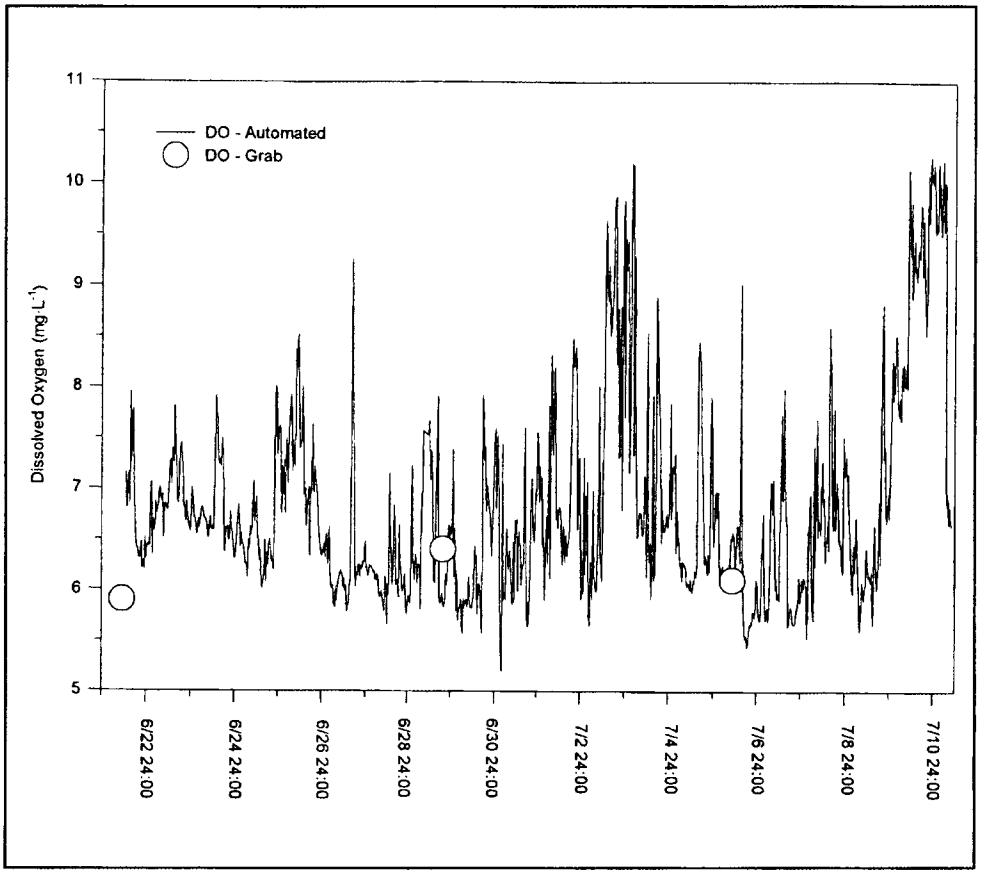


Figure 38. Overlay of dissolved oxygen concentrations measured via automated and grab sampling techniques at Richard B. Russell Station 100B between 21 June and 10 July 1995 (30 m off lake bottom)

differences between stations occurred at heights of 10 m (Figure 41) and 20 m (Figure 42) off the bottom. This most likely resulted from the higher flows for these depths due to RBR Dam operation. While water passage and oxygen injection influenced the measured differences at heights of 0.5 and 30 m off bottom, they were not the dominant influences. Both elevations lie outside of the withdrawal zone, and 0.5-m heights lie at or below the oxygen system's diffuser heads such that the introduction of supplemental oxygen had less of an effect. Depth sensors were not available for all instruments (one instrument had no depth sensor and one instrument's sensor malfunctioned), but examination of the available sensors demonstrated that elevations remained within 1-2 m of their assigned heights. Fluctuations of this magnitude could potentially affect comparisons of individual heights, but should not significantly influence column averages.

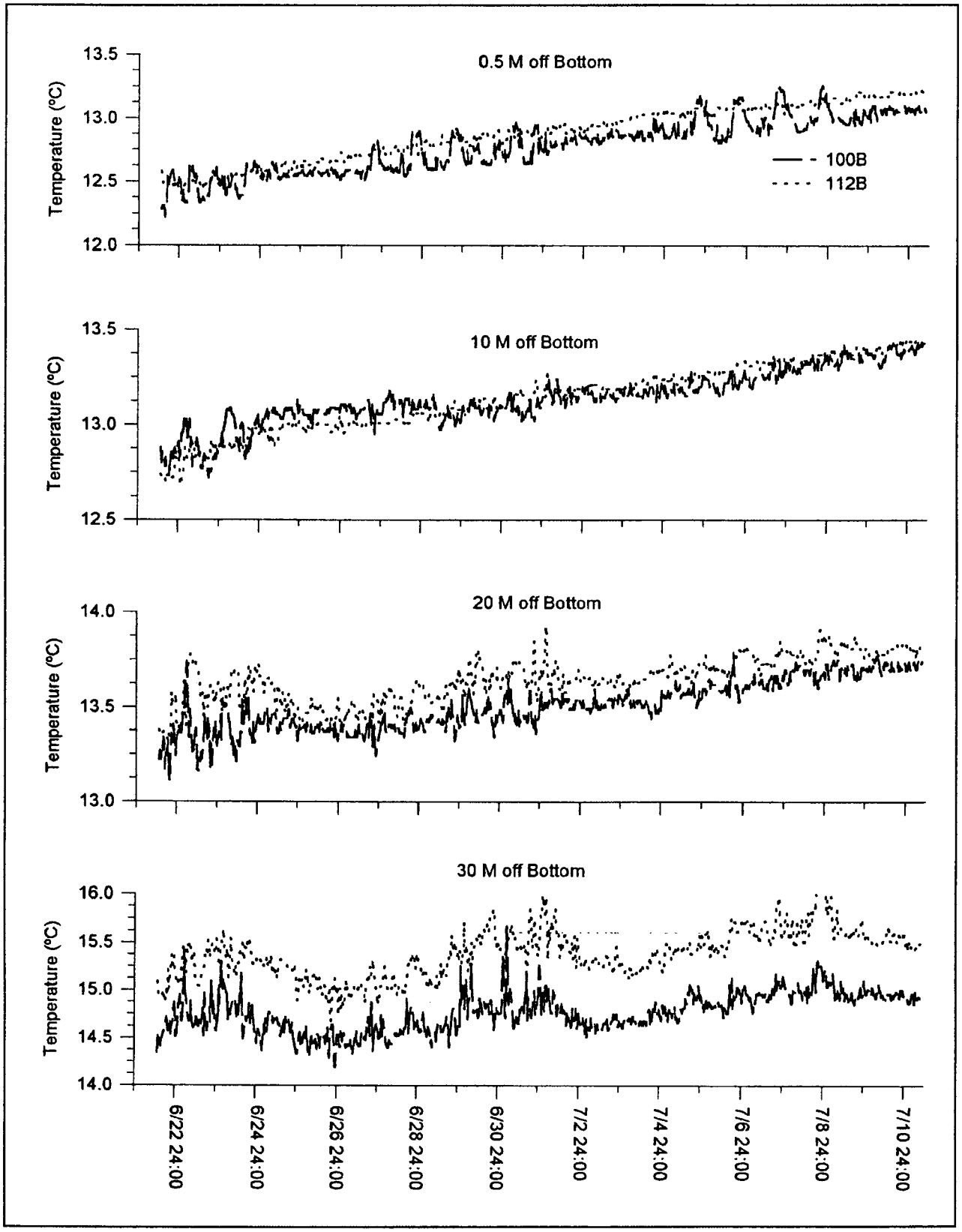


Figure 39. Temperature data for Richard B. Russell Stations 100B and 112B for period from 21 June to 10 July 1995

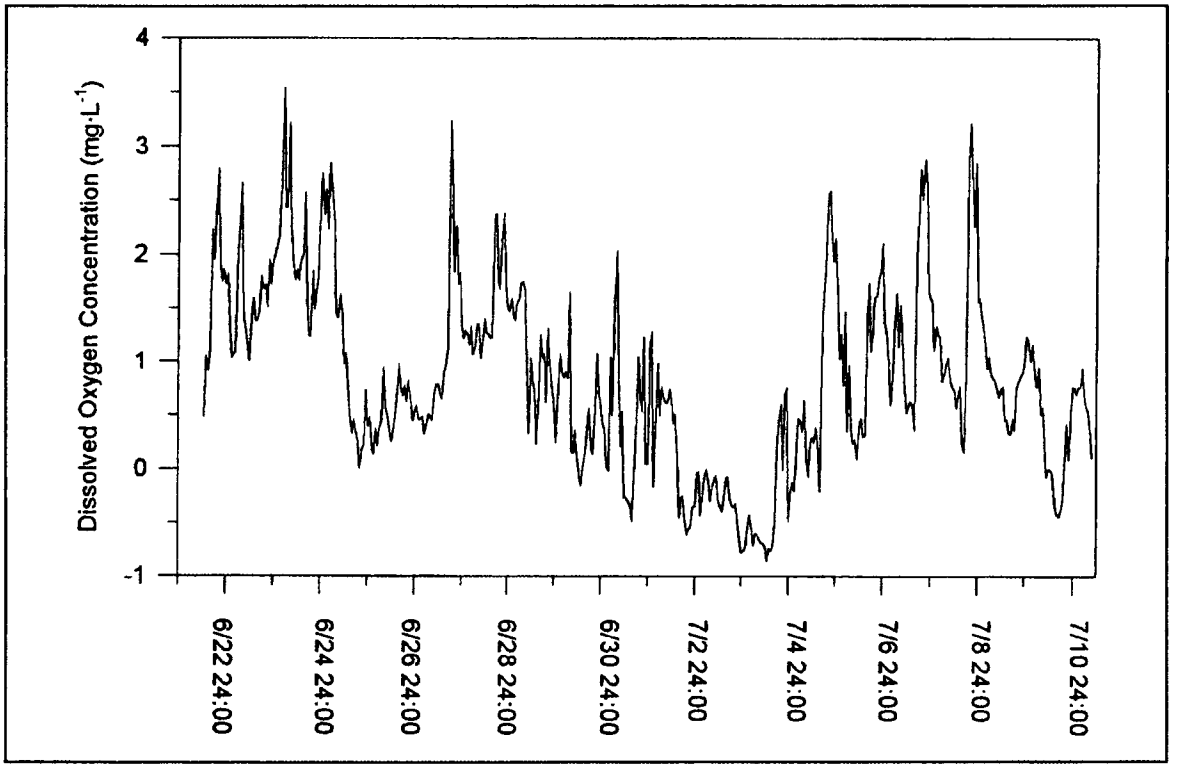


Figure 40. Difference in dissolved oxygen concentrations measured 0.5 m off lake bottom at Richard B. Russell Stations 100B and 112B between 21 June and 10 July 1995

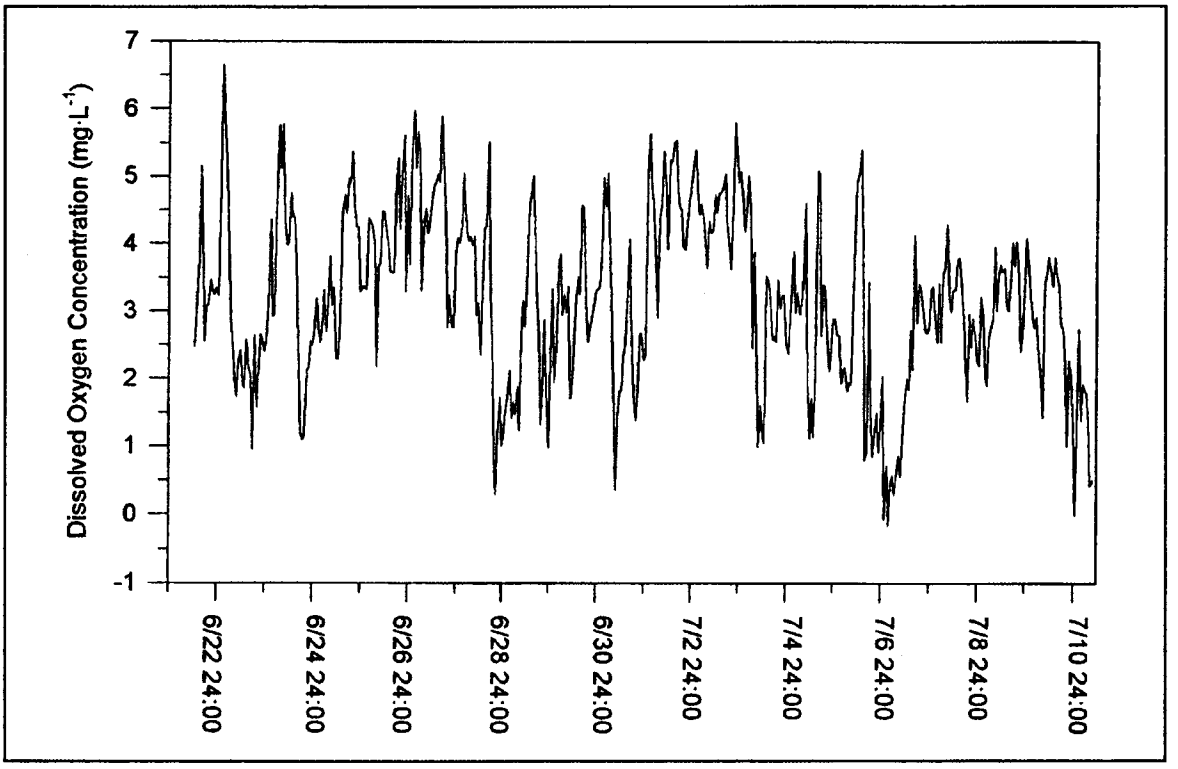


Figure 41. Difference in dissolved oxygen concentrations measured 10 m off lake bottom at Richard B. Russell Stations 100B and 112B between 21 June and 10 July 1995

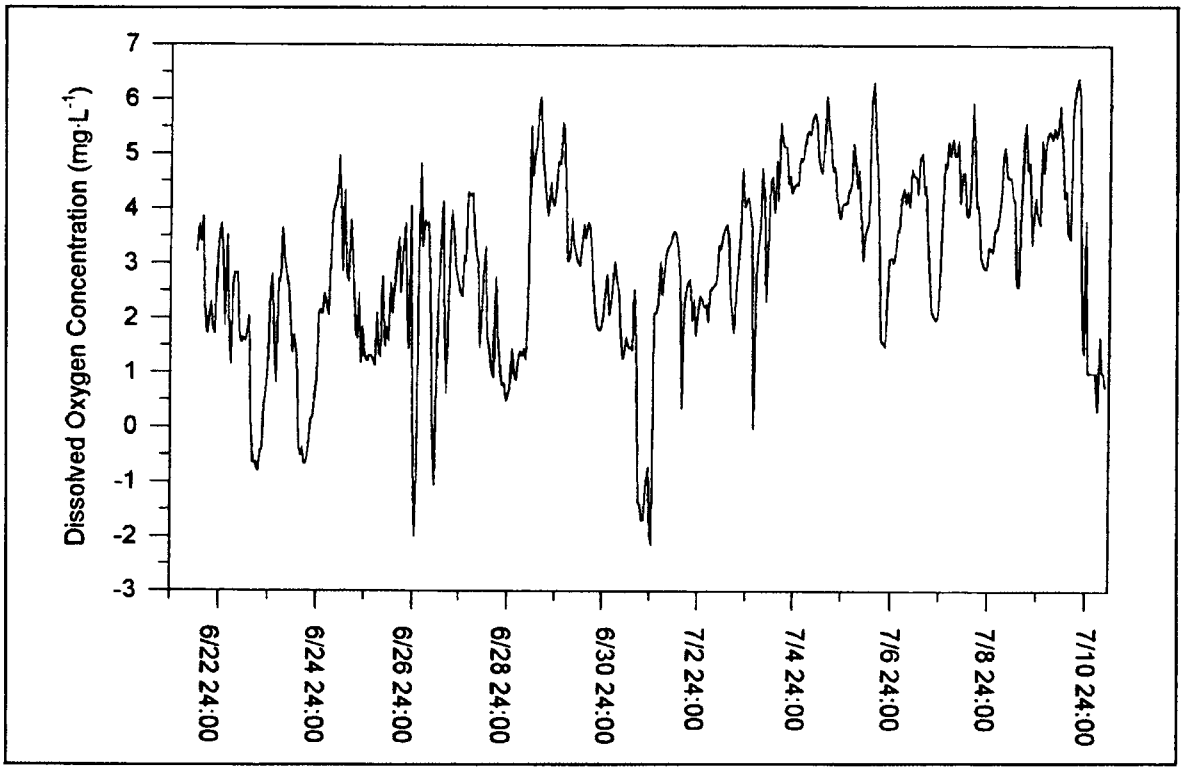


Figure 42. Difference in dissolved oxygen concentrations measured 20 m off lake bottom at Richard B. Russell Stations 100B and 112B between 21 June and 10 July 1995

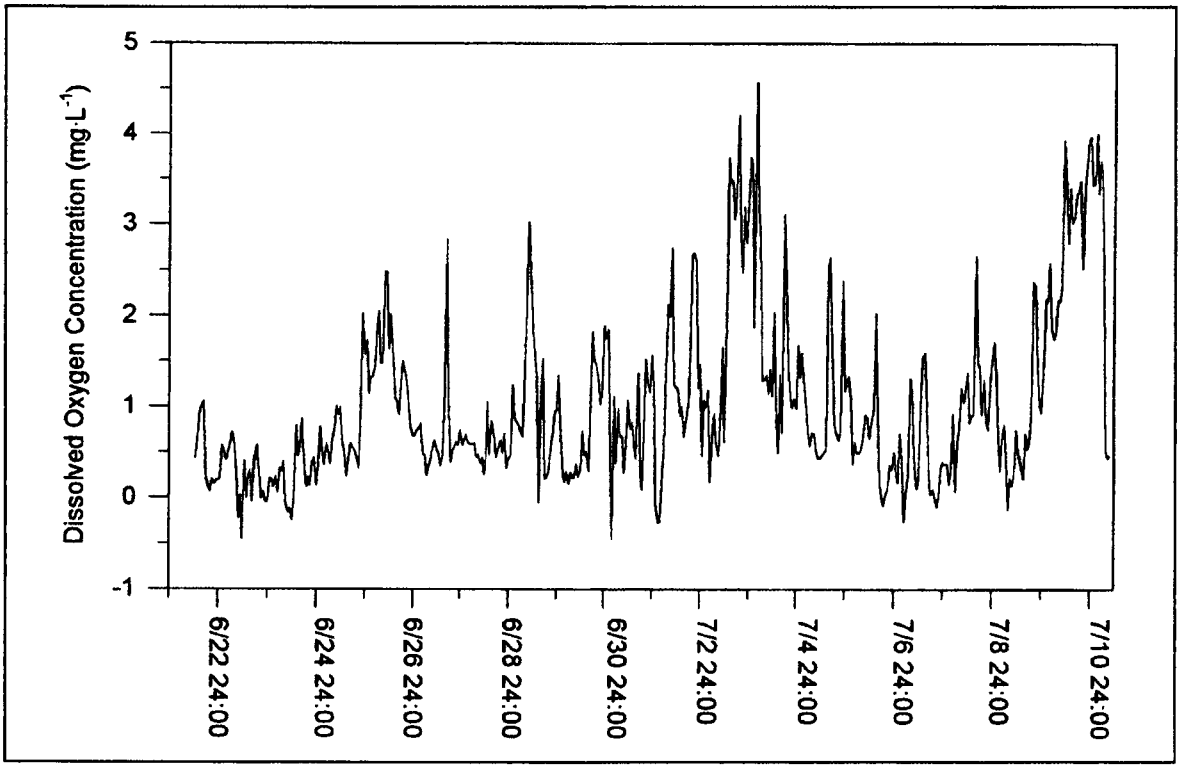


Figure 43. Difference in dissolved oxygen concentrations measured 30 m off lake bottom at Richard B. Russell Stations 100B and 112B between 21 June and 10 July 1995

Injection Efficiency

The efficiency for the period of the study was computed from all the data by determining the mean DO concentrations at 100B, 112B, and the O_2 system as

$$Efficiency = \frac{\overline{DO}_{out} - \overline{DO}_{in}}{\overline{DO}_{input}} \tag{8}$$

where

DO_{out} = mean hypolimnetic DO concentration for Station 100B, $mg \cdot L^{-1}$

DO_{in} = mean hypolimnetic DO concentration for Station 112B, $mg \cdot L^{-1}$

DO_{input} = mean oxygen injection per time interval, $mg \cdot L^{-1}$

Oxygen injection rates were converted to concentrations by utilizing the summary data from Table 2 expanded to encompass the entire study period as

$$O_{2injected}\left(kg \cdot s^{-1}\right) = \frac{\mu\, O_{2injected}\left(kg \cdot day^{-1}\right) \times total\ days}{86{,}400\ \text{sec}} \tag{9}$$

Thus, the average injection rate for the entire study period was calculated to be 0.3706 $kg \cdot s^{-1}$ or 10,083 total kg oxygen. The average flow for the study was determined to be 91.3 $m^3 \cdot s^{-1}$ following the same method. This allowed for calculation of the mean DO concentration added by the system as

$$\mu DO_{conc} = \frac{O_{2total}}{\mu Q} \tag{10}$$

where

μDO_{conc} = average DO concentration ($mg \cdot L^{-1}$) for O_2 system

O_{2total} = total oxygen input (mg) via O_2 system

Q_{total} = total water to pass O_2 system (L) for study period

or

$$4.06 mg \cdot L^{-1} = \frac{6.05 \times 10^{11} mg}{1.49 \times 10^{11} L} \tag{11}$$

The average efficiency for the study period could then be calculated as

$$Efficiency = \left(\frac{7.12\, mg \cdot L^{-1} - 4.88\, mg \cdot L^{-1}}{4.06\, mg \cdot L^{-1}} \right) \times 100\% = 55\% \tag{12}$$

Table 2
Averaged Values Used for Efficiency Calculations

	Mean
DO concentration at 100B	7.12 $mg \cdot L^{-1}$
DO concentration at 112B	4.88 $mg \cdot L^{-1}$
Oxygen injection rate	32,018 $kg \cdot day^{-1}$
RBR Dam discharge	91.3 $m^3 \cdot s^{-1}$

Computing injection efficiency in the preceding manner provided a rough estimate of the overall effectiveness of the system at increasing the DO concentration in RBR forebay; however, estimation in this fashion did not allow for identification of short-term trends and patterns. Determination of such trends required analyses of time-series data. To pair observations of DO concentrations at 112B, 100B, and the O_2 system, time-lagged data sets were needed. Figure 44 displays the lag times, expressed in hours, computed by the BASIC program via Equation 6 that allowed merging of the longitudinal water quality data sets and O_2 injection data.

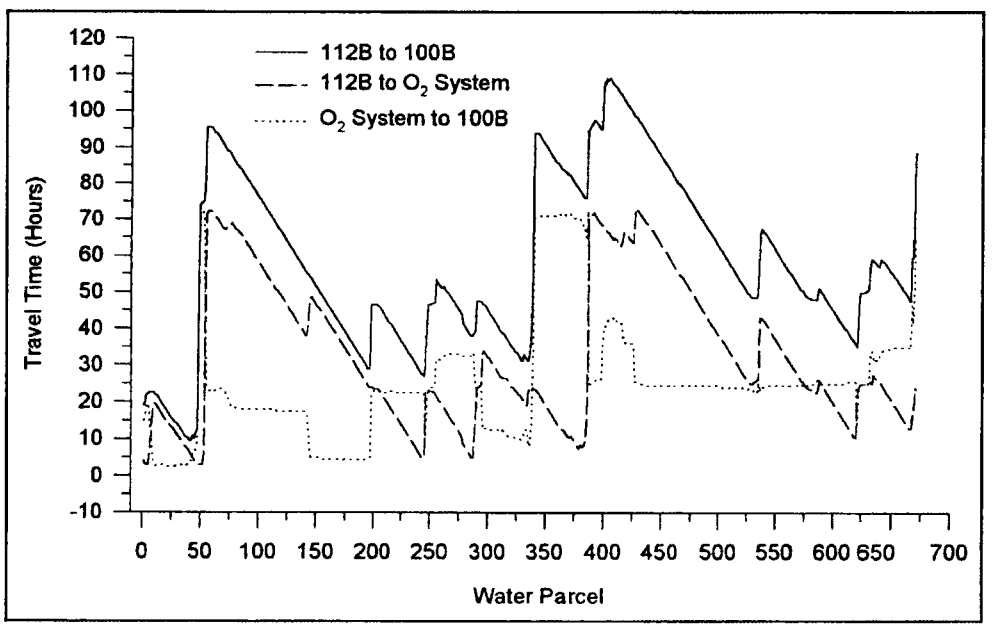


Figure 44. Travel times for water parcels from Station 112B (upstream) to oxygen injection system to Station 100B (downstream)

Efficiencies were computed as previously described for the lagged data set merged by the BASIC program (Appendix A). Figure 45 depicts efficiency data versus time for the period beginning 23 June and ending 11 July 1995. The time variable corresponds to the time of arrival for a water parcel at the downstream station (100B). Travel times ranged from a minimum of 9.5 hr to a maximum of 4.5 days to travel the 1,500 m between each station. The importance of this fact became apparent during attempts to identify trends with respect to efficiency and operations and will be expounded later.

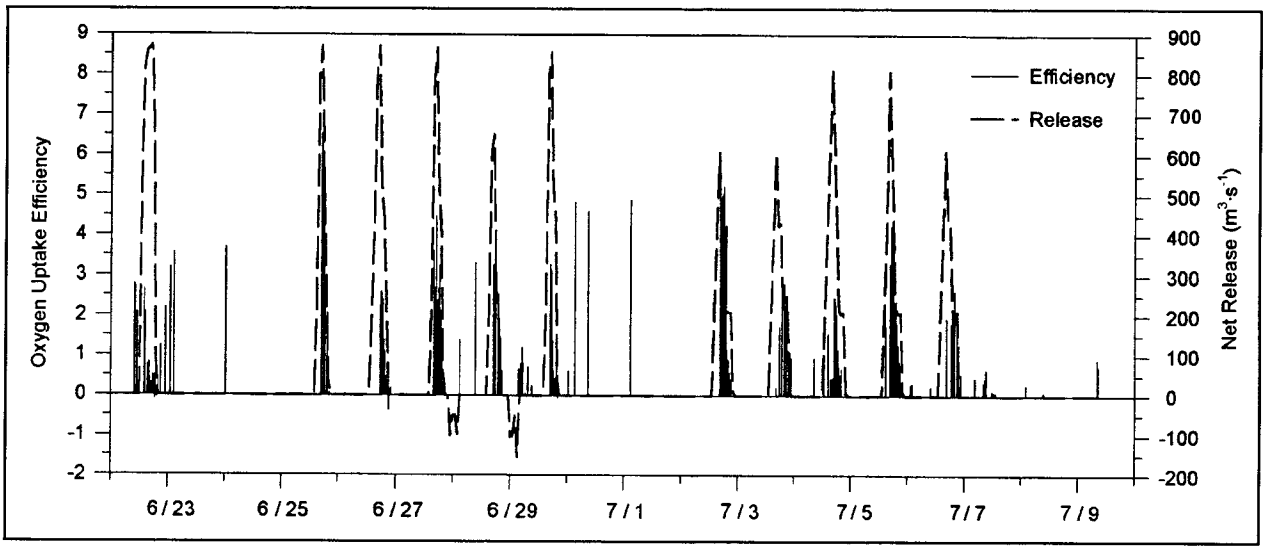


Figure 45. Oxygen uptake efficiencies and Richard B. Russell Dam operations for period from 23 June to July 1995 (Efficiency was calculated as $(DO_{100B} - DO_{112B})/DO_{injected}$. Pumped storage operation is represented as negative)

Column-averaged water velocities at Station 090B were correlated to RBR Dam operation with respect to conventional generation (Figure 21), but did not demonstrate a clear relationship with pumped-storage operation (Figure 22). The lack of correlation with pumped-storage operation was due to the fact that column-averaged velocities were based on hypolimnetic velocities (Figure 19), while pumped-storage-affected velocities were not observed at these depths (Figure 23).

No clear patterns were apparent from preliminary examinations of the efficiency data. Both RBR Dam operation and O_2 uptake efficiency demonstrated a noticeable relationship with the hour of day (Figure 46), but there were no strong correlations. While at first alarming, further scrutiny revealed that the lack of clear relationships should have been expected. Because travel times were often on the order of days, it was necessary to consider the time histories of the water parcels, i.e., RBR Dam operations and O_2 system activity for the times that the parcels were in transit between Stations 112B and 100B.

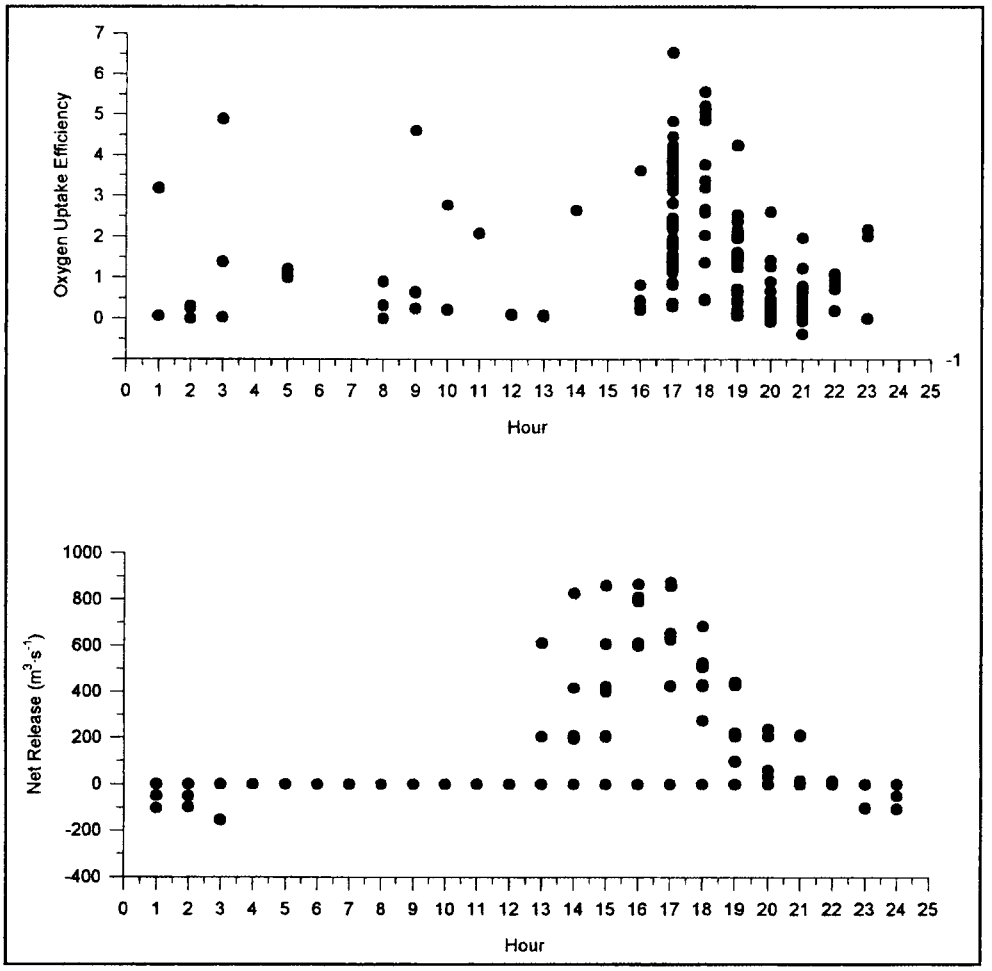


Figure 46. Oxygen uptake efficiency ($DO_{100B} - DO_{112B}/DO_{injected}$) and Richard B. Russell Dam operations (pumped storage represented as negative) plotted against hour of day for period from 23 June to 11 July 1995

To incorporate the time history of each water parcel as it traveled the 1,500 m between the upstream and downstream stations, it was necessary to rework much of the water quality data. This was due to the disproportionate lag times between Station 112B (upstream), the O_2 system, and Station 100B (downstream). Table 3 displays summary information for the travel times computed by the BASIC program during the merging of the separate data sets.

Table 3
Summary Statistics for Water Parcel Travel Times (Hours)

	112B to 100B	112B to O_2 System	O_2 System to 100B
Mean	58.41	33.20	25.22
Minimum	9.50	3.00	2.50
Maximum	109.00	73.00	72.50
Median	53.50	26.50	24.50
Standard Deviation	23.64	19.77	16.31

Because the travel times were not constant throughout each parcel's journey, it was typical to encounter "gaps" in the time series. For example, a water parcel may leave Station 112B and traverse the initial 750 m to the O_2 system quickly where it may slow down or stop. It may then travel slowly until it reached Station 100B where the O_2 uptake efficiency was calculated. This meant that efficiencies were not calculated continuously, but were computed upon the parcel's arrival at the downstream station. The resultant data set contained "gaps" coincident with long travel times followed by short travel times. Figure 44 depicts the travel times for each water parcel for each portion of the total distance between the upstream and downstream stations (1,500 m), highlighting the different travel times.

Operations data for RBR Dam and the injection data used for computing efficiency values were merged with the water quality data set. Conventional generation and pumped-storage records were included as a single variable (flow) by representing generation as positive and pumped storage as negative. The flow variable was lagged from the time of efficiency computation to 1 week prior to computation in 4-hr increments. Injection records exhibited little day-to-day variation and were, therefore, lagged in 24-hr increments from time of computation up to 1 week prior. Including the flow and injection data for the week preceding the efficiency computation revealed a linear relationship between the O_2 uptake efficiency and the lagged data, summarized in Table 4. While the relationship was not a strong one ($r^2 = 0.6893$), all included variables were significant at the $\alpha = 0.05$ level with respect to their contribution to the O_2 uptake efficiency.

It was important to consider travel times to properly merge the water quality and O_2 system data sets, but travel times were also important for understanding the effectiveness of the O_2 system in increasing the DO concentration for the downstream station (100B). The time of travel between the O_2 system and Station 100B provided some indication of the amount of time that the water parcel was exposed to the O_2 injection environment. Figure 47 displays DO concentrations for Station 100B plotted against the number of hours required to travel from the O_2 system to Station 100B (i.e., the length of exposure for the parcel). The resultant quadratic relationship ($r^2 = 0.6346$) indicated that longer exposures allow the water column to take up more oxygen, but that a maximum was reached after about 60 hr, probably due to the water column approaching saturation DO concentrations. Increased exposure (>60 hr) did not result in increased DO concentrations. Because downstream water movement was related to dam operation (Figure 21), this trend supported the hypothesis that nonoperation over weekends should lead to increased DO in the hypolimnion (storage). Since weekend, nonoperational periods did not typically exceed 48 hr, the maximum was not reached, and O_2 uptake was possible throughout the entire nonoperation period.

Table 4
Variables in Oxygen Uptake Efficiency Regression Model

Variable	Hours Lagged	Coefficient
RBR Net Flow	0	0.002408
RBR Net Flow	4	-6.07212×10^{-4}
RBR Net Flow	16	-7.52693×10^{-4}
RBR Net Flow	32	-8.24490×10^{-4}
RBR Net Flow	36	0.001272
RBR Net Flow	44	0.001102
RBR Net Flow	76	-6.22921×10^{-4}
RBR Net Flow	84	5.83217×10^{-4}
RBR Net Flow	92	0.001008
RBR Net Flow	96	7.71465×10^{-4}
RBR Net Flow	100	0.001304
RBR Net Flow	104	-8.80566×10^{-4}
RBR Net Flow	108	−0.001093
RBR Net Flow	116	8.41041×10^{-4}
RBR Net Flow	124	−0.001169
RBR Net Flow	136	9.24958×10^{-4}
RBR Net Flow	156	5.17401×10^{-4}
O_2 Injection ($kg \cdot hr^{-1}$)	24	0.023150
O_2 Injection ($kg \cdot hr^{-1}$)	48	−0.016247
O_2 Injection ($kg \cdot hr^{-1}$)	72	0.042798
O_2 Injection ($kg \cdot hr^{-1}$)	96	−0.045240
O_2 Injection ($kg \cdot hr^{-1}$)	120	0.016713
O_2 Injection ($kg \cdot hr^{-1}$)	144	0.009597
O_2 Injection ($kg \cdot hr^{-1}$)	168	0.013648
Constant		−29.858066

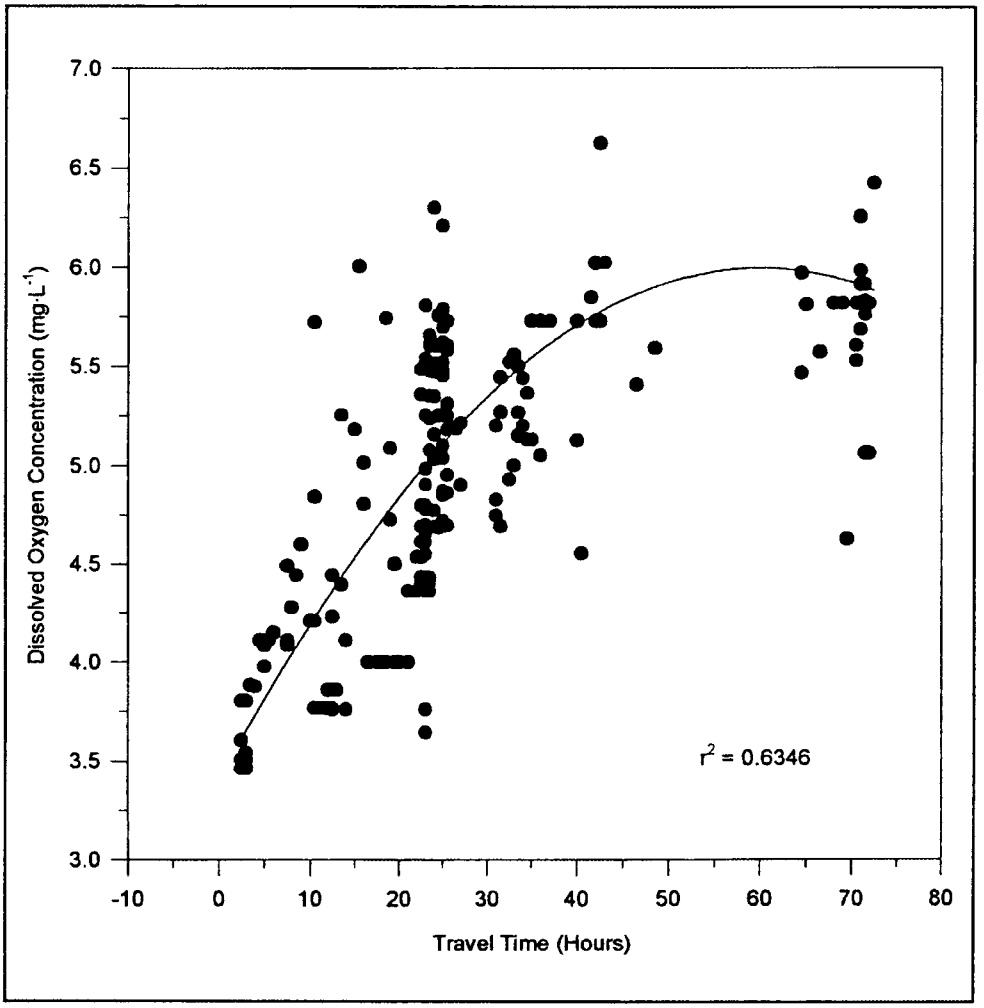


Figure 47. Richard B. Russell Station 100B dissolved oxygen concentrations plotted against time of travel from oxygen injection system to 100B

The data gaps described earlier precluded the time series analyses necessary to identify the trends that were sought for testing the hypothesis that O_2 uptake efficiency depended on operation by RBR Dam. Such analyses required that the data occur at regular, evenly spaced intervals. Linear interpolations were performed to replace "missing" values with reasonable DO concentrations. Interpolation in this fashion was appropriate since the gaps typically occurred when a water parcel stopped moving prior to reaching Station 100B (downstream). A water parcel could only stop during periods of no velocity, making it logical to assume that the DO concentration at a particular point would remain constant except for the biological and chemical processes occurring within the system. These processes would influence both the parcels in transit as well as the stationary ones. Following linear interpolations, data were exponentially smoothed to facilitate spectral analyses.

Spectral analysis for the efficiency data revealed a spike at about 48 hr and a peak at about 168 hr (Figure 48). The 2-day cycle probably resulted from the operationally related cycling of DO concentrations depicted in Figure 47. Furthermore, the importance of weekends in the cycling of O_2 efficiency could explain the 2-day spike and the 1-week peak. The 18 days of data collected during the study were likely insufficient to identify a strong spike indicative of a weekly cycle. More data, collected over a period of weeks, should sharpen this spike and better identify this trend.

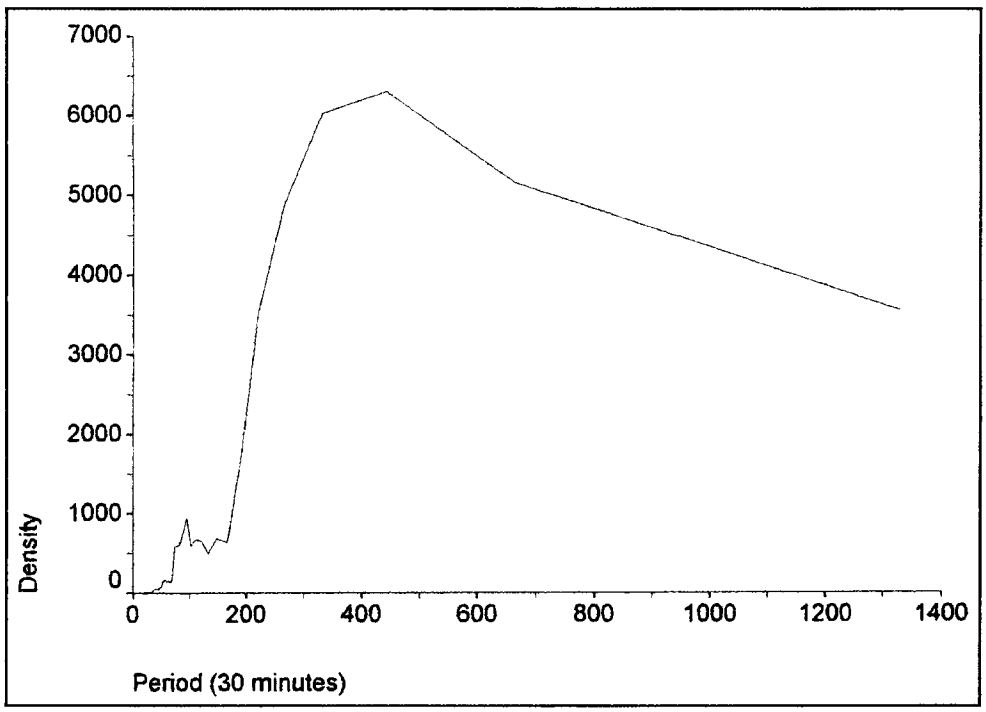


Figure 48. Spectral density plot of oxygen uptake efficiency

Figure 49 consists of DO concentrations for Stations 112B, 100B, and the injection system plotted against time for 23 June to 11 July 1995. Data were exponentially smoothed as previously described; nonetheless, they contain substantial amounts of noise that likely resulted from biological and chemical processes occurring within RBR forebay. Another trend seen was the regular increase in DO concentrations recorded at Station 112B that roughly coincided with an increase in DO concentrations at Station 100B. This coincident increase implied that Station 112B was not entirely removed from the influence of the O_2 system.

The two distinct peaks in O_2 uptake efficiency seen in Figure 50 approximately corresponded to weekends when there was typically no operation by RBR Dam. Interpretation of these peaks was difficult owing to the incorporation of the time histories of the water parcels. It was virtually impossible to confidently associate the measured oxygen concentrations and subsequent efficiency computations with the time of week they occurred. The peaks in efficiency corresponded to the two weekends during the study; however, the time axis represents the time when the

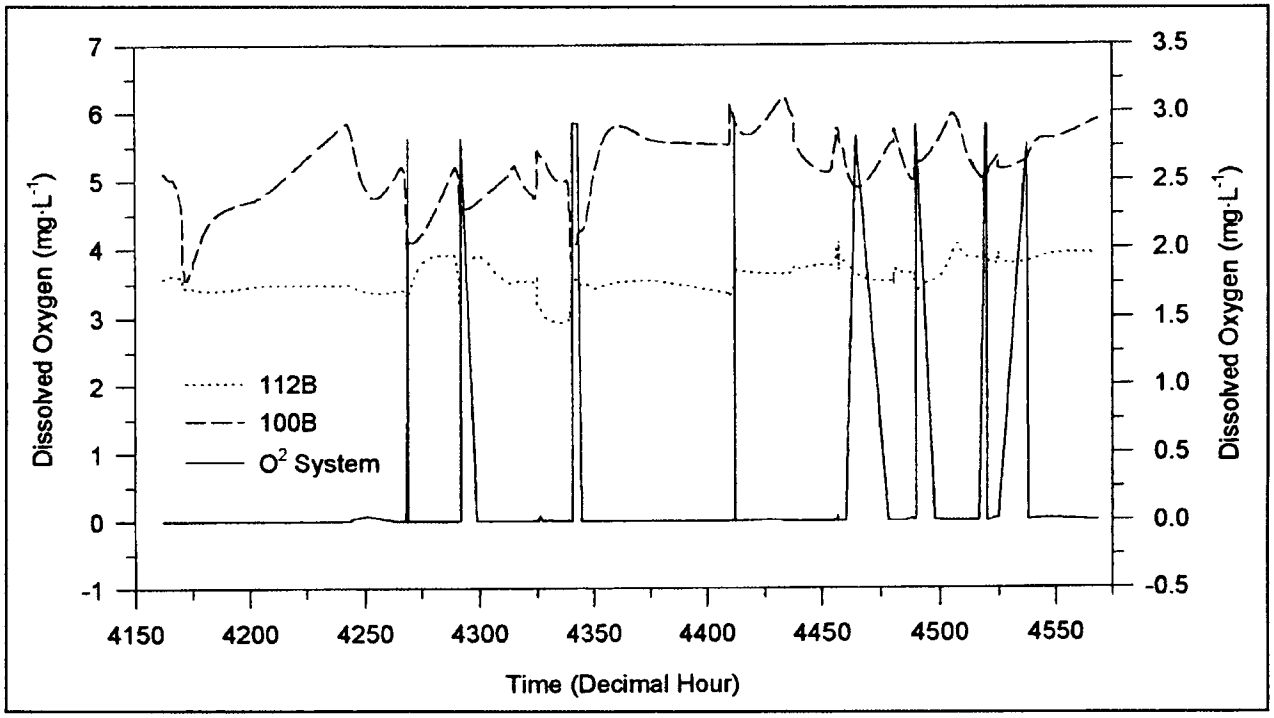


Figure 49. Dissolved oxygen concentrations for Stations 100B, 112B, and oxygen injection system for period from 23 June to 10 July 1995 (Dissolved oxygen concentrations for injection system are displayed on right axis)

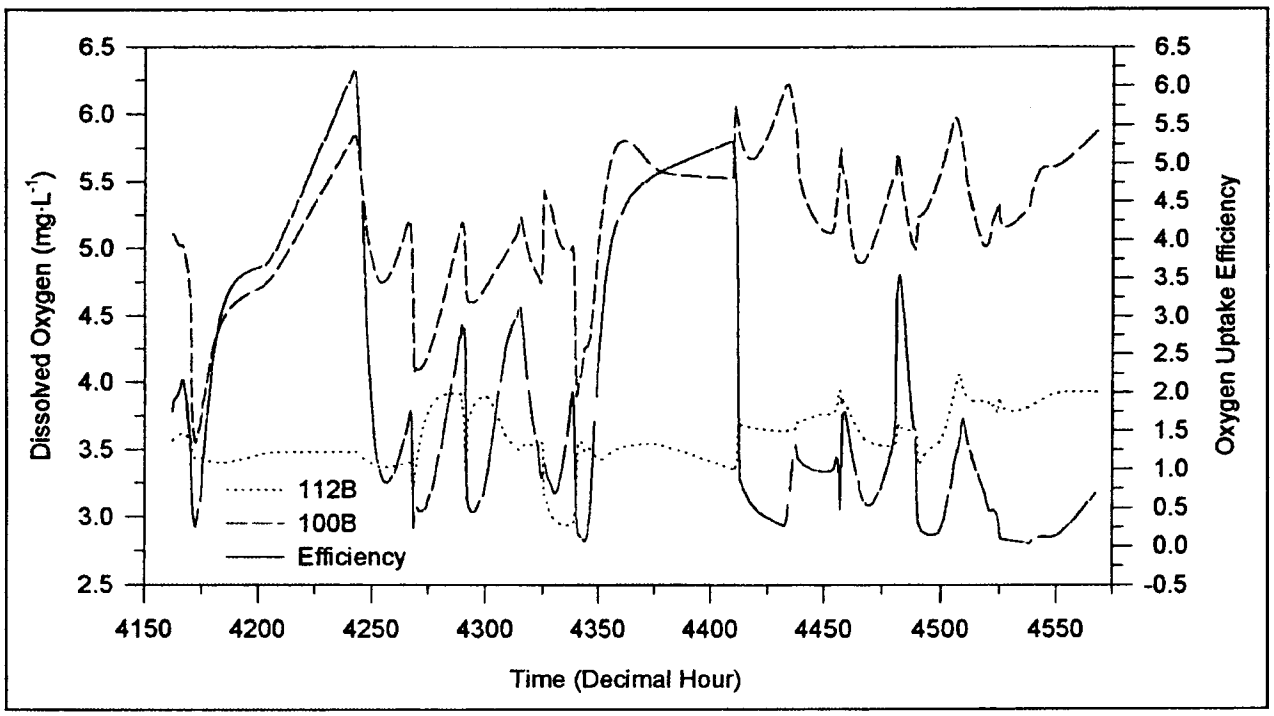


Figure 50. Hourly averaged 100B and 112B dissolved oxygen concentrations and oxygen uptake efficiencies for period from 23 June to 10 July 1995

efficiencies were actually measured. The time of occurrence, therefore, most likely corresponded to some time during the previous week. Because flow data were necessarily lagged by up to 6.5 days to reveal relationships with efficiency (Table 4), it is logical to assume that the plot depicted in Figure 50 would need to be shifted by up to 6.5 days to identify the events leading up to the calculated efficiency.

As was previously mentioned, Station 112B was not entirely isolated from the O_2 system's influence. Complete isolation would have been characterized by a flat line for measured DO concentrations. Because 112B hypolimnetic DO concentrations exhibit periodic increases (Figure 49), the O_2 system was influencing the oxygen levels at the upstream station. During periods when RBR Dam was not releasing water, the O_2 plume arising from the diffusers billowed to encompass more of the upstream region into its area of influence. During routine generation cycles by RBR Dam, the O_2 plume was pulled downstream such that its influence on the upstream station (112B) was minimal. Sustained increases in 112B DO concentrations (greater than 24 hr) were representative of weekends, while increases of lesser duration represented daily dam operational cycling characterized by approximately 6 hr of operation followed by up to 18 hr of no operation.

When travel times were considered, it was reasonable to infer that incidences of greatest efficiency actually coincided with Fridays. Increasing efficiencies during the week implied that as the storage of O_2 that was built up over the weekend was released during routine operation, the greater O_2 deficit that was created allowed O_2 to be taken up more easily and, therefore, more efficiently. This supported the hypotheses that O_2 was stored during long periods of nonoperation (weekends) and that as the disparity between the 112B and 100B DO concentrations increased, O_2 was absorbed more easily; thus the system was more efficient.

5 Conclusions

Based on this study, utilization of H. T. Odum's upstream/downstream approach to measure the efficiency of the RBR O_2 injection system was possible. Transferring the methods that were successful in a small and turbulent stream to a large reservoir, however, required extensive design modification. This study would not have been possible without the availability of multiple data-collection instruments capable of logging data over long periods. In fact, more instruments were necessary to adequately represent the area of concern. To maximize the application of the methods described in this report, preliminary planning should include a cost-benefit analysis to determine if the approach is warranted. The upstream/downstream approach, as described in this report, would obviously prove cost prohibitive in many instances. Because the cost of supplementing the RBR forebay hypolimnetic O_2 mass with liquid oxygen can cost upwards of $10,000 per day, any benefit that could be gained through a better understanding of the workings of the system would justify the expense of this approach.

This study sought evidence for three main ideas. First, oxygen is stored in the forebay during periods when RBR Dam was not operating. This oxygen storage was then released during subsequent hydropower generation. At RBR Dam, the periods characterized by the longest sustained nonoperation cycles were weekends. While it was difficult to confidently associate efficiency computations with the appropriate time period due to the complexity of merging the lagged data sets, it was possible to identify trends that may be attributable to operational patterns. Noticeable increases in DO concentrations were periodically observed at both the upstream and downstream stations. These increases persisted for approximately 2 days and implied that the upstream station was influenced by oxygen injection. Although this was an undesirable realization with respect to other assumptions inherent to this approach, it supported the idea of O_2 storage over weekends. Oxygen levels increased over weekend periods at both stations as the oxygen plume expanded.

The relationship between the DO concentration at the downstream station (100B) and the time of exposure to the O_2 system also supported the idea that oxygen accumulated during weekends. Since water movement, which was dependent on RBR Dam operation, controlled the length of

exposure for individual water parcels, exposure times were greatest over weekends. The relationship was quadratic, indicating that it was linear until a threshold was reached. At this point, increased exposure time did not result in increased DO concentrations. This was probably due to the ability of water to contain dissolved gasses. As DO concentrations approached saturation levels, oxygen was less readily absorbed.

Since efficiencies depended on the difference between the upstream and downstream DO concentrations divided by the amount of oxygen input by the injection system, efficiencies could be high if the difference between the stations was great (i.e., station DO_{100B} concentrations were much larger than DO_{112B} concentrations) or the injection rate by the system was low. Injection rates were fairly consistent throughout the study period so that higher efficiency levels would result from greater differences in the DO concentrations of the two stations. From this it was inferred that O_2 uptake efficiency would be greatest towards the end of the week when hypolimnetic oxygen stored during the preceding weekend had been depleted, assuming that storage was occurring. This trend was supported by the data.

Storage of oxygen over weekends could be used as a management tool by maximizing the efficiency of injection over weekend periods. Such utilization of O_2 uptake efficiency would require that injection rates be coordinated with the time of exposure to take full advantage of the steep slope of the DO_{100B} versus exposure time curve. High injection rates subsequent to the achievement of the saturation oxygen concentration would likely result in increased loss of oxygen to the atmosphere as bubbles.

A second idea tested by this study was that the distributions and dynamics of DO concentrations in RBR forebay depended on RBR Dam operations. The relationship between O_2 uptake efficiency and lagged RBR Dam flow data supported this idea. To predict the efficiency, it was necessary to include flow data from the time of the efficiency calculation to more than 6 days prior and injection data for the previous week. This relationship demonstrated the importance of dam operation on O_2 uptake efficiency, but also highlighted the importance of the water parcel's time history to these computations. The coefficients for the flows lagged by 100 hr were about half as large as those at the time of the efficiency computation indicating that those operations were important for determining the O_2 uptake efficiency. This demonstrated that operations were important to efficiency, but more importantly, the effects of operation on O_2 dynamics were not seen for nearly 1 week. Modifications to injection rates, therefore, may not be realized for up to 1 week.

A third idea tested by this study was that grab sampling would have proven insufficient for identification of the trends and relationships described in this report. Without a continuous data set with measurements at regularly spaced intervals such as this one, it would have been difficult (if not impossible) to develop the relationships presented in this report. The relative weaknesses of many of the regression analyses probably

resulted from the high degree of variation in the data. Point measurements would not have allowed the degree of data smoothing needed for meaningful analyses. The inferences with respect to the RBR forebay flow patterns would not be possible via conventional grab-sampling techniques. Continuous sampling allowed for the integration of velocity data over a period of days that represented the myriad operational scenarios employed by RBR Dam.

Another important factor of automated data collection was that simultaneous water quality and velocity measurements were recorded every 15 min at three stations at multiple depths for 18 days. This level of data density would not have been possible except through automated sampling techniques and allowed for more accurate interpretations and interpolations between data sets. It was therefore possible to volume-weight water quality measurements prior to averaging, determine the major elevations contributing to the flows through RBR forebay, and depict a two-dimensional view of water movement within the forebay representing the vertical and temporal dynamics. Single-point measurements do not yield sufficient data for such comprehensive representations.

Day-to-day operational impacts on oxygen uptake efficiency were less important than weekly cycles of dam operation. That is, daily cycles were important in that they contributed to the time history of individual water parcels and were therefore components of the weekly cycles. Time lagging used to merge the various data sets also depended on the daily operational cycling of dam operations. The duration of this study (about 18 days) was too short to draw strong conclusions with respect to cycles that are thought to occur on a weekly interval. Deployments over longer periods may strengthen conclusions for these relationships. Additionally, more data may allow better data smoothing, thus reducing the degree of variation encountered.

Influences attributed to pumped-storage operation were not revealed during the course of this study. This likely resulted from the fact that there were only three pumpback events during the study period, representing approximately 5 percent of the total flow. The major pumpback influences on water velocity were realized in the epilimnion of the water column. Because this study focused on the hypolimnion, it is reasonable to assume that pumped storage would not directly impact oxygen uptake efficiency. The COE has predicted that prolonged pumped-storage operation should decrease the size of the hypolimnion by displacing those waters with epilimnetic waters from J. S. Thurmond reservoir located downstream (Hains et al., in preparation). Assuming that this occurs, it is possible that prolonged pumped-storage operation will indirectly impact the operation of the O_2 system in that less injected oxygen will be needed to attain the release minimum DO concentration of 6.0 $mg \cdot L^{-1}$ as a result of the reduced volume of water. Also, withdrawal of oxygen-rich surface waters during conventional generation (assuming that pushing the epilimnion deeper will lead to intrusion of the epilimnion into the withdrawal zone) should reduce the O_2 uptake efficiency because of the same

principles used to support the storage hypothesis. Additional research in the presence of sustained pumped-storage operation will be necessary to draw conclusions about the potential effects of pumpback on O_2 uptake efficiency.

Collection of sufficient data to describe weekly trends will require further research over a longer time period. Ideally, data collection would be conducted over several weeks or months. If possible, future data collection should cover different periods within the O_2 injection season. Biological and chemical constituents that act to deplete oxygen concentrations in an oxygen-free environment (e.g., sulfur bacteria) should react differently in an oxygenated environment. It is possible for efficiency computations to test this hypothesis by tracking efficiency as the season progresses. Decreasing efficiency over time indicates that oxygen is not being absorbed by the water column as a result of a decreased oxygen deficit. That is, if the hypolimnetic DO concentration is close to the saturation concentration for that temperature and salinity, the water would tend to absorb oxygen less quickly than if DO concentrations were closer to zero.

Future studies should concentrate on accurately identifying the dimensions of the flow field under varying operational scenarios. This would entail water velocity information to supplement coincident water quality data collection. Data collected via acoustic doppler profilers would be well suited for measuring vertical and lateral variation in water movement. Collection should be timed so that all operation levels are sampled to allow for more accurate extrapolations using the fixed-point velocity meters.

Future studies should also include improved resolution with respect to lateral DO concentration gradients. Deployment of additional lateral stations, both upstream and downstream of the study focus, would allow more confident data analysis and representativeness. If, as was the case with the study documented in this report, there were insufficient instruments for both lateral and vertical deployments, it would be advisable to sacrifice vertical resolution to allow increased lateral resolution.

The upstream/downstream method has potential value for those attempting to quantify longitudinally varying processes within rivers and reservoirs. By treating the study area as a "black box," inferences about the system may be formulated without measuring all perceived variables. Although the black box approach tends to oversimplify the individual processes interacting to control an ecosystem, it does allow for modeling the system without consideration of all variables. This is an important point in that it is impossible to consider and measure all contributing variables in all but the simplest systems. Modeling via the upstream/downstream (or the black box) approach leads to better understanding of the measured parameters as well as highlights potential shortcomings in the understanding of the system. For example, data collected for the study described in this report demonstrated the need for greater understanding

of water movement through RBR forebay and the importance of said movement on the operation of the O_2 injection system. Data collected over a period of weeks also stressed the importance of weekly cycling and the time history of the system. The prevailing idea had been that cycling would be correlated to RBR Dam operation on a scale of hours, but the data demonstrated that the time history of the water was of greater influence to the cycling. The perceived relationships did occur, but did so along different time scales than were expected.

Another significant element to be taken from this study was the importance of water movement to the efficiency measurements. Regression modeling of the system indicated that water movement was almost as important as the actual injection of liquid O_2 by the system. Continuing the analogy presented earlier in this work that the O_2 system could be viewed as an algal community, this point stresses the influence of the physical on the biological in moving water ecosystems. Based on the results of this study, water movement was the factor driving the efficiency of the RBR O_2 injection system. This was supported by both the regression analyses for efficiency and for the exposure times of a water parcel to the system. Attempts to model biological systems should resist the temptation to remove them from their physical environments. Without an understanding of the physical system, it is impossible to explain cycling by the biological constituents. The interactions that have evolved in a "natural" system are necessarily complex to ensure mutability. However, inferences about these systems may be drawn from methods such as those documented herein without quantifying all of the contributing variables or lessening their importance.

References

American Public Health Association. (1992). *Standard method for the analysis of water and wastewater*. 18th ed., American Public Health Association, Washington, DC.

Aquatic Systems Engineering. (1990). *Assessment and guide for meeting dissolved oxygen water quality standards for hydroelectric plant discharges*. Aquatic Systems Engineering, Wellsboro.

Ashby, S. L., Kennedy, R. H., Carroll, J. H., and Hains, J. J. (1994). "Water quality: Richard B. Russell and J. Strom Thurmond lakes; Summary report," Miscellaneous Paper EL-94-6, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Bouk, G. R. (1980). "Etiology of gas bubble disease," *Trans. Amer. Fish. Soc.* 109,703-703.

Cole, G. A. (1983). *Textbook of limnology*. Waveland Press, Inc., Illinois.

Gallagher, J. W., Jr., and Mauldin, G. V. (1987). "Oxygenation of releases from Richard B. Russell Dam." *Proceedings: CE workshop on reservoir releases*. Miscellaneous Paper E-87-3, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Hains, J. J., et al. "Phase III testing and monitoring of pumped-storage operation at Richard B. Russell Dam and Lake: Water quality and hydrodynamic results," Report in preparation, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Horne, A. J., and Goldman, C. R. (1994). *Limnology*. McGraw-Hill, Inc., New York.

Hydrolab Corporation. (1991). *Datasonde 3 multiparameter water quality monitoring instruments operating manual*. Austin, TX.

Lemons, J. W., Vorwerk, M. C., Jabour, W. E., and Carroll, J. H. (1996). "Remote downstream monitoring of Savannah River hydropower releases," Miscellaneous Paper EL-96-5, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Odum, H. T. (1956). "Primary production in flowing waters," *Limnol. & Oceanogr.* 1,102-117.

_____. (1957). "Primary production measurements in eleven Florida springs and a marine turtle-grass community," *Limnol. & Oceanogr.* 2, 85-97.

Vorwerk, M. C., and Carroll, J. H. (1995). "Implications of reservoir release and tailwater monitor placement," *Lake and Reservoir Management.* 9,170-172.

Appendix A
BASIC Program for Time Lagging Water Quality Data Sets

```
'JWLCOMV2.BAS
'THIS PROGRAM MATCHES DATA COLLECTED AT STATION 112B
WITH INJECTION
'DATA AND 100B DATA.  DATA ARE PAIRED BY USING THE
VELOCITY TO
'CALCULATE THE DISTANCE EACH PARCEL OF WATER LEAVING
112B TRAVELS PER
'GIVEN TIME INTERVAL.  WHEN THE DISTANCE A PARCEL
TRAVELS EQUALS THE
'LOCATION OF THE INJECTION SYSTEM, THE INJECTION RATE
FOR THAT LOCATION
'IS PAIRED WITH THE 112B OBSERVATION.  WHEN THE
DISTANCE FOR 100B IS
'REACHED, THE 100B VALUE IS PAIRED WITH THE 112B VALUE.

'THUS, THE DO OF A PARCEL OF WATER IS MEASURED AT 112B,
THE INJECTION
'RATE USED AS THE PARCEL PASSES THE INJECTION SYSTEM IS
RECORDED, AND
'THE PARCEL IS MEASURED AT 100B.  THUS, EFFICIENCY CAN
BE CALCULATED
'BY:

'          (DO100-COMPARED0112)/MGLINJ

'PROGRAM WRITTEN BY KARIN AND MICHAEL VORWERK AND
JOHN LEMONS, 2/15/97

CLS                          '*CLEARS SCREEN

PRINT "RUNNING"              '*TELLS OPERATOR PROGRAM IS
                             RUNNING

'***BEGIN MAIN***
```

```
OPEN "COMPAR.DAT" FOR OUTPUT AS #2 '*OPENS OUTPUT FILE,
PUTS HEADER IN FILE AND ON SCREEN

   PRINT #2, "COMPAREDO112 DO100 MGLINJ
COMPAREDOINJRATE DO112TIME DO100TIME LAGTIME
DOINJLAGTIME"

   PRINT "COMPAREDO112 DO100 MGLINJ COMPAREDOINJRATE
DO112TIME DO100TIME LAGTIME DOINJLAGTIME"

CLOSE (2)

N = 856                    '*SETS STOP CONDITION FOR COUNTER

I = 0                      '*SETS INITIAL CONDITION FOR
                           COUNTER

WHILE I < N                '*LOOP LIMITS NUMBER OF
                           OBSERVATIONS TO N

   DISTANCE = 0            '*SETS INITIAL CONDITION FOR
                           DISTANCE

   OPEN "VORWERK3.dat" FOR INPUT AS #1'*OPENS INPUT FILE

   J = 0                   '*SET INITIAL CONDITION FOR 112
                           OBSERVATION

   WHILE J < I + 1         '*LOOP CAUSES PROGRAM TO START
                           ON NEXT 112 OBSERVATION

      INPUT #1, STIME, DO100, DO112, VEL, O2INJ
                           '*INPUTS DATA J = J + 1

   WEND

   COMPAREDO112 = DO112          '*ASSIGNS COMPARABLE
                                 112 DO TO CURRENT 112
                                 DO VALUE

   DO112TIME = STIME             '*ASSIGNS START TIME AT
                                 112 TO CURRENT TIME

   FOUND$ = "FALSE"              '*SETS INITIAL CONDITION
                                 FOR INJECTION DISTANCE

   '*NEXT WHILE LOOP CONTROLS DISTANCE FOR STATION 100
```

```
WHILE DISTANCE < 83.333 AND NOT EOF(1)
                    '*DISTANCE DIVIDED BY 30

    DISTANCE = DISTANCE + VEL
                    '*MOVES PARCEL ACROSS DISTANCE

    INPUT #1, STIME, DO100, DO112, VEL, O2INJ '*READS IN
OBSERVATIONS

    DO100TIME = STIME
                    '*ASSIGNS 100 TIME TO CURRENT TIME

    '*NEXT IF THEN CONTROLS MID-DISTANCE DO INJECTION
    VALUES

    '*FALSE VALUE ALLOWS OBSERVATION TO BE COUNTED
    ONLY THE FIRST INSTANCE

    IF DISTANCE > 41.65 AND FOUND$ = "FALSE" THEN

        DOINJTIME = STIME        '*ASSIGNS DO INJECTION
                                 TIME TO THE CURRENT
                                 SAMPLE TIME

        COMPAREDOINJRATE = O2INJ
                    '*ASSIGNS COMPARABLE INJECTION
                    RATE TO CURRENT RATE

        VELATINJ = VEL           '*ASSIGNS VELOCITY AT
                                 INJECTION TO CURRENT
                                 VELOCITY

        IF VELATINJ = 0 THEN VELATINJ = .001
            '*NECCESSARY TO PREVENT DIVISION BY ZERO
            MGLINJ = (COMPAREDOINJRATE * 1000) /
            (VELATINJ * 18 * 12950) '
            *CHANGES INJECTION RATE TO MG/L

        FOUND$ = "TRUE"
                    '* ALLOWS ONLY FIRST INSTANCE OF
                    PASSING MID-DISTANCE TO BE USED

END IF

WEND

IF EOF(1) GOTO 999

CLOSE (1)
```

```
OPEN "COMPAR.DAT" FOR APPEND AS #2 '*OPENS OUTPUT FILE

        LAGTIME = DO100TIME - DO112TIME

        DOINJLAGTIME = DOINJTIME - DO112TIME

        '*PRINTS RESULTS TO FILE SPECIFIED ABOVE

        PRINT #2, COMPAREDO112; ","; DO100; ","; MGLINJ; ",";
        COMPAREDOINJRATE; ","; DO112TIME; ","; DO100TIME; ",";
        LAGTIME; ","; DOINJLAGTIME

        PRINT COMPAREDO112; ","; DO100; ","; MGLINJ; ",";
        COMPAREDOINJRATE; ","; DO112TIME; ","; DO100TIME; ",";
        LAGTIME; ","; DOINJLAGTIME

CLOSE (2)

I = I + 1

WEND

'TELLS OPERATOR PROGRAM IS FINISHED AND TELLS NUMBER
OF OBSERVATIONS USED.

999 PRINT "AT END OF FILE, NUMBER OF OBSERVATIONS USED
IS "; I

'***END MAIN***
```

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
April 1998

3. REPORT TYPE AND DATES COVERED
Final report

4. TITLE AND SUBTITLE
Determination of Richard B. Russell Dissolved Oxygen Injection System Efficiency Utilizing Automated Remote Monitoring Technologies

5. FUNDING NUMBERS

6. AUTHOR(S)
John W. Lemons, Michael C. Vorwerk, Joe H. Carroll

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
DynTel Corporation, 3530 Manor Drive, Vicksburg, MS 39180;
U.S. Army Engineer Waterways Experiment Station
3909 Halls Ferry Road, Vicksburg, MS 39180-6199

8. PERFORMING ORGANIZATION REPORT NUMBER
Miscellaneous Paper W-98-1

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Corps of Engineers
Washington, DC 20314-1000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Studies to determine the effectiveness and efficiency of an oxygen injection system were conducted at Richard B. Russell Dam and Lake in 1995. Studies were conducted by deploying an array of automated water quality logging instruments upstream and downstream of the oxygen injection system and comparing their measurements. Hypotheses concerning oxygen accumulation in the forebay during periods of nonrelease and oxygen transfer efficiency as influenced by dam operation were evaluated. Studies point to the importance of operational events occurring up to 4 days prior to the measurement of the system's efficiency.

14. SUBJECT TERMS

Automated monitoring	Richard B. Russell Dam and Lake
Dissolved oxygen	Tailwater
Oxygenation	Water quality
Reservoir	

15. NUMBER OF PAGES
71

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED		

Destroy this report when no longer needed. Do not return it to the originator.