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THE EFFECT OF SEQUOYAH NUCLEAR PLANT ON DISSOLVED OXYGEN
IN CHICKAMAUGA RESERVOIR

TVA/WR/WQ--90/10

Chattanooga, Tennessee

September 1990

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Tennessee Valley Authority. Water Resources.

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THE EFFECT OF SEQUOYAH NUCLEAR PLANT ON DISSOLVED OXYGEN

IN CHICKAMAUGA RESERVOIR

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Chattanooga, Tennessee

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EXECUTIVE SUMMARY

During the summer of 1985, the Tennessee Division of Water Pollution Control and the Tennessee Wildlife Resources Agency measured dissolved oxygen (DO) concentrations downstream from the Sequoyah Nuclear Plant (SQN) discharge mixing zone that were below the state criterion for DO. The Tennessee "General Water Quality Criteria" specifies that DO should be a minimum of 5.0 mg/l measured at a depth of 5 feet for the protection of fish and aquatic life. The Tennessee Valley Authority developed the present study to answer general concerns about reservoir conditions and potential for adverse effects on aquatic biota. Four objectives were defined for this study: (1) to better define the extent and duration of the redistribution of DO in the reservoir, (2) to better understand DO dynamics within the mixing zone, (3) to determine whether DO is being lost (or added) as the condenser cooling water passes through the plant, and (4) to evaluate the potential for impact on aquatic life in the reservoir.

Water is withdrawn from near the reservoir bottom for cooling use at SQN. The temperature of the condenser cooling water rises approximately 14°C when both units are operating in open mode. A mean net decrease of 0.8 mg/l DO concentration was measured in the cooling water. A slight reduction in oxygen demands was observed in the cooling water. Under normal flow conditions, the effect on mean water column DO in the reservoir was estimated to be a decrease of less than 0.1 mg/l. In the extreme case of maximum DO loss in the cooling water under low flow conditions, the mean water column DO in the reservoir could be reduced by approximately 0.5 mg/l. The reduction of DO concentration in the

condenser cooling water is caused primarily by a shift in the gas transfer equilibrium due to the increase in temperature. Overall, SQN has little effect on the DO concentrations and oxygen demands in the condenser cooling water.

A number of factors influence the DO distribution in the vicinity of SQN. Reservoir water is retained upstream from the underwater dam resulting in a vertical DO gradient several times a year. Turbulence caused by the combined effect of increased flow velocity past the underwater dam and the diffuser discharge serve to vertically mix the water column downstream. A statistically significant decrease in DO at five feet was observed downstream from the mixing zone, but no change was detected in the total DO mass. The decrease in DO at five feet may be of regulatory significance, but not important ecologically. These results confirm that DO is not being removed from the reservoir, but is redistributed in the vicinity of SQN due to turbulent mixing. Periods of low or reverse flow at SQN caused by dam operations at Chickamauga and Watts Bar Dams change the pattern of DO distribution over a daily cycle. DO gradients upstream from the underwater dam are reduced during these periods as the thermal discharge influences the distribution pattern further upstream. The DO in the overbank areas is not affected by the mixing that occurs in the main channel. Dissolved oxygen concentrations observed on the overbanks are higher than those in the main channel during the daytime.

The DO conditions in Chickamauga Reservoir are largely influenced by release concentrations from Watts Bar Dam. Hydrologic conditions can result in low DO concentrations in Watts Bar Dam releases during dry

summer months. The water quality model was used to identify the effects of hydrology, thermal discharges from SQN and Watts Bar Nuclear Plant (WBN), and aeration of Watts Bar Dam releases on Chickamauga Reservoir DO concentrations. Depending on flow and stratification, the SQN discharge can result in a small to significant increase in downstream hypolimnetic DO due to redistribution of epilimnetic DO. Watts Bar Nuclear Plant discharge showed no effect on reservoir DO concentrations. Reservoir DO concentrations showed decreases when modeling low flow hydrology due to stratification. Increasing the DO of the Watts Bar Dam releases by 2 mg/l with forebay surface water pumps improved the DO concentrations throughout Chickamauga Reservoir by about 1 mg/l (figures ES-1 and ES-2).

Neither individual fish species nor fishery production are likely to be detrimentally impacted by redistribution of DO concentrations (reduction of epilimnetic DO levels) associated with the discharge mixing zone at SQN. Redistributed DO concentrations (modeled and measured) simply do not fall within ranges known to affect fish distributions or survival. Overall, the mixing of the water column that occurs at SQN increases hypolimnetic DO concentrations and reduces the reservoir volume with the lowest DO concentrations (i.e., those most likely to have detrimental impacts on fisheries).

Under low flow conditions, some impact of Watts Bar Dam releases to production (growth, reproduction, or survival) of particular fish species (e.g., young of channel catfish) in Chickamauga Reservoir is likely. The predominant potential factor for producing negative impacts on fisheries

in Chickamauga Reservoir is seasonally low DO in releases from Watts Bar Dam. Different fish species have varying susceptibilities to suffering impacts from low DO concentrations in the reservoir (table ES-1). The likelihood of impacts occurring is related to fish species and life stages present, their life histories (e.g., time and habitat for adult spawning), specific habitat used (near-shore versus deep channel, or epilimnetic vs hypolimnetic), spatio-temporal co-occurrence with seasonally low DO levels, and specific sensitivities to low DO concentrations.

Table ES-1. Potential Susceptibility of Selected Fish Species Occurring in Chickamauga Reservoir to Impacts from Low Concentrations of Dissolved Oxygen

Fish taxa	Relative susceptibility			Reasons
	High	Mid	Low	
<u>Dorosoma</u> spp. (gizzard and threadfin shad)			X	Broad habitat usage
<u>Cyprinus carpio</u> (carp)			X	Use overbank habitats
<u>Notropis</u> spp. (shiners)			X	Use overbank habitats
<u>Notropis volucellus</u> (mimic shiner)		X		Summer spawn, young prefer deep channels, DO sensitivity unknown
<u>Ictiobus</u> spp. (buffalo fish)		X		Early spawners but larger young inhabit deep channels in summer, DO sensitivity unknown
<u>Ictalurus</u> spp. (catfish)		X		Some deep spawning, young predominately in deep channels, young sensitive to low DO
<u>Morone</u> spp. (white bass, striped bass)			X	Larger young inhabit deep channels in summer, moderately tolerant of low DO
<u>Lepomis</u> spp. (sunfishes)			X	Spawn and predominately remain in overbank
<u>Micropterus</u> (not dolomieu) (largemouth and spotted bass)			X	Spawn and predominately remain in overbank or near-shore habitat
<u>Pomoxis</u> spp. (white and black crappie)			X	Spawn and predominately remain in overbank and embayment habitats, but older young sometimes found on channel slopes, sensitivity to low DO in question

Table ES-1 (Continued)

Fish taxa	Relative susceptibility			Reasons
	High	Mid	Low	
<u>Perca flavescens</u> (yellow perch)			X	Young inhabit channels, but are tolerant of low DO
<u>Stizostedion canadense</u> (sauger)		X		Early spawner, but older young strongly prefer deep waters during day, sensitivity to low DO not well-defined
<u>Aplodinotus grunniens</u> (freshwater drum)		X		Summer deep-water spawner, young prefer deep-water channel, sensitivity to low DO unknown

LEGEND: > 5 mg/l Between 5 mg/l and 3 mg/l < 3 mg/l

Figure ES-1. Computed Dissolved in Mid-June under Low Flows

LEGEND: > 5 mg/l Between 5 mg/l and 3 mg/l < 3 mg/l

Figure ES-2. Computed Dissolved Oxygen in Late July under Low Flows.

1.0. INTRODUCTION

1.1 Purpose and Objectives

On August 16, 1985, the Tennessee Division of Water Pollution Control (TDWPC) wrote to the Tennessee Valley Authority (TVA) about temperature and dissolved oxygen (DO) levels downstream from SQN on Chickamauga Reservoir. Data collected by the Tennessee Wildlife Resources Agency (TWRA) and TDWPC were presented showing DO measurements of less than 5.0 milligrams per liter (mg/l) at a 5-foot (ft) depth just downstream from SQN on two sampling dates, July 9 and August 12, 1985. These DO levels were below the criterion established in the Tennessee "General Water Quality Criteria" for the protection of fish and aquatic life in the Tennessee River in the vicinity of SQN. TDWPC requested any relevant data that TVA had collected and asked that TVA conduct further sampling of temperature and DO through the rest of the summer of 1985.

TVA submitted a technical report to TDWPC on January 22, 1986, which included an analysis of all existing temperature and DO data collected in the vicinity of SQN (Ostrowski, 1985). The report concluded that the diffusers and underwater dam mixed the water column, which was stratified upstream from the underwater dam. This vertical mixing resulted in a redistribution of DO, with concentrations at 5 ft dropping below 5.0 mg/l because deeper water had low DO concentrations. DO levels in the lower strata increased. The data indicated that DO levels at 5 ft increased above 5.0 mg/l a short distance downstream from the diffuser discharge mixing zone due to surface aeration and algal

photosynthesis. Since measurements collected on the nearby overbanks met the DO criterion, only the main river channel seemed to be affected. The report recognized that lower than normal DO levels were observed throughout the reservoir due to low riverflows experienced during the drought in the spring and summer of 1985.

TDWPC responded to the report with a letter dated March 17, 1986, disagreeing with the report's conclusion that SQN does not appear to be producing an adverse effect on DO in the reservoir. The letter posed several questions concerning specific statements made in the report and questioned whether sufficient data was available to answer concerns about conditions in the reservoir. In response to these concerns, TVA developed a workplan, with TDWPC review, to determine the extent and duration of changes in DO concentration in the reservoir due to SQN and the potential for adverse effects on aquatic biota. The studies were begun on April 1, 1987, and the final workplan was forwarded to TDWPC on April 30, 1987.

Four objectives were defined to answer general concerns about reservoir conditions and the potential for adverse effects on aquatic biota caused by SQN: (1) to better define the extent and duration of the redistribution of DO in the reservoir, (2) to better understand DO dynamics within the mixing zone, (3) to determine whether DO is being lost (or added) as the condenser cooling water passes through the plant, and (4) to evaluate the potential for impact on aquatic life in the reservoir. Specific studies were designed to satisfy each of these objectives.

1.2 Description of Chickamauga Reservoir

Chickamauga Reservoir was formed by the 1940 closure of Chickamauga Dam at Tennessee River mile (TRM) 471. The reservoir extends 58.9 miles from Chattanooga, Tennessee, north to Watts Bar Dam (figure 1-1). The reservoir has a major arm formed by the confluence with the Hiwassee River at TRM 499.4. Pool elevation normally varies from 675 ft mean sea level (msl) in winter to 682.5 ft msl in the summer (figure 1-2). The reservoir volume is normally 375×10^3 acre-feet (ac-ft) during winter and increases to 735×10^3 at full summer pool. At full pool, the reservoir surface covers 35,400 acres (ac) and has 810 miles of shoreline. In accordance with the TVA Act of 1933, the project is managed for the primary purposes of navigation, flood control, and power production.

Chickamauga Dam released a mean annual discharge of 33,100 cubic feet per second (cfs) for the period 1959 through 1988. Monthly average discharges ranged from 24,900 cfs in April to 45,500 cfs in January (table 1-1). During the spring of 1984, a severe extended drought began in the Tennessee Valley Region which lasted to the winter of 1988. During the drought years of 1986 and 1988, monthly average discharges in April and May of both years dropped below 10,000 cfs. Current operating guidelines call for a minimum daily average discharge of 6,000 cfs from the dam. Annual average hydraulic residence time for water movement through the reservoir is approximately 10 days based on the annual average flow of about 34,000 cfs (1903-88). Monthly average residence times range between 4 days in January to 12 days in April. This suggests

that inflow concentrations from Watts Bar Reservoir have a great effect on Chickamauga Reservoir water quality, especially during summer months when local runoff is at a minimum. Mean weekly releases from Chickamauga Dam (1903-88) vary from a maximum of 68,000 cfs during the spring rainy season to a minimum of 12,900 cfs in the fall dry season.

TVA uses water from Chickamauga Reservoir for cooling purposes at two nuclear plants--Watts Bar (WBN) and SQN. WBN, located near the tailwater reach of Watts Bar Dam, is in preoperational mode. SQN is located at TRM 484.5 approximately 13.5 miles upstream from Chickamauga Dam (figure 1-3). At this location, the reservoir makes a sharp bend. The main river channel in the vicinity of SQN ranges from 15-20 meters (m) deep, and is bordered by shallow overbank areas. Two public parks and several marinas are located within 5 miles downstream from SQN.

1.3 Sequoyah Nuclear Plant Description

SQN is about 18 miles northeast of Chattanooga, Tennessee, on the west shore of Chickamauga Reservoir at TRM 484.5. It has two pressurized water reactors with a total nameplate rating of 2,441 megawatts (MW). The plant was initially designed in the mid-1960s to use open (once-through) cooling to comply with then existing thermal criteria. More stringent thermal criteria were proposed by the state of Tennessee and approved by the U.S. Environmental Protection Agency (EPA) in 1972. To meet the more stringent criteria, two natural draft cooling towers were constructed to enable the plant to operate in open, helper, or closed modes.

Condenser Cooling Water (CCW) is withdrawn from lower strata of Chickamauga Reservoir under a deep skimmer wall (figure 1-3). The skimmer wall has an opening length of 165 m, an opening height of 3 m, and is situated near the river channel at a depth of approximately 13 m. Because the water drawn from the deep opening at the skimmer wall is normally cooler, the water temperature of the intake embayment may be lower than the adjacent reservoir surface water temperature. The intake embayment has an estimated 1.5 hour (hr) detention time with all six CCW pumps operating. A shoreline-mounted Essential Raw Cooling Water (ERCW) pumping station is located adjacent to the upstream end of the skimmer wall, with a total intake pumping capacity of 108 cfs.

A channel leads from the intake embayment to the CCW pumping structure, which houses six, 3-m wide, vertical traveling screens. Under two unit open-mode operation at maximum power, total water demand is 3,000 cfs. The estimated water temperature rise across the condensers is 14°C with an estimated detention time of 0.2 hr. Water leaving the condensers can be routed in one of four ways: (1) to the diffuser pond and out the diffuser pipes to the reservoir (open mode); (2) through the cooling towers, then to the diffuser pond (helper mode); (3) through the cooling towers and recirculated to the intake embayment (closed mode) with only cooling tower blowdown discharged to the diffuser pond; or (4) a combination of helper and closed modes with part of the cooling tower discharge directed to the diffuser pond and part recirculated to the intake embayment.

Surface area of the diffuser pond is about 13 hectare (ha). Two discharge pipes lead from the diffuser pond to diffuser sections which

are located in the main river channel at TRM 483.6 at an elevation of 635 ft msl. The estimated detention time of the diffuser pond is 1.0 hr with three CCW pumps operating and 0.7 hr with six pumps. Each of the diffuser sections contains several thousand 5-centimeter (cm) diameter ports, through which heated water is discharged at a velocity of about 3 meter/second (m/sec).

An underwater dam, which crosses the river channel approximately 75 m upstream from the diffusers, decreases the likelihood of the thermal discharge moving upstream to the lower strata near the intake skimmer wall. The submerged dam also impounds the cooler water in the lower strata of the reservoir near the skimmer wall making this water available for plant intake. The dam is about 25 m wide by 275 m long with a crest at an elevation of 645 ft msl.

WBN, which is under construction has two units with a total capacity of about 2540 MW. It is located on the right bank of Chickamauga Reservoir near TRM 528.0. WBN will be operated in closed-cycle cooling mode, with only blowdown from the cooling towers discharged through two multiport diffusers at TRM 527.8. Blowdown will be discharged at a rate of between 44.6 and 85.0 cfs from the cooling tower basins to maintain the concentration of dissolved solids in the cooling towers at approximately twice that found in the Tennessee River. Makeup water is supplied via an intake channel and pumping station located at TRM 528.0. The average and maximum intake flow rates are 133 and 143 cfs.

1.4 Sequoyah Nuclear Plant Operations During Study Period

The average monthly power output and percentage of unit capacity is summarized in table 1-2. Both units were shut down in late August 1985, due to safety concerns. The current study began on April 1, 1987, and continued through to May 1988. By early May 1988, the plant had not been restarted. It was expected that operation through the summer would be intermittent. The study was deferred until April 1989, to assure that data would be collected during continuous plant operation. Sampling was restarted in April 1989 and continued through October 1989.

Table 1-1. Long-Term Monthly Average Releases and Travel Times Through Chickamauga Reservoir Compared to Flows and Travel Times During 1989

<u>Long-term average (1959-1988)</u>						
Month	Chickamauga Dam releases		Travel time through Chickamauga Reservoir	1989 Conditions		
	(m ³ /s)	(cfs)	(days)	Chickamauga Dam releases	Travel time	
	(m ³ /s)	(cfs)	(days)	(m ³ /s)	(cfs)	(days)
January	1,290	45,500	4	1,310	46,400	4
February	1,230	43,500	4	1,240	43,900	4
March	1,190	42,100	5	1,270	44,700	4
April	710	24,900	12	470	16,500	18
May	750	26,600	11	950	33,500	9
June	760	27,000	11	1,910	67,400	4
July	820	28,900	10	1,400	32,000	6
August	860	30,300	10	1,030	36,200	8
September	760	26,700	11	1,190	41,900	7
October	770	27,100	11			
November	920	32,400	6			
December	1,190	42,200	5			
Annual average	940	33,100	8			

Table 1-2. Mean Monthly Unit Loads for Sequoyah Nuclear Plant
During Study Period

Date	<u>Unit 1 load</u>		<u>Unit 2 load</u>		<u>Total load</u>	
	(MW)	(%)	(MW)	(%)	(MW)	(%)
Apr-87	0	0	0	0	0	0
May-87	0	0	0	0	0	0
Jun-87	0	0	0	0	0	0
Jul-87	0	0	0	0	0	0
Aug-87	0	0	0	0	0	0
Sep-87	0	0	0	0	0	0
Oct-87	0	0	0	0	0	0
Nov-87	0	0	0	0	0	0
Dec-87	0	0	0	0	0	0
Jan-88	0	0	0	0	0	0
Feb-88	0	0	0	0	0	0
Mar-88	0	0	0	0	0	0
Apr-88	0	0	0	0	0	0
May-88	0	0	309	27	309	13
Jun-88	0	0	347	30	347	15
Jul-88	0	0	871	76	871	38
Aug-88	0	0	1029	90	1029	45
Sep-88	0	0	801	70	801	35
Oct-88	0	0	563	49	563	25
Nov-88	45	4	512	45	557	24
Dec-88	79	7	588	51	667	29
Jan-89	1107	96	439	38	1546	67
Feb-89	988	86	0	0	988	43
Mar-89	1113	97	0	0	1113	48
Apr-89	1120	98	24	2	1144	50
May-89	1093	95	979	85	2072	90
Jun-89	1106	96	1126	98	2232	97
Jul-89	1084	94	808	70	1892	82
Aug-89	1134	99	1113	97	2247	98
Sep-89	1031	90	1012	88	2042	89
Oct-89	1110	97	897	78	2007	87

Figure 1-1. Map of Chickamauga Reservoir

Figure 1-2. Seasonal Plan for Water Level Elevations of Chickamauga Reservoir

Figure 1-3. Location of SQN Intake, Underwater Dam, and Diffusers
(from McIntosh, Johnson, and Speaks, 1983)

Figure 1-4. Major Features of Sequoyah Nuclear Plant

2.0 INPLANT EFFECTS ON DISSOLVED OXYGEN

When water is drawn from the lower strata of the reservoir into the intake embayment for use in cooling at SQN, it is introduced to a number of different physical and chemical regimes. This bottom water first comes in contact with the surface atmosphere. In the condensers, heat is added and the water is then ponded on the surface for another short period before being discharged back to the bottom of the reservoir. With all six CCW pumps in operation, it takes about 2.5 hr for the water to travel from the intake skimmer wall to the diffusers. At normal riverflows and full plant operation, approximately one-tenth of the riverflow is diverted through the plant cooling system. With riverflows that were experienced during the drought, about one-third of the riverflow is diverted. This chapter will describe the studies designed to examine changes in temperature, DO, and oxygen demands as reservoir water passes through the plant cooling system.

2.1 Dissolved Oxygen Concentration

As water is pumped through the plant (figure 1-4), it is first brought into the intake embayment where some reaeration may occur due to mixing at the surface. Any increase in DO due to reaeration is probably minimal because of the short hydraulic detention time within the embayment. The water is then pumped from the intake embayment through the condensers into a short channel terminating with the cooling tower lift pumps. Although the temperature of the water has been raised at this location, the DO has had little time to exchange with the atmosphere due to the short detention time. In open mode, the water is then released to

the diffuser pond where it is retained for approximately one hour before being discharged back to the reservoir. Diel variations of DO in the intake water and diffuser pond require continuous measurements in order to evaluate the effect of the plant on cooling water DO levels.

2.1.1 Materials and Methods

Field--The materials used included: three Hydrolab Data Sonde Model-2H, a cableway, ropes and pulleys, and Radio Shack Model 100 computer with disk drive.

Three stations were located along the plant cooling water stream for monitoring: Station 1 was approximately three hundred feet upstream from the intake pumping station, station 2 was located on the inlet side of the cooling tower pump structure, and station 3 was on the inlet side of the diffuser pipes (figure 2-1). At station 1, a Hydrolab Data Sonde Model-2H was placed at a depth of 1 m in the middle of the intake channel. The data sonde was suspended from a cableway with a rope pulley system to facilitate the recovery of data. At stations 2 and 3, a weighted rope was placed upstream from the structures and the data sonde was attached so it could be pulled up and down the rope. The 1-m depth was maintained at all three stations by having a weight attached to the data sonde and a length of rope attached with a flotation device keeping the probes at exactly 1 m.

The data sondes at each station were recovered approximately once a week and data collected for temperature, DO, conductivity, and pH were downloaded onto a 3.5-inch (in) disk. Each time the data were recovered from the data sonde, the instrument was calibrated for each of the above parameters according to the manufacturer's specifications and placed back

in service. The data were then reviewed and forwarded to TVA's Water Quality Department.

Data Analysis--All hourly measurements were entered into a LOTUS spreadsheet which is available from TVA's Data Systems Department upon request. There were many periods when the data logger malfunctioned resulting in data not being stored. Data that appeared to be unreasonable was compared with field records for interpretation. Several operational problems (e.g., low batteries, fouled DO probe membranes, etc.) cited in the field records explained much of the suspect data. During some periods there was considerable instrument drift between DO calibrations. The data were adjusted to account for the shift identified by calibration. Dissolved oxygen saturation was computed as a function of temperature (Rich, 1973). The change in variables across the plant was calculated as the difference between the measured value at the diffuser pond outflow (station 3) and the CCW inflow (station 1) value measured 1-hr earlier, to account for hydraulic detention time.

2.1.2 Results and Discussion

Adjusted hourly data at the three monitoring locations for temperature, DO, and DO saturation were aggregated by month and presented in figures B-1 through B-18. Daily temperature variations due to daytime heating and nighttime cooling are seen in all of the temperature plots (figures B-1 through B-6). The degree of diel temperature variation is most pronounced in the diffuser pond outflow data due to surface heating and cooling, primarily in the shallow depth of the pond. Shutdown of the reactor units caused large fluctuations in temperature in May 1988 and July 1989. In May 1988, unit 1 was restarted three times, with two automatic shutdowns, which was evident in the temperature data. In all

cases, the diffuser pond outflow temperature was slightly less than inflow temperature, indicating cooling within the pond.

A diel variation was not as evident in the DO data as in the temperature data. Fluctuations in DO appeared erratic over short periods of time (figures B-7 through B-12). However, a closer examination of the data revealed a fairly consistent relationship between monitoring locations. During periods when the plant was operating, DO was highest at the CCW intake location. Dissolved oxygen levels were comparatively lower at the inflow to the diffuser pond. The detention time in the short canal from the plant to the cooling tower lift pumps was sufficient to allow some DO to be driven out of solution. The dissolution of oxygen was due to a change in the gas transfer equilibrium caused by the elevated temperature of the water. The exchange rate constant for the liquid phase was increased while the constant for the gas phase remained the same. This change caused a shift in the two-phase equilibrium resulting in a net flux of oxygen to the gas phase (Stumm and Morgan, 1981).

No consistent relationship is apparent between the DO data collected at the inflow to the diffuser pond and the outflow. In early May 1988 when the plant was not operating, and for a short period in July 1989 with one unit in operation, the DO increased slightly while passing through the diffuser pond. In May 1989, DO data at the inflow and outflow of the diffuser pond were essentially the same. However, available data for the remainder of the summer showed a net loss of DO from the pond. This decrease in DO was probably a result of the continuing transport of oxygen out of solution due to the elevated cooling water temperature.

Patterns of DO saturation were comparable to those patterns observed in the DO data (figures B-13 through B-18). The solubility of oxygen in water is a function of the water temperature, salinity, barometric pressure, and atmospheric humidity. The last three factors were assumed to be constant in comparing data measured hourly at SQN. According to the application of Henry's law using the partial pressure of oxygen in the atmosphere, oxygen solubility decreases as water temperature increases. When water temperature increases, and the DO has not reached equilibrium with the atmosphere, the resulting percent of DO saturation is increased. For periods when the plant was operating, the percent DO saturation for the diffuser pond inflow and outflow was higher than the CCW intake percent DO saturation measured at the same time.

The overall effect that the entire plant has on water used for cooling can be evaluated by the difference between the outflow values from the diffuser pond and CCW intake values for each hourly measurement (figures B-19 through B-24). Changes in values can be compared to the powerload of the plant, indicating periods of plant operation. Dissolved oxygen and temperature were measured during periods when zero, one, and two units were in open-mode operation. The SQN did not operate in helper or closed modes at any time during sampling.

On the average, the temperature of the water passing through the plant was raised by about 14°C during two unit operation at full load. The increase in temperature was slightly less during one unit operation, varying from 8°-12°C, because a CCW pump is often run on the idle unit.

Statistics describing the net change in DO concentration during two unit operation are presented in table 2-1. The mean net decrease in DO

concentration was measured to be 0.8 mg/l. The magnitude of DO loss is slightly higher in the later summer months. The estimated reductions in reservoir DO concentration under normal (30,000 cfs) and low (10,000 cfs) flows are 0.08 mg/l and 0.26 mg/l, respectively. To estimate the maximum reduction likely to occur in mean reservoir DO concentration, the lower fifth percentile from all measurements of net DO change in SQN cooling water (1.45 mg/l) was applied to low flow conditions. Under this worst case situation, the mean water column DO in the reservoir would be reduced by 0.5 mg/l due to the discharge of condenser cooling water from SQN. However, this reduction would occur over a very short period due to the highly variable dissolution rates measured. Estimates derived above from the mean of over 1500 measurements are representative of typical DO dissolution from SQN CCW during two unit operation.

Changes in DO concentration in SQN condenser cooling water during one unit operation were not consistent. A net decrease in DO of about 0.5 mg/l was observed during operational periods of May 1988. However, a net increase in DO of about 0.2 mg/l was observed when the plant operated with one unit in July 1989. This discrepancy is most likely due to an error in calibration for one of the DO probes. The DO increased during May 1988 when no load was being generated but water was being pumped through the cooling system. The increase was caused by reaeration of the water withdrawn from the lower strata of the reservoir. In the diffuser pond, increases in percent DO saturation ranged from approximately 10-20 percent during two unit operation, resulting from the lower saturation potential of the warmer water and state of nonequilibrium for oxygen gas transport.

2.1.3 Conclusions

1. The temperature of the cooling water at SQN is increased approximately 14°C when both units are operating in open mode. This change in water temperature causes a shift in the gas transfer equilibrium with the atmosphere resulting in a reduction in the DO concentration in the cooling water discharge averaging 0.8 mg/l.
2. The percent DO saturation increased due to the oxygen not recovering equilibrium with the atmosphere under the higher temperature.
3. The reduction of DO in the cooling water discharge is estimated to cause a reduction of less than 0.1 mg/l in the DO concentration throughout the reservoir water column during normal flows. Such a reduction would be unmeasurable within the reservoir. In the extreme case of maximum DO loss in the cooling water under low flow conditions, the mean water column DO of the reservoir would be reduced by approximately 0.5 mg/l.

2.2 Oxygen Demands

Reservoir water contains a number of substances that consume DO. The consumption of DO is driven by chemical oxidation reactions and biochemical reactions. Chemical oxygen demand (COD) is a measure of the oxygen required to chemically oxidize reduced substances in a sample. The substances that are oxidized by this method include most organic matter and reduced inorganic compounds. Biochemical oxygen

demand (BOD) is a measure of the oxygen required by bacteria to stabilize organic matter and ammonia under aerobic conditions. Biochemical oxygen demand comprises two separate reactions: the decomposition of organic carbon known as carbonaceous BOD (CBOD), and the oxidation of organic nitrogen and ammonia by nitrifying bacteria, or nitrogenous BOD (NBOD).

Concern has been raised about the effect of plant operation on the oxygen demanding substances in the water used for cooling. When the temperature is raised, oxidation reaction rates rise, potentially causing an increase in immediate DO demands. A number of activities on the plant site also contribute oxygen demanding substances to the cooling water before it is discharged back to the reservoir. Onsite sanitary waste and storm water runoff are introduced into the cooling water stream. A surfactant is added to the ERCW as a biodispersant in the control of microbially induced corrosion. These and other factors may change the complex matrix of oxygen demanding substances in the cooling water before discharge to the reservoir.

2.2.1 Material and Methods

Field--The materials used included: sample ropes, sample bottles, ice, and ice chest.

Approximately once each week, three separate water samples were taken at the three stations discussed in Section 2.1. A sample to be analyzed for BOD, COD, and ammonia was taken from each of the three samples. Once a month, in addition to the above samples, three additional samples were taken and a sample for CBOD and NBOD were taken from each of those three. The samples were placed in ice and transported to the laboratory for analysis.

Laboratory--Analytical methods used to determine concentrations of chemical water quality constituents are shown in appendix A. The referenced laboratory methods are TVA's preferred methods which are approved by EPA. Five water quality parameters were measured analytically. Triplicate field samples of ammonia nitrogen, COD, and 5-day BOD (BOD_5) were analyzed for each date (generally weekly) from three sample locations at the plant. Twenty-eight day incubations for ultimate BOD were conducted on triplicate field samples. A nitrification inhibitor was added to one set of incubations to differentiate between CBOD and NBOD.

Data Analysis--Carbonaceous BOD (CBOD) was computed from the time series data of the incubation with a nitrification inhibitor added. The method of Thomas (1950) was used to calculate ultimate CBOD and the rate constants. Nitrogenous BOD (NBOD) was calculated from the difference between time-series data from incubations with and without added nitrification inhibitor. Ultimate NBOD was determined by identifying the plateau on a plot of the difference in the two incubations. Descriptive statistics were computed for each triplicate sample.

Median and mean were used to characterize the central tendency, and the coefficient of variation (CV) was used to describe the variability in sample collection. Median values best represent the central tendency due to the unsymmetrical distribution of most triplicate samples and were used for all hypothesis testing. The value of the detection limit was used for all samples reported below the detection limit. The Wilcoxon paired-sample hypothesis test was used to determine whether water quality variable concentrations changed while passing through the

plant (Zar, 1984). This nonparametric test is equivalent to the paired-sample student's t test, but does not require that the data be normally distributed. An alternative hypothesis (H_a) that concentrations are different at the two locations is tested against the null hypothesis (H_o) of no difference in concentration between locations with a probability of 0.05 or less of committing a type I error.

2.2.2 Results and Discussion

Chemical oxygen demand concentrations and descriptive statistics are presented in table 2-2. Variations between sample dates is evident, but minimal. Data ranged from 4-13 mg/l, but were generally around 8 mg/l. Sampling variability is very low for most dates, with the highest CV at 23 percent. Data for BOD₅ are listed in table 2-3. Sixty percent of the measurements were below the detection limit of 1.0 mg/l. Sampling variability was low with only 3 of the 69 triplicate sample sets having a CV of 20 percent or more. Little variation between dates is observed with just two median concentrations over 2.0 mg/l. Ultimate CBOD and reaction rates are shown in table 2-4 for the five dates sampled. Some variability occurs in CBOD between dates with the average of all samples being 1.8 mg/l. There was considerable variation in the reaction rate constants between dates but not as much among the three locations. This variation in rates was expected since the incubations were not seeded and the concentrations of ultimate CBOD were very low. The variation was due to different lag times in establishing satisfactory microbial populations for oxidizing the organic matter in the sample. The long incubation time was necessary to determine ultimate BOD in unseeded samples.

Ammonia nitrogen concentrations and descriptive statistics are shown in table 2-5. Variation between sample dates were related to seasonal changes in the reservoir. Sampling variability was very high in most of the triplicate samples, with CV exceeding 100 percent in a number of instances. It is unclear from available information whether this variability was naturally occurring or due to unaccounted sample contamination. Table 2-6 shows the comparison of the ultimate NBOD to ammonia concentrations for samples collected concurrently. The complete oxidation of ammonia, as predicted from stoichiometric equations, requires 4.57 mg of oxygen for each milligram (mg) of ammonia, although studies have shown empirically the ratio to be slightly less due to limiting factors (Wezernak and Gannon, 1967; Ruane and Krenkel, 1978). Using the stoichiometric equivalent as a conservative estimate, ammonia contributed less than 50 percent of the NBOD in every instance. This is most likely due to high amounts of organic nitrogen in the sample contributing to the oxygen depletion during the laboratory incubation.

Comparisons of the measured parameters among locations for each sample date were made using the Wilcoxon paired-sample hypothesis test (table 2-7). Statistical significance was tested at a 95-percent confidence level. Statistically significant reductions in COD and BOD_5 concentrations were observed between the CCW intake and diffuser pond outflow. This result indicates that a reduction in oxygen demand is likely to occur but does not address the magnitude of the reduction. The sample data indicated a mean reduction in COD of -0.8 mg/l and BOD_5 of -0.1 mg/l. Both of these values are near the precision of the analytical methods used. Chemical oxygen demand was also significantly lower

between the inflow and outflow of the diffuser pond. Due to the small sample size, BOD₅ across the diffuser pond could not be tested for significant differences at the 95-percent confidence level, but tested significantly lower at the 80-percent confidence level. This suggests that the small reduction in oxygen demands is occurring in the diffuser pond. Two synergistic factors most likely cause the reduction in immediate oxygen demand during the 1-hr detention in the diffuser pond: (1) increased oxidation rates from elevated temperature, and (2) increased aeration of the water drawn from near the reservoir bottom.

2.2.3 Conclusions

1. No detectable increase in ultimate oxygen demands due to entrainment of plankton or fish larvae was detected as was described in the environmental impact statement for SQN (TVA, 1974).
2. The short-term oxygen demand of the cooling water at SQN is decreased slightly. On the average, chemical oxygen demand was reduced 0.8 mg/l and the 5-day BOD was reduced by 0.1 mg/l.

Table 2-1. Descriptive Statistics for the Change in Dissolved Oxygen Concentration in Sequoyah Nuclear Plant Cooling Water During Two-Unit Operation

Month (1989)	Number of measurements	Mean	Median	Minimum	Maximum	CV (%)	Fifth percentile
May	370	-0.29	-0.03	-1.16	0.16	65	-0.60
June	257	-0.68	-0.66	-1.28	-0.19	32	-1.04
July	25	-0.39	-0.41	-0.53	-0.23	21	-0.52
August	291	-1.13	-1.20	-2.17	-0.35	36	-1.79
September	567	-0.98	-0.98	-3.24	-0.51	24	-1.38
Pooled data	1510	-0.78	-0.78	-3.24	0.16	53	-1.45

Table 2-2. Concentrations and Descriptive Statistics for Chemical Oxygen Demand Measured in Sequoyah Nuclear Plant Cooling Water (Concentrations are Reported as mg COD/l)

Date	COD Intake						Diffuser pond Inflow						Diffuser pond outflow					
	1	2	3	Median	Mean	CV	1	2	3	Median	Mean	CV	1	2	3	Median	Mean	CV
May 09, 1988 ^a	10	10	10	10	10.0	0%	8	8	8	8	8.0	0%	8	7	8	8	7.7	8%
May 16, 1988	5	5	6	5	5.3	11%	5	6	5	5	5.3	11%	4	5	4	4	4.3	13%
May 24, 1988	8	7	7	7	7.3	8%	9	9	10	9	9.3	6%	6	6	5	6	5.7	10%
May 31, 1988	5	5	5	5	5.0	0%	6	6	6	6	6.0	0%	6	5	5	5	5.3	11%
May 15, 1989	7	7	8	7	7.3	8%	9	8	8	8	8.3	7%	7	7	7	7	7.0	0%
May 31, 1989	8	7	8	8	7.7	8%	7	8	7	8	7.3	8%	7	7	8	7	7.3	8%
Jun 05, 1989	7	8	7	7	7.3	8%	7	8	7	7	7.3	8%	6	7	6	6	6.3	9%
Jun 12, 1989	8	9	9	9	8.7	7%	8	7	8	8	7.7	8%	9	8	8	8	8.4	6%
Jun 19, 1989	9	9	10	9	9.3	6%	8	8	9	8	8.3	7%	8	9	8	8	8.3	7%
Jun 30, 1989	10	9	9	9	9.3	6%	9	8	6	8	7.7	20%	7	7	7	7	7.0	0%
Jul 06, 1989	8	8	7	8	7.7	8%	7	8	7	7	7.3	8%	7	8	7	7	7.3	8%
Jul 10, 1989	7	7	6	7	6.7	9%	5	5	5	5	5.0	0%	4	5	5	5	5.0	20%
Jul 18, 1989	8	8	8	8	8.0	0%	9	7	8	8	8.0	13%	9	9	8	9	8.7	7%
Jul 25, 1989	7	7	7	7	7.0	0%	7	8	6	7	7.0	14%	6	7	6	6	6.3	9%
Jul 31, 1989	8	8	7	8	7.7	8%	7	7	9	7	7.7	15%	7	6	6	6	6.3	9%
Aug 07, 1989	7	7	7	7	7.0	0%	7	7	7	7	7.0	0%	7	7	7	7	7.0	0%
Aug 15, 1989	9	9	9	9	9.0	0%	11	10	10	10	10.3	6%	8	8	8	8	8.0	0%
Aug 21, 1989	9	8	8	8	8.3	7%	8	9	9	9	8.7	7%	8	7	8	8	7.7	8%
Aug 30, 1989	6	6	6	6	6.0	0%	6	6	6	6	6.0	0%	6	6	6	6	6.0	0%
Sep 06, 1989	6	6	6	6	6.0	0%	7	6	7	7	6.7	9%	6	6	7	6	6.3	9%
Sep 11, 1989	7	6	7	7	6.7	9%	7	8	8	8	7.7	8%	6	4	5	5	5.0	20%
Sep 19, 1989	8	8	8	8	8.0	0%	8	7	7	7	7.3	8%	9	7	7	7	7.7	15%
Sep 26, 1989	8	7	5	7	6.7	23%	13	12	12	12	12.3	5%	6	6	5	6	5.7	10%

a. SQW not in operation

Table 2-3. Concentrations and Descriptive Statistics for 5-day Biochemical Oxygen Demand Measured in Sequoyah Nuclear Plant Cooling Water (Concentrations are Reported as mg O₂/l at 20°C)

Date	CW Intake					Diffuser pond Inflow					Diffuser pond outflow							
	1	2	3	Median	Mean	CV	1	2	3	Median	Mean	CV	1	2	3	Median	Mean	CV
May-09-88 ^a	2.8	2.6	2.8	2.8	2.73	6%	1.8	1.6	1.6	1.6	1.67	6%	5.2	5.0	4.8	5.0	5.00	4%
May-16-88	1.2	1.2	1.2	1.2	1.20	0%	<1.0	<1.0	<1.0	1.0	1.00	0%	<1.0	<1.0	<1.0	1.0	1.00	0%
May-24-88	<1.0	<1.0	<1.0	1.0	1.00	0%	1.1	1.0	1.0	1.0	1.03	5%	<1.0	<1.0	<1.0	1.0	1.00	0%
May-31-88	1.1	1.0	1.1	1.1	1.07	7%	<1.0	<1.0	<1.0	1.0	1.00	0%	<1.0	<1.0	<1.0	1.0	1.00	0%
May-15-89	1.4	1.5	1.5	1.5	1.47	4%	1.0	1.0	1.0	1.0	1.00	0%	<1.0	<1.0	<1.0	1.0	1.00	0%
May-31-89	1.5	1.5	1.7	1.5	1.57	7%	1.2	1.4	1.3	1.3	1.30	8%	<1.0	1.1	1.0	1.0	1.03	8%
Jun-05-89	<1.0	1.3	<1.0	1.0	1.10	21%	<1.0	<1.0	<1.0	1.0	1.00	0%	1.1	1.1	1.0	1.1	1.07	5%
Jun-12-89	1.4	1.2	1.2	1.2	1.27	8%	1.1	<1.0	<1.0	1.0	1.03	5%	<1.0	<1.0	1.2	1.0	1.67	10%
Jun-19-89	1.3	1.3	1.3	1.3	1.30	0%	1.4	1.3	1.3	1.3	1.33	4%	1.4	1.3	1.1	1.3	1.27	12%
Jun-30-89	1.2	1.2	1.3	1.2	1.23	4%	<1.0	<1.0	<1.0	1.0	1.00	0%	<1.0	<1.0	<1.0	1.0	1.00	0%
Jul-06-89	1.0	<1.0	1.4	1.0	1.13	19%	1.0	<1.0	<1.0	1.0	1.00	0%	<1.0	<1.0	<1.0	1.0	1.00	0%
Jul-10-89	<1.0	<1.0	<1.0	1.0	1.00	0%	<1.0	<1.0	1.1	1.0	1.03	5%	1.0	1.0	<1.0	1.0	1.00	0%
Jul-18-89	1.2	1.2	1.4	1.2	1.27	8%	<1.0	<1.0	<1.0	1.0	1.00	0%	<1.0	<1.0	<1.0	1.0	1.00	0%
Jul-25-89	<1.0	<1.0	<1.0	1.0	1.00	0%	<1.0	<1.0	<1.0	1.0	1.00	0%	<1.0	<1.0	<1.0	1.0	1.00	0%
Jul-31-89	<1.0	1.1	<1.0	1.0	1.03	8%	<1.0	<1.0	<1.0	1.0	1.00	0%	<1.0	<1.0	<1.0	1.0	1.00	0%
Aug-07-89	1.6	1.4	1.8	1.6	1.60	13%	1.2	1.7	2.2	1.7	1.70	29%	1.1	1.4	1.1	1.1	1.20	20%
Aug-15-89	<1.0	<1.0	<1.0	1.0	1.00	0%	<1.0	<1.0	<1.0	1.0	1.00	0%	<1.0	<1.0	<1.0	1.0	1.00	0%
Aug-21-89	<1.0	<1.0	<1.0	1.0	1.00	0%	<1.0	<1.0	<1.0	1.0	1.00	0%	<1.0	<1.0	<1.0	1.0	1.00	0%
Aug-30-89	<1.0	1.0	<1.0	1.0	1.00	0%	<1.0	<1.0	<1.0	1.0	1.00	0%	<1.0	<1.0	<1.0	1.0	1.00	0%
Sep-06-89	<1.0	<1.0	<1.0	1.0	1.00	0%	<1.0	<1.0	<1.0	1.0	1.00	0%	<1.0	<1.0	<1.0	1.0	1.00	0%
Sep-11-89	<1.0	<1.0	<1.0	1.0	1.00	0%	<1.0	<1.0	<1.0	1.0	1.00	0%	<1.0	<1.0	<1.0	1.0	1.00	0%
Sep-19-89	1.3	1.4	1.4	1.4	1.37	4%	2.2	2.0	1.7	2.0	1.97	13%	1.5	1.3	1.2	1.3	1.33	11%
Sep-26-89	<1.0	<1.0	<1.0	1.0	1.00	0%	<1.0	<1.0	<1.0	1.0	1.00	0%	<1.0	<1.0	<1.0	1.0	1.00	0%

a. SQN not in operation

Table 2-4. Concentrations and Rate Constants for Ultimate Carbonaceous Biochemical Oxygen Demand Measured in Sequoyah Nuclear Plant Cooling Water (Concentrations Reported as mg O₂/l at 20°C)

Date	CCW intake		Diffuser pond inflow		Diffuser pond outflow	
	CBOD (mg/l)	Rate (1/day)	CBOD (mg/l)	Rate (1/day)	CBOD (mg/l)	Rate (1/day)
May 16, 1988	1.6	0.080	1.2	0.078	1.3	0.073
May 31, 1989	1.6	0.107	1.6	0.111	1.4	0.128
Jun 30, 1989	1.9	0.064	1.8	0.038	2.2	0.027
Aug 30, 1989	2.6	0.027	1.9	0.029	2.1	0.026
Sep 26, 1989	1.7	0.038	1.7	0.039	2.3	0.025

Table 2-5. Concentrations and Descriptive Statistics for Ammonia Nitrogen Measured in Sequoyah Nuclear Plant Cooling Water
(Concentrations are Reported as mg NH₃-N/l)

Date	CW Intake				Diffuser pond Inflow				Diffuser pond outflow			
	replicate number				replicate number				replicate number			
	1	2	3	Median	Mean	CV	1	2	3	Median	Mean	CV
May 09, 1988 ^a	0.04	0.04	0.05	0.04	0.043	13%	0.05	0.06	0.05	0.05	0.05	0%
May 16, 1988	0.11	0.12	0.11	0.11	0.113	5%	0.12	0.12	0.12	0.12	0.12	0%
May 24, 1988	0.17	0.17	0.17	0.17	0.170	0%	0.18	0.17	0.17	0.17	0.17	0%
May 31, 1988	0.06	0.06	0.07	0.06	0.063	9%	0.08	0.07	0.07	0.08	0.07	8%
May 15, 1989	0.01	0.02	0.01	0.01	0.013	43%	0.03	0.04	0.02	0.04	0.02	43%
May 31, 1989	0.02	0.01	0.01	0.01	0.013	43%	0.02	0.01	0.03	0.02	0.02	25%
Jun 05, 1989	0.02	0.03	0.03	0.03	0.027	22%	0.03	0.06	0.03	0.04	0.03	33%
Jun 12, 1989	<0.01	0.02	<0.01	0.01	0.013	43%	0.01	0.01	<0.01	0.01	0.01	152%
Jun 19, 1989	0.04	0.03	0.03	0.03	0.033	17%	0.04	0.04	0.04	0.04	0.04	35%
Jun 30, 1989	0.02	0.03	0.02	0.02	0.023	25%	0.06	0.03	0.02	0.03	0.04	51%
Jul 06, 1989	0.04	0.05	0.26	0.05	0.117	106%	0.21	0.04	0.04	0.04	0.04	16%
Jul 10, 1989	0.06	0.07	0.01	0.06	0.047	67%	0.01	0.01	0.01	0.04	0.04	35%
Jul 18, 1989	0.03	0.03	0.03	0.03	0.047	62%	0.03	0.04	0.03	0.04	0.02	43%
Jul 25, 1989	0.04	0.02	0.03	0.03	0.030	33%	0.08	0.04	0.13	0.08	0.083	72%
Jul 31, 1989	0.03	0.03	0.03	0.03	0.030	0%	0.03	0.05	0.03	0.03	0.037	69%
Aug 07, 1989	0.03	0.01	0.02	0.02	0.020	50%	0.01	0.01	0.02	0.01	0.013	43%
Aug 15, 1989	0.07	0.04	0.07	0.07	0.060	29%	0.11	0.05	0.04	0.05	0.067	25%
Aug 21, 1989	0.00	0.14	0.24	0.24	0.460	102%	0.54	0.09	0.06	0.09	0.230	71%
Aug 30, 1989	0.32	0.03	0.03	0.03	0.127	132%	0.02	0.10	0.03	0.03	0.050	46%
Sep 06, 1989	0.03	0.03	0.03	0.03	0.027	22%	0.03	1.10	0.05	0.05	0.393	108%
Sep 11, 1989	0.03	0.03	0.03	0.03	0.030	0%	0.03	0.03	0.03	0.03	0.030	22%
Sep 19, 1989	0.03	0.03	0.03	0.03	0.030	0%	0.06	0.03	0.03	0.03	0.030	0%
Sep 26, 1989	0.07	0.04	0.05	0.05	0.053	29%	0.05	0.06	0.04	0.05	0.04	13%

a. SW not in operation

Table 2-6. Concentrations of Ultimate Nitrogenous Biochemical Oxygen Demand Measured in Sequoyah Nuclear Plant Cooling Water

Date	CCW Intake			Diffuser pond Inflow			Diffuser pond outflow		
	MBOD (mg O ₂ /l)	NH ₃ -N (mg N/l)	Percent from NH ₃ -N	MBOD (mg O ₂ /l)	NH ₃ -N (mg N/l)	Percent from NH ₃ -N	MBOD (mg O ₂ /l)	NH ₃ -N (mg N/l)	Percent from NH ₃ -N
May 16, 1988	1.1	0.11	46%	1.1	0.12	50%	1.2	0.12	46%
May 31, 1989	1.9	0.01	2%	0.8	0.02	12%	0.8	0.02	17%
Jun 30, 1989	0.9	0.02	10%	0.8	0.03	17%	0.6	0.04	31%
Aug 30, 1989	2.0	0.03	7%	1.0	0.03	14%	0.5	0.03	28%
Sep 26, 1989	0.9	0.05	26%	1.0	0.05	23%	0.4	0.04	46%

Table 2-7. Summary Statistics of Wilcoxon Paired-Sample Test on Parameters Measured in Sequoyah Nuclear Plant Cooling Water

H_0 : Concentrations are the same in the CCW intake and Diffuser Pond Outflow;
 H_a : Concentrations are NOT the same in the CCW intake and Diffuser Pond Inflow;
 $\alpha (2) = 0.05$

Parameter	Mean difference (mg/l)	N ^a	Positive rank sum	Negative rank sum	Probability	Significant at 95% confidence ^b
COD	0.2	15	67.5	52.5	$p = >0.50$	No
BOD ₅	-0.04	9	10.5	34.5	$<10.20 p = <0.50$	No
CBOD	-0.24	3	0	6	$p = >0.50$	No
Ammonia-N	-0.005	13	49.5	41.5	$p = >0.50$	No
NBOD	-0.42	4	1.5	8.5	$<0.20 p = <0.50$	No

H_0 : Concentrations are the same in the Diffuser Pond Inflow and Outflow;
 H_a : Concentrations are NOT the same in the Diffuser Pond Inflow and Outflow;
 $\alpha (2) = 0.05$

Parameter	Mean difference (mg/l)	N ^a	Positive rank sum	Negative rank sum	Probability	Significant at 95% confidence ^b
COD	-1.0	15	6	114	$p = 0.001$	Yes
BOD ₅	-0.07	4	1	9	$<0.20 p = <0.50$	No
CBOD	0.06	5	12	3	$<0.20 p = <0.50$	No
Ammonia-N	0.008	11	39.5	26.5	$p = >0.50$	No
NBOD	-0.24	4	1	7	$<0.20 p = <0.50$	No

H_0 : Concentrations are the same in the CCW Intake and Diffuser Pond Outflow;
 H_a : Concentrations are NOT the same in the CCW Intake and Diffuser Pond Outflow;
 $\alpha (2) = 0.05$

Parameter	Mean difference (mg/l)	N ^a	Positive rank sum	Negative rank sum	Probability	Significant at 95% confidence ^b
COD	-0.8	16	6.5	129.5	$p = <0.001$	Yes
BOD ₅	-0.11	10	2	53	$<0.005 p = <0.01$	Yes
CBOD	-0.02	5	8.5	7.5	$p = >0.50$	No
Ammonia-N	0.003	16	78.5	57.5	$p = >0.50$	No
NBOD	-0.66	5	1	14	$<0.10 p = <0.20$	No

- a. Test sample size used to compute Wilcoxon T Statistic. Differences of zero are ignored in the analysis.
- b. Testing for significance at 95% confidence is not possible for N less than 6.

Figure 2-1. Locations of Sampling Stations for Inplant Monitoring

3.0 NEAR-FIELD RESERVOIR DISSOLVED OXYGEN DISTRIBUTION

As water flows past SQN, a number of factors influence the distribution of DO in the reservoir. The underwater dam, built to retain bottom water to provide cooler intake water temperatures and prevent short circuiting of the downstream thermal discharge, impedes the downstream movement of water in the lower strata of the reservoir. The submerged dam forms a pool of water in the reservoir that remains in contact with the bottom sediment for a longer period than in the riverine section of the reservoir. Prolonged contact with the sediment increases the oxygen consumed due to the oxygen demand exerted by the sediment on the overlying water. Because the underwater dam forms a pool at lower depths, the reservoir reach just upstream from the dam exhibits intermittent weak thermal stratification and a clinograde oxygen profile (Cole, 1975). As water flows over the underwater dam, lower strata from upstream are entrained towards the surface and velocity increases. Reservoir water is then vertically mixed by turbulence as the water "spills" over the dam.

Mixing of the water column is also promoted by the thermal discharge just downstream from the submerged dam. The added heat in the discharge plume creates a buoyant jet that helps to further destratify the reservoir (Gu and Stefan, 1988). However, if the reservoir is strongly stratified, the momentum and buoyancy of the thermal plume may not be sufficiently strong to force the plume to rise completely to the surface (Hauser et al., 1988). The mixed water column begins to return to a weakly stratified condition just downstream from the diffuser mixing zone.

Some of the factors that affect the redistribution of DO in the reservoir occur on a daily cycle. Algae and aquatic macrophytes on the overbanks and adjacent embayments, and phytoplankton in the main channel, alter the DO concentrations through photosynthesis and respiration. Regulating Chickamauga Dam releases for peaking power demand can cause flows in the lower reaches of the reservoir to reverse toward Watts Bar Dam for a few hours daily.

Many studies of Chickamauga Reservoir in the vicinity of SQN have observed patterns of DO distribution that can be explained by the factors described above. However, these studies have been limited in scope and do not define the extent and duration of the DO redistribution. This section will describe studies designed to examine the dynamics of DO redistribution and important influencing factors.

3.1 Underwater Dam Mixing Processes

Evidence of vertical mixing of the water column in the vicinity of the SQN underwater dam and diffuser has been observed during water quality surveys in Chickamauga Reservoir (McIntosh et al., 1983). The SQN intake, underwater dam, and diffuser structures complicate the natural flow and mixing patterns in this portion of Chickamauga Reservoir (figure 1-3). A dye study was conducted by the Water Center Of Tennessee Technological University to determine the magnitude of vertical mixing caused by flows passing over the underwater dam (Brown and Gordon, 1987).

There were four important variables sampled during the dye study; DO, temperature, velocity, and dye concentration. Sufficient data were obtained for each of these to show the vertical patterns in the vicinity of the underwater dam. All of the measurements were generally consistent with the hypothesis that the dam produced significant upwelling with increased vertical mixing, especially in the layers between the top of the dam and the water surface. However, this vertical mixing was not sufficient to eliminate the relatively weak thermal stratification of 1°C that existed in the upper 6 m depth. Both the dam and diffuser structures provide significant perturbations in the flow patterns of the lower layers of the reservoir. The dye measurements indicated that natural vertical mixing upstream from the dam was significant, distributing dye over a depth of 6 m within 1,000 ft of the injection point. This conceptual description of mixing in the vicinity of the Sequoyah Dam and diffuser is illustrated in figure 3-1.

Observations made during the study suggested that the 90-degree bend in the main channel may also have a significant effect on vertical circulation patterns in the vicinity of the SQN. A large spiraling of the flow occurs in the vicinity of SQN, with the bottom water moving toward the outside of the bend and the surface water moving toward the inside of the bend. An upwelling is created along the outside of the bend, especially near the bluff downstream from the dam and diffuser.

3.2 Distribution of Dissolved Oxygen in the Vicinity of SQN

Daytime DO concentrations in Chickamauga Reservoir exhibit large spatial and temporal variations. These variations are largest near SQN due to gradients created by the underwater dam and thermal diffuser discharge. Within this short reach, conditions in the main channel can change from stratified to well mixed. The large overbank areas adjacent to the main channel can exhibit different characteristics in DO and temperature. In previous water quality surveys, measurements made at the compliance depth of 5 ft in the main channel have indicated a reduction of DO within and downstream from the diffuser mixing zone. Analysis of available data indicated that the low DO water in the lower strata of the reservoir is mixed with surface layers, thereby reducing the DO concentration at 5 ft within the diffuser mixing zone (Ostrowski, 1985). Concern has been raised about the relationship between the oxygen demands of the thermal discharge and the observed reduction in DO in the mixing zone. Seasonal data covering the entire reservoir reach in the vicinity of SQN, including overbank areas, are required to compute volume weighted mass balances to determine whether DO is being consumed or just redistributed within the water column.

3.2.1 Materials and Methods

Field--Hydrolab profiles and secchi disc readings were performed at 39 locations on the Tennessee River in and around the mixing zone near SQN (table 3-1). A Hydrolab profile included readings for temperature, conductivity, DO, and pH. Hydrolab readings were taken at 0.3, 1.0, 1.5, 3.0 m and continued at 1.5-m increments to 1 m from the bottom. The Hydrolab profiles and secchi disc measurements were made at several

horizontal locations for each river mile (table 3-1) and were conducted weekly from July 1, 1987 through September 22, 1987 achieving a 13-week monitoring period. The 39 stations were divided into two groups with 24 stations monitored during the odd weeks (1, 3, 5, 7, 9, 11, and 13) and 15 stations monitored during the even weeks (2, 4, 6, 8, 10, and 12) (table 3-1). Data from the Chickamauga Reservoir regular monitoring program were used when the stations were the same for both studies to eliminate duplication of work.

Boats were used to perform Hydrolab and secchi disc surveys. Topographic maps and two-way FM radios were used to locate specific stations. Data collection was accomplished using the Hydrolab Surveyor II Water Quality Instrument, the Hydrolab 5100-A Field Data Logger and Water Quality Data Field Worksheets for Reservoirs.

The Hydrolab Surveyor II instruments were standardized prior to and following every survey. The standardizations were performed according to procedures given in the TVA Field Engineering Procedures Manual (TVA, 1990), using a precalibrated thermometer for standardization of temperature, conductivity standards of 150 and 300 micromhos per centimeter ($\mu\text{mhos/cm}$) for standardization of conductivity, the Winkler Method for standardization of DO and pH buffers of 4.0, 7.0, and 10.0 for standardization of pH. Hydrolab instruments were also sent to the Field Instrumentation Laboratory in Muscle Shoals, Alabama for cleaning and calibration every six months or when a problem with a particular instrument occurred.

Data Analysis--All collected data were entered into EPA's water quality database (STORET). Dissolved oxygen mass was calculated for both main channel water column and reservoir cross-sections. The deepest DO measurement was extrapolated to a fixed depth representing the reservoir bottom at each sampling location. Data collected at many stations not in the main channel were reported with widely differing maximum sampled depths from one week to the next. This data problem was most likely the result of sampling in different locations than reported and not from variations in the bottom. Data were not used in the volumetric analysis if the maximum depth sampled varied by 3 m or more from the actual reservoir bottom at a particular location. Cross-sectional DO mass was calculated from the horizontal locations sampled at each river mile with the assumption that each profile represented one-third of the reservoir width at that point. All DO mass calculations were normalized with the column or segment volume for comparisons as volume weighted mean DO concentrations.

Data were statistically compared using the Wilcoxon paired-sample hypothesis test (Zar, 1984) from three different river miles representing locations upstream from the underwater dam (TRM 484.1), the downstream edge of the diffuser mixing zone (TRM 483.4), and one-half mile downstream from the mixing zone (TRM 482.9). The test was applied to seasonal data for spring (April, May, and June) and summer (July, August, and September). Data collected at all locations were compared by visual inspection of plots for each sampling date in the spring and summer. Isopleth graphs were generated with the software GCONT (Harper, 1987).

Dissolved oxygen saturation was computed as a function of temperature (Rich, 1973). The surface to bottom temperature differential was calculated from the difference between the temperature measurement made at 0.3 m minus the temperature at the maximum depth sampled for each profile.

3.2.2 Results and Discussion

Isopleth plots of data collected from the main channel for the spring and summer sampling dates of the study are presented in figures C-1 through C-84. These figures show vertical contours for temperature, DO, and DO saturation in the vicinity of the underwater dam (location indicated by a triangle). On most dates, the reservoir appears to be more strongly stratified upstream from the dam (right side of the plot) relative to downstream conditions. The degree of stratification varies considerably between dates and does not appear to relate to a specific season or to plant operation. The frequent mixing of the water column upstream from the submerged dam is the result of many interrelated factors that influence mixing including air temperature, wind speed, flow velocity, and dam operations.

On most of the sampling dates the DO, temperature, and pH are vertically mixed downstream from the underwater dam. The reservoir is strongly stratified for those dates where vertically mixed conditions are not evident downstream from the submerged dam (e.g. May 27, 1987). None of these dates occurred when the plant was operating, indicating the importance of the thermal discharge on mixing. Although it is difficult to separate the relative influence of the submerged dam and the thermal plume on destratification, they both undoubtedly contribute to mixing

the water column. However, it has been observed that neither factor is sufficient to mix the entire water column during periods of strong stratification (Hauser, 1988).

Isopleth plots for data collected from three horizontal locations at river miles upstream from the mixing zone, in the mixing zone, and downstream are presented in figures C-85 through C-210. The upstream and downstream locations have large overbank areas adjacent to the main channel. Overbank areas commonly have conditions different from the main channel due to relatively reduced vertical mixing and water velocity. Temperatures are generally higher on the overbanks since surface heated water is not mixed into deeper water. Dissolved oxygen and pH are also generally higher on the overbanks due to higher photosynthetic rates from algae and aquatic macrophytes. The shallower depths on the overbanks allow algae to remain within the photic zone in contrast to the main channel, increasing the time of photosynthetic activity. Water from the overbanks is continually entrained into main channel flow moving downstream and replaced through continuity with upstream water.

Three different plots are presented in each of the figures C-211 through C-252. Each figure shows the longitudinal relationship of volume weighted mean DO calculated for a water column in the main channel and a cross-section of the reservoir at each river mile sampled for a particular date. These plots represent a mass balance of DO, normalized to a concentration to account for different volumes at each river mile. A shorter river reach with more closely spaced locations was sampled on alternating weeks during the summer of 1987. Some of the cross-sectional mean DO values were not presented due to suspect data. The second graph

on each figure displays the DO in the main channel measured at 5 ft. The third graph shows the surface to bottom temperature differential as an indication of thermal stratification.

On a majority of the dates sampled there was no apparent difference between the volume weighted mean DO calculated for the main channel and the cross-section. There was also no apparent difference between river miles indicated by the general flatness of the line connecting the data points. This implies that there is no observable net increase or decrease in DO along the reservoir channel near the plant. When the cross-sectional mean DO was different from the main channel mean water column DO, it was generally upstream from the submerged dam (e.g., July 28, 1987). This was due to the influence of overbank photosynthesis on the DO mass balance. Downstream from the underwater dam on these dates, the main channel mean DO increased, probably due to entrainment of the upstream overbank water into the mixing zone.

The DO measured at 5 ft showed little longitudinal change in early spring because stratification had not become established. When the water upstream became stratified, as implied by the greater surface to bottom temperature difference, DO at 5 ft tended to be lowest just downstream from the submerged dam. The temperature difference also dropped at this point, indicating mixing of the water column. For the dates in the summer of 1987, when more intensified sampling was conducted around the mixing zone, the drops in DO and temperature difference were observed only along a short reach of the reservoir before returning to upstream levels.

Data from 1989 did not show the same magnitude of DO reduction at 5 ft as was observed in 1987 and 1988, even though some thermal stratification was evident. The unusually high flows during the summer of 1989 resulted in well mixed conditions throughout the reservoir. Dissolved oxygen at 5 ft was below the state of Tennessee criterion of 5.0 mg/l for the protection of fish and aquatic life only twice during the study; 4.7 mg/l on July 1, 1987, and 4.9 mg/l on September 22, 1987. Both of these measurements occurred just downstream from the underwater dam (TRM 483.7) and when SQN was not in operation. These are the result of entrainment of low DO water from the bottom to the surface, as the water passes over the underwater dam just upstream from the diffuser mixing zone.

Three stations were chosen to statistically evaluate changes in DO distribution near SQN; upstream from the submerged dam (TRM 484.1), the downstream edge of the diffuser mixing zone (TRM 483.4), and one-half mile further downstream from the mixing zone (TRM 482.9). A paired-sample hypothesis test was required since the observations at each river mile were not independent. The analysis tested whether there was a consistent concentration difference between locations, but did not explicitly test the magnitude of any difference. The nonparametric Wilcoxon paired-sample test has an advantage over the commonly used student t test because it does not require the data to be normally distributed.

Data for DO measured at 5 ft and mean water column DO were divided according to the season for hypothesis testing. The differences in DO between each station were calculated for each sample date and are

presented in tables 3-2 and 3-3. Dissolved oxygen differences were used to test for significant changes between upstream and downstream sample locations. Summary statistics for the hypothesis tests are shown in tables 3-4 and 3-5. A statistically significant reduction in DO at 5 ft was observed during the spring for all three consecutive years. This reduction occurred only along the reach of river upstream from the underwater dam to the downstream edge of the diffuser mixing zone. There was no statistically significant reduction observed in DO at 5 ft during either of the summers (1987 and 1989). The mean reduction in DO at 5 ft for data collected from all three springs was 0.9 mg/l.

The only season to show a statistically significant change in mean water column DO was the spring of 1989 (table 3-5). This reduction occurred downstream from the diffuser mixing zone and averaged 0.3 mg/l. Combining all data collected in the spring and summer for the study increased the sample size for hypothesis testing and improved the ability to detect statistically significant changes. The pooled data set indicated that there was a statistically significant increase in mean water column DO of 0.2 mg/l from upstream of the submerged dam to the downstream edge of the mixing zone and a significant decrease of 0.2 mg/l DO one-half mile downstream from the mixing zone. Overall, analysis of the pooled data show no statistically significant net change in mean water column DO from upstream to downstream from the plant.

3.2.3 Conclusions

1. The underwater dam produces significant upwelling with increased vertical mixing, especially in the layers between the top of the dam and the water surface.

2. Both the underwater dam and diffuser structures provide significant perturbations in the flow patterns of the lower layers of the reservoir.
3. The natural bend in the main channel may have a significant effect on vertical circulation patterns in the vicinity of SQN.
4. A statistically significant decrease in DO measured at 5 ft during three consecutive springs averaging 0.9 mg/l was observed downstream from the mixing zone as compared to upstream from the underwater dam.
5. No statistically significant change in mean water column DO was observed between the upstream and downstream locations tested.
6. SQN does not change the mass of DO in the reservoir, but does redistribute the DO into a mixed water column.

3.3 Diel Variations of Dissolved Oxygen in the Vicinity of SQN

Dissolved oxygen concentrations in reservoirs can vary considerably over a short period due to many different factors. While photosynthesis from algae and aquatic macrophytes contributes DO to the water, respiration consumes DO continually, with the lowest DO concentrations observed at night, when photosynthesis does not occur. Meteorological conditions such as wind and temperature affect the rate of oxygen flux between water and the atmosphere. Changing hydrodynamic flow regimes alters the patterns of oxygen redistribution. The variation in DO can also be large spatially. The daily photosynthetic contribution of DO is greatest in

shallow overbanks and embayments where algae remain in the photic zone in contrast to the main river channel. These shallow areas also contain aquatic macrophytes which produce DO during the day. At night, these stationary macrophyte beds consume DO through respiration, having the greatest effect on overbank areas. Thus within a 24-hr period, DO can be extremely variable throughout the reservoir.

Operation of Chickamauga Dam may also change the pattern of DO distribution observed during the day. When the dam is operated to meet peaking power demands, there is typically a period in the early morning when the flow stops or is reduced. The constriction of flow at the dam causes an increase in hydrostatic pressure relative to upstream resulting in a reversal of flow in the reservoir. The distance traveled and magnitude of the reverse flow depends on the quantity and timing of water releases from both Watts Bar and Chickamauga Dams. Preliminary modeling of hydraulic routing in Chickamauga Reservoir with several typical dam operating schedules estimated the 24-hr minimum flows at SQN to range from -13,000 to 38,000 cfs. The frequency that reverse flows occur at SQN is unknown. Moving between upstream and downstream flows at SQN is dynamic and can have a great effect on the mixing regime around the diffuser discharge and underwater dam. Frequent sampling over the diel cycle was required to characterize the changing distribution of DO in the reservoir reach near SQN.

3.3.1 Materials and Methods

Field--The materials and equipment used in this study were divided into four categories: transportation, navigation, data collection, and data storage. Transportation equipment included boats with support

equipment and a mobile lab. The navigation equipment consisted of topographic maps, Interphase DC-2000™ electronic long-range navigational (LORAN™) units, Interphase DC-1000™ electronic depth finders, marker buoys, strobe lights, and two-way radios. Data collection was accomplished using the Hydrolab Surveyor II™ analysis instrument with the Hydrolab 5100-A Field Data Logger™, backed up by handwritten field sheets. Data storage equipment included the Zenith Lap Top Computer™ Model ZFL-181-93, an IBM Personal Computer Graphics Printer™ Model 5152, 3.5-in diskettes, and the handwritten field sheets.

In order to accomplish the objective of this study, Field Engineering divided the 48-hr period into four 12-hr shifts manned by two 2-man boat crews and two shore-based support personnel. The study area was divided into 8 river mile transects with each transect containing three horizontal locations. One 2-man boat crew sampled one transect (three horizontal locations) per hr. One boat crew sampled the upper 4 river mile transects, working downstream to upstream, while the other boat crew simultaneously sampled the lower 4 river mile transects, working upstream to downstream. By using this procedure, it was expected that the study area would be sampled on 4-hr intervals. However, unanticipated delays in the field caused some data not to be collected. A severe thunderstorm prohibited the collection of data for an 8-hr period on the first diel survey. The resulting sampling scheme is shown in figures D-1 and D-2. In general, good coverage of the study area was realized with this sampling plan.

Field Engineering crews located the selected sampling sites, river mile transects and horizontal locations, using topographic maps and electronic depth finders. Before launching, generally identifiable landforms were located on the U.S. Geological Survey (USGS) 7.5-min series Snowhill, Tennessee, quadrangle topographic map. By using this technique, the crews were able to visually locate the selected river mile transects while on the reservoir. The boat crews verified the locations of the river mile transects at the underwater structures and all of the horizontal locations by the depths measured with the electronic depth finders.

All of the sampling sites were marked with strobe-light buoys for return-navigation aid. In addition to this physical marking, the crews entered the LORAN™ positions of the sampling sites into the memories of the LORAN™ units and recorded the LORAN™ positions on navigational field sheets. Shore-support personnel worked in the boats with the boat crews during the first 4-hr sampling period to facilitate deployment of these site markers.

The boat crews sampled each site by lowering the Surveyor II™ analysis instrument to a depth of 0.3 m below the surface of the water and taking the selected parameter readings. The second and third depths at which readings were taken were 1.0 and 1.5 m, respectively. The remaining portions of the water column below the 1.5-m depth were sampled at 1.5-m increments of depth. When the bottom was touched, the instrument was pulled back up 1 m from the bottom for the final reading at this site.

The Surveyor II™ analysis instruments were calibrated at the beginning of each 12-hr shift and at the end of the final 12-hr shift. At the end of each 4-hr interval, the boat crews returned to the shore base (Harbor Lights Marina) to turn in the electronic field data loggers and the field sheets for that period. During the time on shore, the boat crews checked the calibration of the analysis instruments and made any necessary adjustments. Fresh data loggers were issued to the boat crews as the crews returned to the reservoir for the next 4-hr sampling interval.

Shore-support personnel downloaded the field data loggers with the Zenith Lap Top Computer™ to 3.5-in diskettes and then printed a hard copy of the data. These data were compared to the field sheet data for instrument-related data collection problems. Hard copy, field sheet, and diskette-stored data were reserved for later permanent data storage and further data manipulation by Field Engineering and Data Management personnel.

Six aerial photographs using thermal infrared scanning equipment were made from 7000 ft above ground level on September 9 at 12:01 a.m., 1:57 a.m., 4:04 a.m., 10:33 a.m., and 5:43 p.m.

Data Analysis--All water quality data were entered into EPA's STORET water quality file. Isopleth plots were prepared with the software SURFER--Version 4 (Golden Software, 1989) using the kriging and normal search methods for interpolation between sampled data. Estimates of flows at SQN were made using hourly discharges from Watts Bar and Chickamauga Dams in the hydraulic routing routine of the BETTER model adaptation for Chickamauga Reservoir.

3.3.2 Results and Discussion

Meteorological conditions for the first diel survey are presented in table 3-6. The 48-hr period was characterized by light and variable winds, with daytime high air temperatures near 90°F. An intense thunderstorm occurred in the afternoon of the second day, precluding sampling for a 9-hr period. This storm event was typical of weather for that time of year and resulted in over 0.5-in. of rainfall. Discharges from both Watts Bar and Chickamauga Dams during the first diel survey are shown in table 3-7. Flows during the summer of 1989 were well above normal due to abundant rainfall causing frequent discharges over the spillways of both dams. Special reservoir operations were scheduled to achieve two periods of zero flow at Chickamauga Dam. Although the estimated flow at SQN was reduced substantially by these operations, the anticipated reverse flow probably did not occur due to the continuous high discharges from Watts Bar Dam.

Longitudinal isopleth plots of DO and temperature in the main channel plotted at depth and laterally (percent horizontal location from right bank looking upstream) at 5 ft for each sampling round are presented in figures D-4 through D-45. Approximate bottom elevations, navigation channel, and sampling locations are identified in figure D-3. The first sampling round of the first diel survey took most of the day. The thermal discharge plume was evident in the temperature data, where the surface temperature was raised by approximately 2°C in a localized area (figure D-4). A small pocket of increased DO also appeared near the bottom downstream from the discharge, but the DO was nearly uniform in the rest of the reservoir reach. Surface DO upstream from the submerged

dam was substantially higher during the next sampling round indicating increased photosynthesis (figure D-6). Mixing that occurred downstream from the underwater dam distributed algae throughout the water column, reducing photosynthesis by limiting light. Increases in DO and temperature relative to the main channel were also observed in the overbank areas, as a result of greater photosynthetic activity and shallower depths.

Plots of the fourth sampling round (figures D-10 and D-11) show a weakening of the large gradients observed during the prior day of sampling. The relatively low flows at SQN that occurred during this period had the effect of spreading the thermal discharge evenly in all directions. Spreading of the discharge plume was even more evident during the fifth sampling round (figures D-12 and D-13). However, when the flows increased and daylight began, a pattern similar to the previous day appeared (figure D-14). This pattern remained evident until sampling was halted by the thunderstorm. Plots of the last two sampling rounds of the first diel survey show the same even spreading of the discharge plume under similar low flow conditions (figures D-18 through D-21).

Weather conditions during the second diel survey were similar to conditions during the first survey, but without thunderstorms (table 3-8). Wind speed was light and wind direction was more consistent. Dam flows were similar to the first diel survey, but with reduced discharges from Watts Bar Dam during the periods of zero discharge from Chickamauga Dam. As a result, two periods of reverse flow were estimated to have occurred at SQN (table 3-9).

The dynamic patterns of DO and temperature distribution for the second diel survey were very similar to results from the first survey (figures D-22 through D-45). A strong thermal gradient was observed in the main river channel in the vicinity of the diffuser discharge. Dissolved oxygen was greatest upstream from the submerged dam in the main channel and on the overbanks towards the end of each day. During periods of reverse flow, thermal profiles showed an even longitudinal temperature distribution within the discharge plume, with the highest temperatures recorded directly over the diffuser. Dissolved oxygen also has a fairly uniform distribution during periods of reverse flow. The combined effect of the thermal plume and reversed flows mixed the DO uniformly throughout this reach of the reservoir.

The upstream movement of the thermal discharge was greater in the second diel survey than the first survey. Presumably, this was caused by periods of reverse flow, but a steady southwest wind may have also contributed to moving some surface water upstream. Aerial infrared photographs of the reservoir reach are shown in figures 3-2 through 3-6. The lighter areas on these photographs indicate higher relative temperatures. Figure 3-2 clearly shows the thermal discharge flowing downstream from the diffuser. When flows approached zero, the thermal plume began to spread out evenly on the reservoir surface (figure 3-3). As flows began to reverse, the surface temperature increased further upstream from the underwater dam (figure 3-4). Even after full downstream flows had been reestablished, surface temperatures remained relatively high upstream from the submerged dam, evident in the 10:33 a.m. photograph (figure 3-5). The depth of this warmer water

is fairly shallow as observed by upwelling of colder water over the submerged dam and behind a barge. By afternoon, the surface temperature pattern returned to that observed before the reverse flow (figure 3-6).

Overall, there was very little difference in the observed temperature and DO distribution patterns for the two diel surveys. Isopleth depth plots of every station during each survey period are displayed in figures D-46 through D-93 for comparison of patterns between the two surveys. The temperature and DO distributions over time were remarkably similar in most cases. Most differences can be explained by a lack of data from the first survey when fewer samples were taken. Patterns for pH tended to be different. However, the pH did not differ considerably in space or time, except during periods of high photosynthetic activity. As a result, high pH values are more common at overbank locations. In general, conditions were similar for both diel surveys and comparable dynamic patterns of DO and temperature distribution observed during both surveys.

3.3.3 Conclusions

1. The distribution patterns of DO and temperature near SQN were extremely dynamic over a diel period.
2. During the daytime, overbank areas showed higher DO and temperature levels compared to the adjacent main channel. These higher levels resulted from shallower depths and higher photosynthetic activity.

3. The surface water upstream from the underwater dam contained relatively more daytime DO from photosynthesis. Mixing of the water column downstream from the submerged dam distributed algae to depths where light limits productivity, suppressing the relative daytime DO.
4. A strong thermal gradient was observed at the diffuser discharge for most of the diel period. When low or reverse flows caused by Chickamauga Dam operations were encountered at SQN, the thermal discharge spread upstream from the underwater dam. During these periods of low and reverse flow, the DO became uniformly distributed throughout the reservoir reach.

Table 3-1. Chickamauga Reservoir Sampling Locations Near Sequoyah Nuclear Plant

TRM	Horizontal location from right bank looking upstream (percent)	Odd weeks	Even weeks
484.70	30		x
	60		x
	80		x
484.10	25		x
	30	x	
	50		x
	60	x	
	75		x
483.80	90	x	
	30	x	
	60	x	
	90	x	
483.70	30	x	
	60	x	
	90	x	
483.65	30	x	
	60	x	
	90	x	
483.55	30	x	
	60	x	
	90	x	
483.45	30	x	
	60	x	
	90	x	
483.40	17		x
	30	x	
	40		x
	60	x	
	75		x
482.90	90	x	
	20		x
	30	x	
	50		x
	60	x	
482.40	80		x
	90	x	
	30		x
	55		x
	80		x

Table 3-2. Seasonal Comparison of Dissolved Oxygen at 5 Feet from Three Main Channel Locations Near Sequoyah Nuclear Plant

Date	Main channel DO (mg/l) at a 5-ft depth			Change in main channel DO at a 5-ft depth		
	Upstream	Mixing zone	Downstream	Upstream to mixing zone	Mixing zone to downstream	Upstream to downstream
	TRM 484.1	TRM 483.4	TRM 482.9			
Apr 01-87	10.3	10.4	10.2	0.1	-0.2	-0.1
Apr 16-87	11.2	10.8	10.7	-0.4	-0.1	-0.5
Apr 29-87	10.8	10.2	10.4	-0.6	0.2	-0.4
May 13-87	11.7	10.3	10.8	-1.4	0.5	-0.9
May 27-87	10.4	9.8	9.8	-0.6	0	-0.6
Jun 10-87	10.5	9.9	9.8	-0.6	-0.1	-0.7
Jun 23-87	8.4	7.0	7.4	-1.4	0.4	-1
Spring 1987						
Mean =	10.5	9.8	9.9	-0.7	0.1	-0.6
Jul 01-87	7.7	8.2	7.8	0.5	-0.4	0.1
Jul 07-87	9.2	7.1	6.8	-2.1	-0.3	-2.4
Jul 14-87	6.9	7.1	5.7	0.2	-1.4	-1.2
Jul 21-87	7.8	7.1	7.5	-0.7	0.4	-0.3
Jul 28-87	7.2	8.8	8.5	1.6	-0.3	1.3
Aug 04-87	7.9	6.0	7.6	-1.9	1.6	-0.3
Aug 11-87	6.4	6.4	6.0	0	-0.4	-0.4
Aug 18-87	6.2	5.6	5.3	-0.6	-0.3	-0.9
Aug 25-87	6.4	6.4	6.2	0	-0.2	-0.2
Sep 01-87	5.9	5.7	6.0	-0.2	0.3	0.1
Sep 08-87	7.1	7.7	6.5	0.6	-1.2	-0.6
Sep 15-87	5.8	5.8	5.2	0	-0.6	-0.6
Sep 22-87	5.0	5.4	5.7	0.4	0.3	0.7
Summer 1987						
Mean =	6.9	6.7	6.5	-0.2	-0.2	-0.4
Apr 05-88	13.8	12.5	10.3	-1.3	-2.2	-3.5
Apr 12-88	10.0	9.5	9.4	-0.5	-0.1	-0.6
Apr 19-88	10.0	9.5	9.5	-0.5	0	-0.5
Apr 16-88	9.2	8.4	8.8	-0.8	0.4	-0.4
May 03-88	9.2	8.4	8.7	-0.8	0.3	-0.5
May 10-88	9.6	9.2	9.2	-0.4	0	-0.4
Spring 1988						
Mean =	10.3	9.6	9.3	-0.7	-0.3	-1.0

Table 3-2 (Continued)

Date	Main channel DO (mg/l) at a 5-ft depth			Change in main channel DO at a 5-ft depth		
	Upstream	Mixing zone	Downstream	Upstream	Mixing	Upstream
	TRM 484.1	TRM 483.4	TRM 482.9	to mixing zone	zone to downstream	to downstream
Apr 05-89	10.7	10.2	9.9	-0.5	-0.3	-0.8
Apr 19-89	11.7	10.5	10.3	-1.2	-0.2	-1.4
May 03-89	8.2	7.9	8.2	-0.3	0.3	0
May 17-89	9.1	8.4	8.3	-0.7	-0.1	-0.8
May 31-89	11.5	8.6	8.4	-2.9	-0.2	-3.1
Jun 14-89	9.5	7.6	7.7	-1.9	0.1	-1.8
Jun 28-89	8.9	8.7	8.5	-0.2	-0.2	-0.4
Spring 1989						
Mean =	9.9	8.8	8.8	-1.1	-0.1	-1.2
Jul 12-89	8.8	8.3	7.8	-0.5	-0.5	-1
Jul 26-89	8.2	7.3	7.0	-0.9	-0.3	-1.2
Aug 09-89	6.9	6.4	6.7	-0.5	0.3	-0.2
Aug 22-89	6.6	5.3	6.4	-1.3	1.1	-0.2
Sep 05-89	6.1	5.6	5.6	-0.5	0	-0.5
Sep 19-89	5.7	5.9	5.9	0.2	0	0.2
Summer 1989						
Mean =	7.1	6.5	6.6	-0.6	0.1	-0.5

Table 3-3. Seasonal Comparison of Mean Water Column Dissolved Oxygen from Three Locations Near Sequoyah Nuclear Plant

Date	Main channel DO (mg/l)			Change in main channel DO		
	Upstream TRM 484.1	Mixing zone TRM 483.4	Downstream TRM 482.9	Upstream to mixing zone	Mixing zone to downstream	Upstream to downstream
Apr 01-87	10.2	10.3	10.2	0.1	-0.1	0
Apr 16-87	11.1	10.7	10.7	-0.4	0	-0.4
Apr 29-87	10.4	10.2	10.1	-0.2	-0.1	-0.3
May 13-87	8.1	8.6	8.1	0.5	-0.5	0
May 27-87	6.4	6.7	7.1	0.3	0.4	0.7
Jun 10-87	5.9	7.0	6.7	1.1	-0.3	0.8
Jun 23-87	5.3	5.7	5.6	0.4	-0.1	0.3
Spring 1987 Mean =	8.2	8.5	8.4	0.3	-0.1	0.2
Jul 01-87	5.0	5.8	5.0	0.8	-0.8	
Jul 07-87	6.5	6.3	6.1	-0.2	-0.2	-0.4
Jul 14-87	5.1	-	5.0	-	-	-0.1
Jul 21-87	-	6.1	5.6	-	-0.5	-
Jul 28-87	5.6	6.3	5.7	0.7	-0.6	0.1
Aug 04-87	5.0	5.1	5.4	0.1	0.3	0.4
Aug 11-87	5.2	5.6	5.2	0.4	-0.4	0
Aug 18-87	5.0	5.1	5.3	0.1	0.2	0.3
Aug 25-87	5.5	5.8	5.0	0.3	-0.8	-0.5
Sep 01-87	5.3	5.8	6.0	0.5	0.2	0.7
Sep 08-87	6.4	6.3	5.9	-0.1	-0.4	-0.5
Sep 15-87	5.5	5.5	5.2	0	-0.3	-0.3
Sep 22-87	5.1	5.5	5.5	0.4	0	0.4
Summer 1987 Mean =	5.4	5.8	5.5	0.2	-0.2	0.0
Apr 05-88	9.5	9.9	9.4	0.4	-0.5	-0.1
Apr 12-88	9.1	9.3	9.1	0.2	-0.2	0
Apr 19-88	9.9	9.4	9.2	-0.5	-0.2	-0.7
Apr 26-88	8.3	7.9	7.9	-0.4	0	-0.4
May 03-88	7.4	7.2	6.9	-0.2	-0.3	-0.5
May 10-88	7.9	8.3	7.9	0.4	-0.4	0
Spring 1988 Mean =	8.7	8.7	8.4	0.0	-0.3	-0.3

Table 3-3 (Continued)

Date	Main channel DO (mg/l)			Change in main channel DO		
	Upstream TRM 484.1	Mixing zone TRM 483.4	Downstream TRM 482.9	Upstream to mixing zone	Mixing zone to downstream	Upstream to downstream
Apr 05-89	9.9	10.0	9.8	0.1	-0.2	-0.1
Apr 19-89	10.5	10.5	10.4	0	-0.1	-0.1
May 03-89	7.6	7.9	7.5	0.3	-0.4	-0.1
May 17-89	8.5	8.6	8.2	0.1	-0.4	-0.3
May 31-89	8.2	8.4	8.1	0.2	-0.3	-0.1
Jun 14-89	7.9	7.8	7.7	-0.1	-0.1	-0.2
Jun 28-89	8.7	8.7	8.4	0	-0.3	-0.3
Spring 1989						
Mean =	8.8	8.8	8.6	0.1	-0.3	-0.2
Jul 12-89	8.2	8.4	7.8	0.2	-0.6	-0.4
Jul 26-89	6.4	7.1	6.9	0.7	-0.2	0.5
Aug 09-89	6.5	6.4	6.5	-0.1	0.1	0
Aug 22-89	5.5	5.6	6.4	0.1	0.8	0.9
Sep 05-89	5.6	5.9	5.4	0.3	-0.5	-0.2
Sep 19-89	5.6	5.7	5.8	0.1	0.1	0.2
Summer 1989						
Mean =	6.3	6.5	6.5	0.2	0.1	0.2

Table 3-4. Summary Statistics of Wilcoxon Paired-Sample Test for Dissolved Oxygen Measured at 5 Feet Near Sequoyah Nuclear Plant

H₀: Concentrations are the same upstream (TRM 484.1) and in the mixing zone (TRM 483.4)

H_a: Concentrations are NOT the same in the upstream and in the mixing zone

$\alpha(2) = 0.05$

Season	Mean difference (mg/l)	N ^a	Positive rank sum	Negative rank sum	Probability	Significant at 95% confidence ^b
Spring 1987	-0.7	7	1	27	<0.02 p = <0.05	Yes
Summer 1987	-0.2	10	32	23	p >0.50	No
Spring 1988	-0.7	6	0	21	p = 0.05	Yes
Spring 1989	-1.1	7	0	28	p = 0.02	Yes
Summer 1989	-0.6	6	1	20	<0.05 p = <0.10	No
Pooled Data	-0.6	36	80	586	p = <0.001	Yes

H₀: Concentrations are the same in the mixing zone (TRM 483.4) and downstream (TRM 482.9)

H_a: Concentrations are NOT the same in the mixing zone and downstream

$\alpha(2) = 0.05$

Season	Mean difference (mg/l)	N ^a	Positive rank sum	Negative rank sum	Probability	Significant at 95% confidence ^b
Spring 1987	0.1	6	14.5	6.5	p = >0.50	No
Summer 1987	-0.2	13	29	62	<0.20 p = <0.50	No
Spring 1988	-0.3	4	5	5	p = >0.50	No
Spring 1989	-0.1	7	8	20	<0.20 p = <0.50	No
Summer 1989	0.1	4	5.5	4.5	p = >0.50	No
Pooled Data	-0.1	34	256.5	338.5	<0.20 p = <0.50	No

H₀: DO concentrations are the same upstream (TRM 484.1) and downstream (TRM 482.9)

H_a: DO concentrations are NOT the same upstream and downstream

$\alpha(2) = 0.05$

Season	Mean difference (mg/l)	N ^a	Positive rank sum	Negative rank sum	Probability	Significant at 95% confidence ^b
Spring 1987	-0.6	7	0	28	p = 0.02	Yes
Summer 1987	-0.4	13	22.5	68.5	<0.10 p = <0.20	No
Spring 1988	-1.0	6	0	21	p = 0.05	Yes
Spring 1989	-1.2	6	0	21	p = 0.05	Yes
Summer 1989	-0.5	6	2	19	p = 0.10	No
Pooled Data	-0.7	38	66	675	p <0.001	Yes

a. Test sample size used to compute Wilcoxon T Statistic. Differences of zero are ignored in the analysis.

b. Testing for significance at 95 percent confidence is not possible for N less than 6.

Table 3-5. Summary Statistics of Wilcoxon Paired-Sample Test for Mean Water Column Dissolved Oxygen Near Sequoyah Nuclear Plant

H_0 : Mean water column DO concentrations are the same upstream (TRM 484.1) and in the mixing zone (TRM 483.4)

H_a : Mean water column DO concentrations are NOT the same upstream and in the mixing zone

$\alpha(2) = 0.05$

Season	Mean difference (mg/l)	N ^a	Positive rank sum	Negative rank sum	Probability	Significant at 95% confidence ^b
Spring 1987	0.3	7	21.5	6.5	<0.20 $p = <0.50$	No
Summer 1987	0.2	9	39	6	<0.05 $p = <0.10$	No
Spring 1988	0	6	9.5	11.5	$p = 0.50$	No
Spring 1989	0.1	5	13	2	$p = 0.20$	No
Summer 1989	0.2	6	19	2	$p = 0.10$	No
Pooled Data	0.2	34	461	134	<0.001 $p = <0.005$	Yes

H_0 : Mean water column DO concentrations are the same in the mixing zone (TRM 483.4) and downstream (TRM 482.9)

H_a : Mean water column DO concentrations are NOT the same in the mixing zone and downstream

$\alpha(2) = 0.05$

Season	Mean difference (mg/l)	N ^a	Positive rank sum	Negative rank sum	Probability	Significant at 95% confidence ^b
Spring 1987	-0.1	6	5	15	<0.20 $p = <0.50$	No
Summer 1987	-0.2	9	8.5	46.5	<0.10 $p = <0.20$	No
Spring 1988	-0.3	5	0	15	$p = 0.10$	No
Spring 1989	-0.3	7	0	28	$p = 0.02$	Yes
Summer 1989	0.1	6	9	12	$p = >0.50$	No
Pooled Data	-0.2	35	105	525	$p = <0.001$	Yes

H_0 : Mean water column DO concentrations are the same upstream (TRM 484.1) and downstream (TRM 482.9)

H_a : Mean water column DO concentrations are NOT the same upstream and downstream

$\alpha(2) = 0.05$

Season	Mean difference (mg/l)	N ^a	Positive rank sum	Negative rank sum	Probability	Significant at 95% confidence ^b
Spring 1987	0.2	5	10.5	4.5	$p = >0.50$	No
Summer 1987	0	10	27	28	$p = >0.50$	No
Spring 1988	-0.3	4	0	10	$p = 0.20$	No
Spring 1989	-0.2	7	0	28	$p = 0.02$	Yes
Summer 1989	0.2	5	10.5	4.5	$p = >0.50$	No
Pooled Data	0	31	220.5	275.5	$p = >0.50$	No

a. Test sample size used to compute Wilcoxon T Statistic. Differences of zero are ignored in the analysis.

b. Testing for significance at 95% confidence is not possible for N less than 6.

Table 3-6. Hourly Meteorological Conditions Recorded at Sequoyah Nuclear Plant During the First Diel Survey

Date	Time	Wind speed 10 meters (mph)	Wind direction 10 meters azimuth bearing	Air temperature 10 meters (°F)	Solar radiation (ly/min)	Rainfall (inches)
Aug 25-89	8 a.m.	2.5	331	NW	71	0.08
	9 a.m.	1.9	325	NW	72	0.21
	10 a.m.	1.9	177	S	74	0.37
	11 a.m.	2.5	206	SW	76	0.76
	12 noon	3.3	171	S	79	1.27
	1 p.m.	2.6	195	S	81	1.31
	2 p.m.	2.2	170	S	84	1.26
	3 p.m.	3.5	193	S	86	1.16
	4 p.m.	3.6	204	SW	87	0.96
	5 p.m.	1.7	216	SW	88	0.59
	6 p.m.	1.7	228	SW	88	0.37
	7 p.m.	0.4	234	SW	86	0.07
	8 p.m.	1.0	138	SE	82	0
	9 p.m.	1.3	266	W	80	0
	10 p.m.	1.1	22	N	79	0
	11 p.m.	1.4	10	N	78	0
	12 midnight	0.8	50	NE	77	0
Aug 26-89	1 a.m.	1.4	332	NW	76	0
	2 a.m.	1.5	209	SW	76	0
	3 a.m.	1.3	246	SW	76	0
	4 a.m.	0.9	250	W	75	0
	5 a.m.	0.5	272	W	75	0
	6 a.m.	0.7	205	SW	75	0
	7 a.m.	0.9	171	S	75	0.03
	8 a.m.	1.5	203	S	75	0.20
	9 a.m.	4.0	213	SW	79	0.51
	10 a.m.	5.2	222	SW	81	0.81
	11 a.m.	5.1	212	SW	83	1.07

Table 3-6 (Continued)

Date	Time	Wind speed 10 meters (mph)	Wind direction 10 meters azimuth bearing	Air temperature 10 meters (°F)	Solar radiation (ly/min)	Rainfall (inches)
Aug 27-89	12 noon	4.4	224	85	1.15	0
	1 p.m.	5.5	213	88	1.32	0
	2 p.m.	3.6	243	86	0.45	0
	3 p.m.	3.2	79	80	0.21	0
	4 p.m.	6.0	2	76	0.06	0.08
	5 p.m.	2.9	137	73	0	0.35
	6 p.m.	2.8	213	73	0	0.08
	7 p.m.	3.6	232	72	0	0.05
	8 p.m.	3.2	175	73	0	0
	9 p.m.	1.6	159	73	0	0
	10 p.m.	0.9	231	72	0	0
	11 p.m.	1.5	283	72	0	0
	12 midnight	1.1	326	71	0	0
	1 a.m.	1.5	335	71	0	0
	2 a.m.	1.2	346	70	0	0
	3 a.m.	1.3	342	70	0	0
	4 a.m.	2.4	342	70	0	0
	5 a.m.	2.2	353	70	0	0
	6 a.m.	2.0	336	70	0	0
	7 a.m.	2.7	341	70	0.02	0
	8 a.m.	2.2	3	70	0.06	0

Table 3-7. Hourly Discharge from Chickamauga and Watts Bar Dams and Estimated Flow at Sequoyah Nuclear Plant for the First Diel Survey

Date	Time	Watts Bar (cfs)	Chickamauga (cfs)	SQN (cfs)
25-Aug-89	8 a.m.	31,900	42,100	39,370
	9 a.m.	31,900	42,400	39,189
	10 a.m.	31,900	42,400	39,367
	11 a.m.	31,900	42,500	39,123
	12 noon	31,900	42,700	39,283
	1 p.m.	31,800	42,600	39,299
	2 p.m.	31,800	41,000	39,065
	3 p.m.	31,700	42,400	38,294
	4 p.m.	31,700	42,600	39,296
	5 p.m.	31,700	42,300	39,096
	6 p.m.	31,700	42,600	39,145
	7 p.m.	31,700	42,300	39,121
	8 p.m.	31,700	42,500	39,037
	9 p.m.	31,700	42,200	39,067
	10 p.m.	31,700	42,100	38,928
	11 p.m.	31,700	28,800	35,933
26-Aug-89	12 midnight	31,700	9,800	23,440
	1 a.m.	31,800	0	8,454
	2 a.m.	31,800	0	3,236
	3 a.m.	24,000	0	6,444
	4 a.m.	23,500	0	9,934
	5 a.m.	23,200	0	11,974
	6 a.m.	23,200	4,000	8,970
	7 a.m.	25,400	17,000	12,281
	8 a.m.	31,900	37,600	25,784
	9 a.m.	31,900	40,600	39,941
	10 a.m.	31,900	40,600	40,619
	11 a.m.	32,100	40,700	40,387
	12 noon	32,100	40,500	38,824
	1 p.m.	32,000	40,600	37,913
	2 p.m.	32,000	40,400	37,985
	3 p.m.	32,100	40,600	37,870
	4 p.m.	32,100	40,300	38,076
	5 p.m.	32,100	41,700	38,058
	6 p.m.	32,100	41,800	39,022
	7 p.m.	32,000	41,900	38,829
	8 p.m.	32,000	41,900	39,002
	9 p.m.	32,000	42,100	38,882
	10 p.m.	32,000	41,900	39,064
	11 p.m.	32,000	28,100	35,746

Table 3-7 (Continued)

Date	Time	Watts Bar (cfs)	Chickamauga (cfs)	SQN (cfs)
27-Aug-89	12 midnight	32,000	19,000	25,049
	1 a.m.	32,100	0	14,863
	2 a.m.	32,100	0	1,705
	3 a.m.	32,100	0	6,427
	4 a.m.	28,500	0	8,105
	5 a.m.	25,000	0	11,992
	6 a.m.	25,000	0	11,298
	7 a.m.	24,900	28,400	16,359
	8 a.m.	28,400	42,000	35,671

Table 3-8. Hourly Meteorological Conditions Recorded at Sequoyah Nuclear Plant During the Second
Diel Survey

Date	Time	Wind speed 10 meters (MPH)	Wind direction 10 meters azimuth bearing	Air temperature 10 meters (°F)	Solar radiation (ly/min)	Rainfall (inches)
Sep 08-89	8 a.m.	1.3	248 W	69	0.20	0
	9 a.m.	2.6	194 S	73	0.43	0
	10 a.m.	4.0	222 SW	76	0.75	0
	11 a.m.	4.7	209 SW	78	1.05	0
	12 noon	5.4	222 SW	80	1.10	0
	1 p.m.	5.4	226 SW	82	1.19	0
	2 p.m.	5.5	223 SW	83	1.18	0
	3 p.m.	5.6	222 SW	84	1.11	0
	4 p.m.	4.9	224 SW	85	0.91	0
	5 p.m.	4.6	229 SW	85	0.61	0
	6 p.m.	2.0	239 SW	85	0.34	0
	7 p.m.	1.1	180 S	83	0.05	0
	8 p.m.	1.2	156 SE	78	0	0
	9 p.m.	0.1	103 E	76	0	0
	10 p.m.	0.7	92 E	75	0	0
	11 p.m.	0.9	38 NE	74	0	0
	12 midnight	2.0	8 W	72	0	0
	1 a.m.	1.3	17 N	71	0	0
	2 a.m.	1.2	354 N	71	0	0
	3 a.m.	2.1	11 N	70	0	0
Sep 09-89	4 a.m.	2.0	13 N	69	0	0
	5 a.m.	1.5	23 N	69	0	0
	6 a.m.	1.6	341 N	69	0	0
	7 a.m.	1.5	19 N	68	0.02	0
	8 a.m.	1.7	304 NW	69	0.14	0
	9 a.m.	2.3	201 S	73	0.45	0
	10 a.m.	3.8	215 SW	77	0.78	0
	11 a.m.	4.9	220 SW	80	1.03	0

Table 3-8 (Continued)

Date	Time	Wind speed 10 meters (MPH)	Wind direction 10 meters azimuth bearing	Air temperature 10 meters (°F)	Solar radiation (ly/min)	Rainfall (inches)
Sep 10-89	12 noon	5.3	211	83	1.21	0
	1 p.m.	5.5	225	84	1.26	0
	2 p.m.	5.6	222	86	1.25	0
	3 p.m.	5.5	211	87	1.08	0
	4 p.m.	4.6	208	87	0.77	0
	5 p.m.	4.9	207	87	0.59	0
	6 p.m.	4.6	183	87	0.33	0
	7 p.m.	4.1	175	84	0.05	0
	8 p.m.	2.1	187	80	0	0
	9 p.m.	2.6	221	78	0	0
	10 p.m.	2.3	226	77	0	0
	11 p.m.	2.2	153	76	0	0
	12 midnight	1.9	201	75	0	0
	1 a.m.	1.9	204	74	0	0
	2 a.m.	2.2	219	74	0	0
	3 a.m.	2.2	181	74	0	0
	4 a.m.	2.4	222	74	0	0
	5 a.m.	2.2	244	72	0	0
	6 a.m.	1.5	285	72	0	0
	7 a.m.	1.8	144	73	0.02	0
	8 a.m.	0.6	327	72	0.05	0

Table 3-9. Hourly Discharge from Chickamauga and Watts Bar Dams and Estimated Flow at Sequoyah Nuclear Plant for the Second Diel Survey

Date	Time	Watts Bar (cfs)	Chickamauga (cfs)	SQN (cfs)
Sep 08-89	8 a.m.	32,400	43,200	37,156
	9 a.m.	34,300	43,300	43,760
	10 a.m.	40,800	43,300	43,367
	11 a.m.	41,200	43,600	40,770
	12 noon	41,300	43,600	40,358
	1 p.m.	41,300	43,600	41,712
	2 p.m.	41,300	43,300	43,005
	3 p.m.	41,500	43,200	42,941
	4 p.m.	41,500	43,100	42,725
	5 p.m.	41,500	43,000	42,544
	6 p.m.	41,500	43,100	42,564
	7 p.m.	41,600	43,100	42,675
	8 p.m.	41,600	43,200	42,706
	9 p.m.	41,500	43,300	42,752
	10 p.m.	41,500	43,200	42,820
	11 p.m.	40,800	35,900	41,300
Sep 09-89	12 midnight	33,900	10,600	31,784
	1 a.m.	16,700	0	11,993
	2 a.m.	15,500	0	6,814
	3 a.m.	7,500	0	6,749
	4 a.m.	7,500	0	3,202
	5 a.m.	7,800	0	-2,115
	6 a.m.	7,800	1,300	-7,086
	7 a.m.	7,900	19,400	1,736
	8 a.m.	23,700	41,300	31,146
	9 a.m.	32,300	42,000	46,813
	10 a.m.	42,700	42,000	40,871
	11 a.m.	41,900	42,000	39,965
	12 noon	41,900	41,900	40,448
	1 p.m.	41,000	42,100	41,918
	2 p.m.	41,000	42,100	42,847
	3 p.m.	41,000	42,000	42,371
	4 p.m.	41,000	31,700	39,897
	5 p.m.	41,200	27,400	32,185
	6 p.m.	41,200	27,500	30,263
	7 p.m.	41,200	27,700	30,923
	8 p.m.	41,300	41,600	34,714
	9 p.m.	41,300	42,000	43,877
	10 p.m.	33,800	42,100	42,777
	11 p.m.	7,400	21,800	38,098

Table 3-9 (Continued)

Date	Time	Watts Bar (cfs)	Chickamauga (cfs)	SQN (cfs)
10-Sep-89	12 midnight	7,900	11,100	21,546
	1 a.m.	7,900	0	13,137
	2 a.m.	8,000	0	3,885
	3 a.m.	7,900	0	-4,485
	4 a.m.	7,900	0	-13,103
	5 a.m.	7,900	0	-5,977
	6 a.m.	7,900	0	5,251
	7 a.m.	7,900	19,800	18,117
	8 a.m.	9,700	40,200	34,775

Figure 3-1. Vertical Mixing in the Vicinity of SQN Underwater Dam and Diffusers
(from Brown and Gordon, 1987)

Figure 3-2. Aerial Infrared Photograph Taken at 12:01 a.m. on September 9, 1989

Figure 3-3. Aerial Infrared Photograph Taken at 1:57 a.m. on September 9, 1989

Figure 3-4. Aerial Infrared Photograph Taken at 4:04 a.m. on September 9, 1989

Figure 3-5. Aerial Infrared Photograph Taken at 10:33 a.m. on September 9, 1989

Figure 3-6. Aerial Infrared Photograph Taken at 5:43 p.m. on September 9, 1989

4.0 DISSOLVED OXYGEN DISTRIBUTION IN CHICKAMAUGA RESERVOIR

Dissolved oxygen in Chickamauga Reservoir is the direct result of inflow water quality from Watts Bar Dam and the development of thermal stratification in the lower half of the reservoir. Inflow temperatures from Watts Bar Dam are relatively cool during the spring and early summer periods while inflow DOs are quite low (2-4 mg/l in a dry year; 4-6 mg/l in a wet year) during most of the summer months. Most of the reservoir releases from Chickamauga are through the turbines which withdraw water from the lower strata of the reservoir with a gate opening extending over 35 ft. The combination of low inflow temperature, bottom withdrawal, and surface heating results in a surface wedge of warm water (thermal stratification) which extends from Chickamauga Dam to approximately halfway up the reservoir. Thermal stratification in the lower half of the reservoir normally begins in midspring and is fully developed by late May or early June. It usually lasts until reservoir turnover in late August or early September. During this period, inflow enters the reservoir as an underflow and continues to Chickamauga Dam. Wind mixing, turbulent mixing, and periods of convective mixing from surface cooling act to intermittently weaken the stratification.

One of the objectives of this study is to better define the extent and duration of the redistribution of DO in the reservoir. To achieve the objective, DO in the vicinity of SQN must be evaluated in terms of the overall DO regime in Chickamauga Reservoir, especially since WBN is expected to be coming online in the near future and will discharge into the upper end of Chickamauga. Therefore, a two-dimensional water quality model was developed to evaluate the effects of SQN heat load on

DO patterns in Chickamauga Reservoir as well as the combined effects of SQN and WBN in terms of overall reservoir DO dynamics. However, only far-field plant effects (beyond the mixing zone, i.e., 1500 ft downstream from the diffuser) will be simulated because the diffuser mixing zone is smaller than the limit of resolution of the water quality model and its simplified hydrodynamic formulations. The results of the model will provide information on the extent, frequency, and duration of plant-induced effects on reservoir DO outside the diffuser mixing zone for reservoir conditions (e.g., hydrology, meteorology, multiple heat loads, and inflow water quality) other than those encountered during the sampling program. It will also help fill spatial and temporal gaps in field data.

4.1 Processes Affecting Dissolved Oxygen Dynamics in Reservoirs

Reservoir processes affecting DO include replenishment and withdrawal during inflow and outflow; surface reaeration; algal photosynthesis and respiration; organic decay; oxidation of ammonia; and sediment oxygen demand. Reservoir DO in Chickamauga Reservoir depends largely on inflow DO, i.e., Watts Bar Dam release DO, which can be low (2-4 mg/l) in the summer months because of upstream organic loading and because of bottom withdrawal from the stratified Watts Bar Forebay. DO depletion in Chickamauga Reservoir occurs near the river bottom around TRM 500, the same point where the Hiwassee River inflow joins the Tennessee River and plunges under the warm surface wedge as an underflow. Hypolimnetic DO depletion progressively increases downstream as a result of numerous processes including decay of inflowing organic

materials, sediment oxygen demand (SOD), and decomposition of algae biomass settling from surface. Inflow BOD₅ usually is in the range of 1-3 mg/l. Significant algal growth occurs in early spring when nutrients are in relative abundance. Algal respiration and decomposition contribute to the vertical and longitudinal DO stratification. However, due to the relative short hydraulic residence time, its contribution is not as significant as observed in deep tributary reservoirs. A detailed discussion of reservoir DO processes in the context of the reservoir water quality model is given in the following section.

4.2 Reservoir Modeling

4.2.1 Materials and Methods

Field--Hydrolab profiles and secchi disc readings were performed at 33 locations on the Tennessee and Hiwassee Rivers above and below SQN (table 4-1). Hydrolab measurements and calibrations were conducted in the same manner as described in Section 3.2.1. The Hydrolab profiles and secchi disc measurements were made at midchannel for those river miles marked with one horizontal location and at locations evenly spaced across the river for those river miles marked with three horizontal locations (table 4-2), and were conducted once every two weeks from April 1, 1987 through March 31, 1988, once a week from April 1, 1988 through May 10, 1988, once a month from May 11, 1988 through June 30, 1988, twice a month from July 1, 1988 through August 31, 1988, and once every two weeks from April 1, 1989 through September 30, 1989 (table 4-3).

Nutrient sampling was conducted on a monthly schedule during the entire sampling program at the indicated stations and only at midchannel

locations (table 4-4). Samples were collected at the water surface, middepth, and 1 m off the bottom. Nutrient analyses included the following parameters: $\text{NO}_2 + \text{NO}_3 - \text{N}$, $\text{NH}_3 + \text{NH}_4 - \text{N}$, organic N, total phosphorus, dissolved phosphorus, ortho-phosphorus, long-term BOD (multiple measurements over 28 days), turbidity, total suspended solids, volatile suspended solids, total organic carbon, and total alkalinity.

Boats were used to obtain Hydrolab measurements, secchi disc readings, and nutrient samples. Nutrient samples were collected using a Kemmerer Sampler and then poured into individual sample containers previously cleaned and prepared according to the type of sample to be analyzed. Total alkalinities were performed by the Field Engineering survey crews within 24 hr from collection time. All the samples, excluding total alkalinities, were sent to the Environmental Chemistry Laboratory for analyses. Analytical methods used to determine concentrations of chemical water quality constituents are shown in appendix A.

4.2.2 Sediment Oxygen Demand Determinations

Sampling Sites--To provide valid estimates of sediment oxygen demand (SOD) for calibrating the BETTER model, the TVA Environmental Unit Operations Laboratory (EUOL) conducted SOD determinations on sediment core samples from eight sites in Chickamauga Reservoir. These sites, which correspond to the end points of segments of the two-dimensional grid model, are listed in table 4-3.

Method--The EUOL SOD method as described by Longaker and Poppe (1986) was selected to evaluate the SOD. Previous testing indicated this method more consistently approximated the results of the EPA in-situ method than other laboratory methods (Longaker, 1986; Murphy 1986). The

reduced costs associated with EUOL SOD determinations in comparison with in-situ determinations were also a factor in the selection.

In accordance with the EUOL SOD method, 16 or more sediment core samples and 12-15 gallons (gal) of river water were collected at each sampling location. In obtaining the core samples, divers carefully inserted plexiglass tubes (7.5 cm outside diameter, 6.87 cm inside diameter, and 15 cm in length) into the riverbed to a depth of approximately 10 cm, leaving approximately 5 cm of river water on top of a relatively undisturbed circular section of the riverbed. The sample tubes were then stoppered on the ends with two No. 13-1/2 rubber stoppers. The core sample tubes and the river water samples were transported on ice to the EUOL. The river water was filtered with a spiral-wound glass fiber filter to remove suspended solids and algae which might interfere in the SOD measurements. The top stoppers of the sediment core sample tubes were removed and the tubes inserted in the SOD apparatus. The SOD apparatus consists of up to five 24-liter plastic carboys fitted with plastic tubing and pumps for externally recirculating water. Eight sample tubes were placed in each 24-liter reactor vessel (except for two instances in which loss of core sample tubes necessitated use of only 7 and 6 cores). The remaining reactor volume was filled with filtered air-saturated river water, and each reactor was sealed. Probes located on the water recirculating lines continuously monitored DO. The SOD apparatus was kept in a controlled temperature chamber set at 15°C. The apparatus was kept in the dark except for brief inspections one or two times per day to check for leaks and note instrument readings for comparison with values recorded on data acquisition devices. A more detailed description of the method appears in Longaker and Poppe (1986).

Analysis of Raw Sediment Oxygen Demand Data--From the hourly values for DO concentrations, DO versus (vs) time curves were generated. For each SOD reactor in each test, the corresponding DO and time data points were subjected to linear regression. From the slopes of these lines, SOD values were calculated by the following equation:

$$\text{SOD} = 0.024 \text{ } b \text{ } V/A$$

Where SOD is in grams oxygen/square meter/day ($\text{g O}_2/\text{m}^2/\text{d}$), b is the slope of the DO vs time curve in milligrams oxygen/liter/hour ($\text{mg O}_2/\text{l/hr}$), and V/A is the reactor volume to sediment surface area ratio in liters/square meter (l/m^2), and 0.024 is a conversion factor.

Based on 8 core samples per reactor with an average distance of 5.08 cm between the sediment surface and the top of the sample tubes, the volume to sediment ratio for 11 of the 13 successful SOD determinations in this study was calculated to be 678 l/m^2 . For the two cases in which 7 and 6 core samples were used, the reactor volume to sediment surface area ratios were 795 l/m^2 and 951 l/m^2 respectively. The volume to sediment surface area ratios for the SOD determinations are included in table 4-3.

Sediment Oxygen Demand Results and Discussion--Sediment oxygen demand rates for the 8 sample sites appear in table 4-3. The standard five day (0-120 hr) SOD rates ranged from $0.57\text{--}1.28 \text{ g O}_2/\text{m}^2/\text{d}$. The R^2 coefficients of the linear least squares fits of the first 120 hours of data exceeded 0.97 for all but two of the SOD determinations. Core samples from these two sample sites, TRM 473 and TRM 490.5, produced data which yielded 0-120 hour linear fits with R^2 correlation coefficients less than 0.92. Since in these two instances the DO vs time curves could be better described by two line segments joining at

inflection points on the curves, linear fits of the data from different portions of the curves were used to derive initial and final SOD rates. The R^2 coefficients for the initial and final line segments for these sites equaled or exceeded 0.92. This information is included in table 4-3.

Figures 4-1 and 4-2 show DO vs time data resulting from the SOD determination on sediment core samples from sample site TRM 473. Figure 4-1 illustrates the first 120 hours of data and the linear least squares fit of that data. Figure 4-2 illustrates 170 hours of data and the linear least squares fits over the 0-48 hour and 48-144 hour sections of the curve. For comparison, the 0-120 hour linear fit is also included in figure 4-2 as a dashed line. The DO data points are designated "R-1" and "R-2" in the figure legends indicating the tests were conducted in SOD reactors 1 and 2, respectively. As can be seen in figures 4-1 and 4-2, no data from reactor 2 is shown after 25 hours, the time at which leaks developed in the reactor 2 system and rendered all additional data useless. Because of the limited amount of reactor 2 data, only data from reactor 1 was used in the linear fits to calculate the SOD rates. The SOD rates and the R^2 values of the linear fits over the various ranges appear in table 4-3.

Figure 4-3 illustrates DO vs time data for two sets of sediment core samples from TRM 483.4 and the average linear fit of the two curves. As can be seen in the figure, the two replicates were in close agreement and the average linear fit accurately approximates the first 120 hours of data.

Figure 4-4 illustrates DO vs time data for the one successful SOD determination on sediment core samples from TRM 490.5 and linear least

squares curve fits of the data over the 0-120 hour range, the 0-36 hour range, and the 36-144 hour range. As with the data from sample site TRM 473, the R^2 correlation coefficient for the line segments in the initial and final ranges are higher than for the 0-120 hour range, indicating that the assumption of initial and final SOD rates may more accurately describe conditions at the sample site.

Figure 4-5 illustrates DO vs time data for two sets of sediment core samples from TRM 498 and the linear least squares curve fits of the first 120 hour of data in both curves. As can be seen in the figure, the linear fit lines are almost parallel, with the DO concentrations from the samples evaluated in reactor 4 averaging about one mg/l higher than those evaluated in reactor 3. The DO concentrations in reactor 4 were higher because only 7 core samples were evaluated in reactor 4, instead of the usual 8. The almost parallel linear approximations of the data resulted in SOD values in close agreement as can be seen in table 4-3. This agreement seems to justify the assumption that variation in the reactor volume to sediment surface area ratio does not significantly effect SOD as determined by the EUOL method.

Figure 4-6 illustrates DO vs time data for two sets of sediment core samples from TRM 519.2, the linear least squares curve fits of the first 120 hour of data in both curves, and the average fit of the first 120 hour of data. As can be seen in the figure, the difference in DO concentrations in the two reactors used to evaluate samples from TRM 519.2 becomes much more pronounced after the first 36 hour of the determination. This difference in DO concentrations was apparently caused by a difference in the SOD rates. The R^2 correlation coefficients for linear fits of the first 120 hour of data for both sets of samples were 0.998 and 0.997, and the SOD values were 1.039 and

0.640 g/m²/day, yielding an average SOD value of 0.840 g/m²/day.

This information is included in table 4-3.

Figure 4-7 illustrates DO vs time data for two sets of sediment core samples from TRM 506.5, and the linear least squares curve fits of the first 120 hours of data in both curves. As in the case with figure 4-4 and the data from site TRM 498, the linear least squares curve fit lines of the first 120 hours of data in both curves are almost parallel, with the DO concentrations from the samples evaluated in reactor 4 averaging about one mg/l higher than those evaluated in reactor 3. The DO concentrations in reactor 4 were higher because only 6 core samples were evaluated in reactor 4, while reactor 3 contained the usual 8. The almost parallel linear approximations of the data resulted in SOD values in reasonably good agreement as can be seen in table 4-3.

Figure 4-8 illustrates DO vs time data for two sets of sediment core samples from HRM 3.0, and the average linear least squares curve fit of the first 120 hours of data on both curves. As can be seen in the figure, the data from the two determinations produced curves which superimpose. The R² coefficients of the linear least squares fits for the two curves were both equal to 0.998. The SOD values calculated from the slope of the fitted lines were 0.952 and 0.932 g/m²/day, which gave an average value of 0.942 g/m²/day. This information is included in table 4-3.

Figure 4-9 illustrates DO vs time data for the one successful SOD determination on sediment core samples from HRM 15.0 the linear least squares curve fit of the data over the 0-120 hour range. As can be seen in table 4-3, the linear least squares curve fit had an R² correlation coefficient of 0.995, and the slope of this curve fit yielded an SOD value of 0.838 g/m²/day.

4.2.3 Model Description

Geometry and Flow Patterns--The Box Exchange Transport Temperature Ecology Reservoir (BETTER) model (Brown et al., 1985; Hauser et al., 1987) calculates flow exchanges between a two dimensional array of boxes representing reservoir geometry. A heat budget including wind mixing and convective cooling simulates the seasonal patterns of warm surface wedge and cold bottom water. A DO balance including BOD and ammonia, SOD, surface reaeration, and photosynthesis and respiration from algae produces a seasonal DO pattern.

The Chickamauga Reservoir BETTER model was segmented into a two-dimensional array of volume elements as shown in figure 4-10. Volume elements are smaller for surface layers because these are the regions where the largest gradients in water quality are expected. A floating layer scheme is used so that all layers remain at specified depths from the surface. This preserves near surface gradients and allows direct comparison with field measurements at fixed depths. The reservoir is segmented longitudinally based on sampling locations and transition zones between reasonably homogeneous segments of the reservoir. For each element, the model determines volume, downstream conveyance area, and surface interfacial area at each time step. Element volumes are determined from cross-section measurements, maps, and sediment ranges and adjusted as necessary to preserve the correct volume-elevation relationship. At this time, water quality in embayments and overbank areas is not included and the computations represent only water quality in the main channel of the Tennessee River and in the Hiwassee River arm. Local reservoir inflows are determined using daily outflows and midnight reservoir elevations so that the model matches daily changes in reservoir volume.

Flow patterns are estimated in the model with a procedure that distributes inflow and outflow based on geometric properties (surface area and conveyance area) of the volume elements. Inflows are deflected vertically toward layers with matching density using a densimetric Froude number, which represents the relative importance of downstream flow momentum compared to the buoyancy force of the density gradient. Thus, during high flows, large flow momentum tends to reduce density deflections. During low flows and strong stratification, maximum density deflections occur. Outflows are withdrawn from a withdrawal zone that increases with flowrate and decreases with temperature gradient. Thus, during low flows and strong stratification, a smaller withdrawal zone is used.

Three distinct mixing mechanisms inducing vertical mixing between layers are simulated. These are convective mixing due to surface cooling and sinking of more dense water, wind mixing due to wind shear at the surface, and turbulent mixing between layers driven by the ambient flow pattern.

The SQN thermal discharge is simulated with a two-dimensional diffuser mixing model which determines entrainment of ambient water along the path of the buoyant plume and distributes loadings of water quality constituents into appropriate volume elements of the reservoir water quality model. Only far-field plant effects (beyond the mixing zone) are simulated because the diffuser mixing zone is smaller than the limit of resolution of the water quality model and its simplified hydrodynamic formulations.

The decrease in DO in SQN condenser cooling water due to temperature increase is fairly small and highly variable. As described

previously, the estimated reductions in reservoir DO concentration during two-unit operation vary from 0.08 mg/l for normal flow (30,000 cfs) to 0.26 mg/l for low flow (10,000 cfs). When no load was being generated, pond outflow DO actually increased slightly due to reaeration. In light of all the uncertainties and simplifications in model processes and in inflow loadings, these small changes in reservoir DO will have little effect on model results. To reduce complication in comparing different model runs, the DO concentration in the discharge was assumed to be equal to the concentration at the SQN intake.

Heat Budget--Reservoir temperatures are the result of a reservoir heat budget which depends on the rate and temperature of the inflow and outflow and heat transfer across the air/water interface. Surface heat transfer includes long wave radiation from the atmosphere and water surface, wind driven evaporation and conduction (using Bowen's ratio), and absorption of solar radiation at water surface. The BETTER model assumes that 50 percent of incoming solar radiation is absorbed as heat at the surface with the remaining half absorbed by lower layers according to an exponentially decreasing light extinction formulation. The extinction coefficient for solar radiation is composed of a background light extinction coefficient (0.5) and the shading effects of algae and suspended solids. The extinction coefficient is the only feedback mechanism in the model for biochemical processes to influence the heat budget.

Wind mixing of near surface layers is simulated using an energy balance approach that iteratively increases the mixing depth until the potential energy required to mix layers equals the kinetic energy transferred from the wind.

Dissolved Oxygen Balance--Dissolved oxygen in the reservoir is governed largely by inflow concentrations, decay of organic materials, SOD, algal productivity, and oxidation of ammonia. Organic materials in the model consist of two components: detritus (particulate organics) and dissolved organics. Both enter the reservoir with inflow and waste discharges. Detritus, which settles slowly in the reservoir and has a smaller decay rate than that of dissolved organics, is also replenished by algal mortality. Ammonia enters the reservoir in the inflow and in waste discharges, undergoes nitrification to nitrate, and is released during algal respiration, detritus decay, and anaerobic sediment decomposition. Sediment oxygen demand is modeled as an areal demand ($\text{g O}_2/\text{m}^2/\text{day}$) specified for each longitudinal segment. All these modeled processes are temperature dependent. Algal photosynthesis adds oxygen to surface layers where light conditions are favorable. This DO production depends on algae biomass and growth rate and can produce supersaturation in the surface layer. Algal respiration, on the other hand, can be a major oxygen demand in the metalimnion. Both algal growth and respiration are modeled as first order kinetics. Reaeration is another way of adding oxygen in the surface. It is modeled as a function of windspeed and DO deficit below saturation.

Aquatic macrophyte infestation has become an important issue in Chickamauga Reservoir in recent years. Macrophytes obtain their nutrients via roots and, therefore, grow best in shallow water (<10 ft) with nutrient-rich sediments. Excessive macrophyte growth can sometimes create local DO stratification, especially in shallow overbank areas. Photosynthesis enriches DO at surface layers while vertical mixing (a primary mechanism to transfer DO to the DO depleted bottom layers)

is hindered by the surface mat formed by macrophytes. Broken macrophytes, like algae, consume DO while decomposing. This usually happens in late fall and early winter when river flow is high. Since the residence time corresponding to high flow is relatively small (<10 days) in Chickamauga Reservoir, the effects of broken macrophytes on DO in the main water body is not considered significant; however, they may pose a DO problem to downstream reservoirs.

Original modeling plans called for addition of an algorithm to account for the additional photosynthesis and respiration of weeds. Addition of an algorithm specifically for macrophytes was considered during model development but was decided against during calibration for the following reasons. First, the model is laterally averaged and limited to simulation of vertical and longitudinal gradients representative of the main channel, while the primary DO effects of macrophyte growth are in the shallow overbank areas. The model is, therefore, limited to simulation of the aggregated effect of conditions that tend to be localized over the macrophyte beds. Second, review of available field data showed that the observed effect of macrophytes on DO in the main river was not distinguishable from that of algae, making proper calibration of the balance of the two separate processes uncertain. Both algae and macrophytes are near surface phenomena that contribute DO via photosynthesis and consume DO via respiration, and are net producers during daytime and net users at night. Therefore, rather than add an additional set of uncertain process coefficients to the model for simulation of macrophytes, it was decided to simulate the combined photosynthetic and respiration effects of all aquatic plants using the

algorithm existing in the model with coefficients calibrated for laterally averaged DO conditions.

Algae and Nutrients--Algae plays an important role in affecting levels of DO and dissolved inorganic nutrients (nitrogen, phosphorus, carbon dioxide). Algae biomass in the model represents an assemblage of diatoms, greens, and blue-greens and is modeled as a function of temperature and growth-limiting factors including light and nutrient concentrations.

Light fluctuates daily, but usually remains adequate for plant growth. In a system with a dense algal population, however, several days of overcast weather can drastically limit growth while a large number of light-starved algae may die. As described before, the model assumes 50 percent of solar radiation to be photosynthetically active radiation (PAR) and useful for algae. Modeled PAR decreases exponentially as a function of depth based on an extinction coefficient that depends on concentrations of suspended solids, algae, and detritus. Light limitation is determined by a Monod expression with a half-saturation light coefficient.

Nitrogen is available for uptake as ammonia ($\text{NH}_3\text{-N}$) and nitrate ($\text{NO}_3\text{-N}$) without preference. Phosphorus (in the form of $\text{PO}_4\text{-P}$) is assumed to be bioavailable. The source of carbon for algae growth is carbon dioxide. Any one of these three nutrients can limit algae productivity when the demands for growth exceed the supply. In most of the TVA reservoirs, the limiting nutrient had been identified to be either phosphorus or nitrogen or both. Nutrient limitations are determined

using a Monod expression and a corresponding half-saturation concentration. Through algal respiration and decomposition of dead algae cells, a portion of the absorbed nutrients are recycled back into the reservoir water body.

To avoid sudden crashes of algae biomass in the model, grazing of algae by zooplankton is not modeled. Instead, a first order mortality form is used which allows a direct conversion of algae to detritus. This practice simulates a fairly uniform algae biomass over the summer period which responds only to temperature, light, and nutrients.

4.2.4 Model Calibration

Normally, model calibration is done by matching model results with field measurements in one single year. In the case of Chickamauga Reservoir, three years of field data, i.e., 1985, 1986, and 1987, were used. No individual year provided a set of data which allowed for a complete model calibration.

In August 1985 SQN was shut down due to safety concerns. In 1985, there were only two reservoir water quality surveys in the modeling period (from days 60-270) which were not enough for a complete model calibration. However, since the plant was in operation for a major part of the year, hourly water temperatures recorded at temperature monitoring Stations 13 (TRM 484.7) and 8 (TRM 483.4) provided the necessary data for calibration of the thermal mixing component of the model. This component is used to evaluate the impacts of thermal discharge from the plant on downstream water quality.

Severe drought occurred in spring and summer of 1986. To study its impact on reservoir water quality, weekly temperature, DO and pH profiles were taken in the forebay of Chickamauga Dam from June to September.

These data, in conjunction with hourly temperatures at Stations 13 and 8 (without thermal discharge from SQN) allowed for a preliminary calibration on reservoir temperature and DO. Emphasis, however, was given in reproducing the reduced mixing and corresponding low DO in Chickamauga Reservoir because of low flows and strong stratification. An extensive water quality survey was conducted in 1987 with biweekly Hydrolab profiles and monthly nutrient samples taken at 19 locations (see table 4-1). These data along with the hourly temperatures collected at Stations 13 and 8 (without thermal discharge from SQN) were used for final model calibration.

Hydrology--Hydrologically, 1985 was characterized by a very dry spring (March to May) and a moderately dry summer (June to August). As shown in figure 4-11, the average release from Chickamauga Dam was about 12,000 cfs for the spring period and about 20,000 cfs for the summer period while the historical median flows (1903-88) were about 48,800 cfs and 17,400 cfs for spring and summer, respectively. One important factor governing reservoir water quality is the duration that each parcel of water stays in the reservoir. This is approximated by the hydraulic residence time defined as number of days that the accumulated reservoir inflows (backward from the current time) equals the current reservoir volume, which is estimated using the measured headwater elevation. In 1985, the computed water residence time shown in figure 4-11 increases from 10-15 days in early spring to 30-35 days in late spring. The increase in water residence time is usually accompanied by a reduction of DO in the hypolimnion of the reservoir.

In 1986, severe drought in spring and summer significantly reduced releases from Watts Bar and Chickamauga Reservoirs. Watts Bar and Chickamauga Dam releases and the computed water residence time are presented in figure 4-12. The 1986 average spring and summer flows at Chickamauga Dam were about 10,600 cfs and 13,100 cfs. These flows represented a reduction from the historical median flows of about 74 percent in spring and 25 percent in summer. The excessively long water retention time (30-35 days), which lasted about 2 months, resulted in depressed DO conditions in the reservoir.

Hydrologically, 1987 was slightly dry in spring (28,000 cfs) but moderately wet in summer (25,000 cfs). The 1987 Watts Bar and Chickamauga Dam releases and the computed water residence time are shown in figure 4-13. Computed water residence times on days that field surveys were conducted range from 10-20 days. This indicates that each biweekly survey was probably measuring a new batch of water released from the upstream reservoir--a criteria for designing field survey in a reservoir with short water retention time.

Meteorology--Water temperature and surface heat exchange computations in the BETTER model require meteorological data such as dry bulb and dewpoint temperatures, wind speed, cloud cover and solar radiation. To reproduce the diurnal variations of surface temperatures observed at Stations 13 and 8, a time step of 12 hours (day/night) was used in all model runs. The 12-hour average values of dry bulb, dew-point, wind speed, cloud cover and solar radiation were computed using hourly meteorological data recorded at Chattanooga Airport and are shown in figures 4-14, 4-15, and 4-16 for 1985, 1986, and 1987.

Inflow Water Quality and Sediment Oxygen Demand--For a weakly stratified reservoir with relative short residence time, inflow water quality usually plays an important role on water quality in the reservoir. For all three calibration years, release water temperature and DO at Watts Bar Dam were measured approximately weekly. Other water quality parameters, however, were not monitored routinely at the upstream inflow point with the exception of a period from April to November in 1987 when monthly samples of nutrients were taken. Available measurements of Watts Bar release nutrients (ammonia, nitrate, phosphorus, organic nitrogen, and total organic carbon) for the three calibration years (1985, 1986 and 1987) are given in table 4-4. These data are too sparse to provide a true seasonal variation of release water quality; instead, a constant seasonal average concentration for each parameter was used. Using a constant concentration has the advantage of reducing model uncertainties introduced by that parameter, especially when the parameter shows little variation over time such as inflow $\text{PO}_4\text{-P}$ and BOD_5 (table 4-4). Constant concentrations were also used for parameters not readily available such as algae and organics (dissolved and particulate). These constant inflow nutrients are given in table 4-5 and are used in all three calibration runs. Measured Watts Bar Dam release temperature and DO for 1985, 1986, and 1987 are presented in figures 4-17, 4-18, and 4-19. A linear interpolation was used to fill in gaps between measurements. Also shown in the figures are temperatures measured at the WBN intake channel (TRM 528.0) and at the intake of Dayton Water Treatment Plant (TRM 503.7). The WBN intake channel

temperature shows a good correlation with Watts Bar Dam release temperature. Intake temperature at Dayton Water Treatment Plant, about 16 miles downstream from the dam, shows the characteristics of an intermittent stratified water body where large temperature variations resulted when river mixing broke up the weakly stratified water body. The seasonal temperature pattern at the Dayton Water Treatment Plant intake, nevertheless, follows that of Watts Bar Dam release. The interpolated Watts Bar Dam release temperature and DO were used in model calibration. Also available at the Dayton Water Treatment Plant intake are daily readings of pH and turbidity as shown in figures 4-17, 4-18, and 4-19 for 1985, 1986, and 1987, respectively. These measurements are used as inflow pH and turbidity in model calibrations.

Available water quality and nutrients data in the Hiwassee River arm are not adequate to identify the inflow characteristics for the three calibration years. Daily intake temperature and DO as well as pH and turbidity readings at Cleveland Water Treatment Plant, Hiwassee River mile (HRM) 22.7, are the best available data for Hiwassee inflow. These data are shown in figures 4-20, 4-21, and 4-22 for 1985, 1986, and 1987. Constant nutrient concentrations for Hiwassee River inflow are given in table 4-5.

Local surface runoff is another source of nutrients which could have a significant impact on reservoir water quality. Local runoff is computed by a mass balance among measured inflows, outflow, and change in reservoir storage (which is a function of headwater elevation). The computation works well under flat pool conditions. For a reservoir with great length, the flat pool assumption may, sometimes, produce a negative

local runoff. Since the local runoff is at least an order of magnitude smaller than riverflow, the negative local runoff was treated as zero in the model.

In the BETTER model, the computed daily local runoff is distributed, based on drainage area distribution, to the surface layer of each column. High runoff nutrient concentrations normally increase algal productivity which has the effects of increasing DO in the surface layers and reducing DO in the hypolimnion. Information on local runoff water quality is usually scarce and unreliable. For this study, a constant concentration for each nutrient was used so that the uncertainty introduced by local runoff is minimized. These nutrient concentrations are given in table 4-5.

Sediment oxygen demand was sampled at six locations (TRMs 473, 483.4, 490.5, 498, 506.5, and 519.2) in Chickamauga Reservoir and two locations (HRMs 3.0 and 15.0) in the Hiwassee River arm. Sediment oxygen demand numbers vary from about $0.6-1.2 \text{ g/m}^2/\text{day}$ in Tennessee River and from about $0.8-0.9 \text{ g/m}^2/\text{day}$ in Hiwassee River (see table 4-6). Sediment oxygen demand used for model calibration ranged from $1.0-1.2 \text{ g/m}^2/\text{day}$. This set of SOD yields a good match of DO in the hypolimnion with field data.

Temperature Calibration--The main objective of temperature calibration was to reproduce observed seasonal temperature patterns in the reservoir under different hydrologic and meteorological conditions. Comparison with a few days of measured temperature does not guarantee that the overall seasonal patterns have been simulated properly, and can,

sometimes, lead to erroneous conclusions. Results of temperature calibration are demonstrated with three types of plots, they are (1) time vs. depth temperature contour plot; (2) surface and bottom temperatures time series at Stations 13 (TRM 484.7) and 8 (TRM 483.4); and (3) Chickamauga Dam release temperature plot.

Figure 4-23 compares 1987 simulated time-depth temperature contours (left-hand side) with measured data (right-hand side) at TRMs 518, 496.5, 484.7, 482.9, 482.4, and 471.1, and HRMs 20 and 7.4. These stations represent conditions in upstream, middle, and downstream reservoir segments as well as segments immediately upstream and downstream from SQN. Note that measured data look smoother than modeled temperatures because it is contoured based on a sparser time series. The observed pattern of longitudinal warming at upstream stations and the development of a weakly stratified water body at downstream stations were all well simulated. On the other hand, more stratification was modeled for the Hiwassee River than measured. Field temperatures at the upstream station (HRM 20) suggested that Hiwassee River inflow temperature may have been as much as 2°C hotter than used in the modeling (i.e., Cleveland Water Treatment intake temperature). The cold modeled inflow caused an early start of thermal stratification and helped maintain an exceedingly strong stratification in the Hiwassee River arm throughout the summer period. Another reason for the strong stratification is due to lack of mixing. Since inflow into the Hiwassee River arm consists of dam releases from Apalachia, Ocoee No. 1, and several unregulated secondary rivers, it is conceivable that convective mixing by inflow in the Hiwassee River arm would be different from that of a regulated one such as peaking release

below Watts Bar Dam. Currently, the model assumes the same inflow convective mixing, which is defined by a mixing coefficient (DC) in the model, for both the Hiwassee River and the Tennessee River branches. This contributes more stratification in the Hiwassee River arm than field measurements. Hiwassee inflow is about an order of magnitude smaller than flow in the Tennessee River, so its effects on water quality in the main river were not considered significant.

At first look, the model seems to slightly overestimate surface temperature in the summer period. However, a close examination of surface and bottom temperatures at Stations 13 and 8 (figures 4-24 and 4-25) showed that surface temperatures were well reproduced. This is also substantiated by the computed release temperature at Chickamauga Dam presented in figure 4-26, which shows a close match with measured data.

In 1986, the only place where enough field data were collected for seasonal temperature patterns is in the forebay area at Chickamauga Dam. As shown in figure 4-27, the time-depth temperature contours computed by the model (left-hand side) compares well with the measured one (right-hand side). The observed stratification was stronger than normal due to low flow in the late spring and early summer and this effect was well reproduced. As shown in figures 4-28 and 4-29, the match between computed and measured surface and bottom temperatures at Stations 13 and 8 was remarkably close. Several times field data showed that the reservoir was intermittently mixed; these mixing episodes are the results of strong storms which cannot be adequately reproduced by the current model with a 12-hour time step. As was the case in 1987, the observed release temperatures shown in figure 4-30 were well reproduced.

Available field data (two seasonal measurements) in 1985 are not adequate to identify reservoir temperature patterns and the emphasis is on the calibration of the thermal mixing component of the model. Model calibration was done by matching computed surface and bottom temperatures both upstream and downstream from the diffuser with field measurements at Stations 13 and 8. The agreement between computed and observed temperatures at Station 13, figure 4-31, is good with the exception that the computed bottom temperature is slightly cooler than the observed one in August. Since river bottom temperatures in summer months are the direct results of upstream release at Watts Bar Dam (an underflow), a more frequent inflow temperature monitoring (perhaps daily) might reduce this discrepancy. Measured bottom temperatures at station 8, figure 4-32, display large temperature variations--typical for a turbulent flow induced by thermal discharge. The SQN thermal discharge causes an increase in bottom temperature of about 2-3°C at full load (2 units) operation. This warming in bottom temperature is well reproduced except for the later half of July where the computed surface and bottom temperatures were about 2°C higher than the measured ones which, incidentally, showed an uncharacteristic sudden drop of about 2°C, an indication of instrument malfunction. Computed and observed Chickamauga Dam release temperature and DO presented in figure 4-33 again demonstrate the success of the model.

Dissolved Oxygen Calibration--The 1987 computed time-depth DO contours (left-hand side) are compared with measured DO patterns (right-hand side) in figure 4-34. Hydrologically, 1987 had a slightly dry spring and near average summer. Reservoir DO ranges from 6-10 mg/l

in spring and from 5-8 mg/l in summer. Field DO measurements indicate that there was an algal bloom in early summer which is characterized by a patch of high surface DO extending from dam to about a third of the reservoir length (around TRM 485). This strong algal activity was only partially reproduced, primarily due to the fact that phosphorus in the surface layers was exhausted during the initial bloom and supply from inflows was cut off by reservoir stratification. The low local runoff phosphorus concentration (0.01 mg/l) also contributed to the shortage of phosphorus in the surface layers which could not sustain the kind of growth indicated by field data. At this time, the model does not simulate increases in local inflow nutrient concentrations due to storm activities.

Computed hypolimnion DO was slightly overestimated (as much as 1 mg/l) in the summer months at all sampling stations. The underestimated algal biomass discussed previously may contribute to this discrepancy. Another possibility would be that the constant inflow BOD and organics were underestimated. The seasonal DO patterns, however, were well reproduced.

A comparison of measured and modeled Chickamauga Dam release DO is shown in figure 4-26. Release DO was well simulated with the exception of about a month period in early summer (from day 150-180) where DO was slightly overestimated.

The 1986 DO comparison in the forebay area is shown in figure 4-27. Dissolved oxygen in the surface layers was slightly underestimated (about 1 mg/l) due to phosphorus shortage which limited algal productivity. Depressed hypolimnion DO was well simulated except that the timing of the second low DO patch was off by about 10 days.

The discrepancy between computed and measured release DO shown in figure 4-30 is somewhat difficult to explain. With a good match of reservoir DO in the forebay area, it is puzzling why the computed release DO failed to reproduce the pattern suggested by the observed data which, incidentally, followed the same pattern of release DO from Watts Bar Dam. It is possible that, under low flow and stratified conditions, the cold releases from Watts Bar Dam were able to travel all the way to Chickamauga Dam with little mixing with ambient water. Lack of field data prevented a close examination of the true extent of flow mixing.

For 1985, the computed Chickamauga Dam release DO shown in figure 4-33 was slightly higher than measured data, especially in late summer from about day 210-240 where the discrepancy amounts to about 1 mg/l. Phosphorus shortage in the surface layers which resulted in lower algal productivity and higher hypolimnion DO is believed to be the main reason of this high release DO in late summer. Using a constant inflow BOD and organics from Watts Bar Dam could, to some degree, also contribute to the discrepancy. As described before, limited field data do not allow a more precise assessment of the inflow water quality.

The large variations in measured Chickamauga Dam release DO (figure 4-30) suggests a withdrawal zone that increases directly with dam release and decreases with vertical temperature gradient. Therefore, higher releases would tend to draw more surface (warm and high DO) water and result in a release with warmer temperature and higher DO than smaller releases. This effect is more pronounced in 1986 (a dry year without SQN thermal discharge) than in 1985 (a dry year with SQN thermal discharge) and 1987 (a moderate year without SQN thermal discharge) due to greater temperature and DO stratification.

Algae and pH Calibration--A direct quantitative comparison of computed and measured algal biomasses is difficult, if not impossible, with present monitoring technology. Chlorophyll a concentration provides a direct measure of standing crop (i.e., all aquatic plants) in the water body. Translation of chlorophyll a concentration to algal biomass, however, requires a great deal of biological judgment.

Field measurements of chlorophyll a concentration in 1987 are shown in figure 4-35. Using a conversion factor of 1 mg/l algal mass = 5 µg/l chlorophyll a, an equivalent algal biomass might range from about 0.4-3.6 mg/l which is in line with the computed algae concentrations ranging from about 0.5-3.0 mg/l (figure 4-36).

Indirect measures such as elevated pH, DO supersaturation, depletion of nutrients ($\text{PO}_4\text{-P}$, $\text{NO}_3\text{-N}$, etc.), and measurements of organics (TOC, TON, VSS, etc.), in most cases, can be used as surrogate (qualitative) indicators of algal activity. The 1987 computed and observed pH patterns shown in figure 4-37 reveals that surface pH was slightly underestimated in the Tennessee River and overestimated in the Hiwassee River. This corroborates the idea described previously in the DO calibration section that algae in the surface layers were underestimated (due to phosphorus shortage). The extra algal biomass calculated in the Hiwassee River arm was the result of the exceedingly strong stratification computed by the model due to cold Hiwassee River inflow. Flow exchange between the Hiwassee River arm and the Tennessee River probably brought some badly needed phosphorus from the Tennessee River to the surface layers of the Hiwassee River arm. This infusion of phosphorus allowed the extra algal biomass discussed above.

For 1986, the computed and measured pH seasonal patterns in the forebay area are shown in figure 4-27. The first algal bloom in early summer was well reproduced. Due to phosphorus shortage in the surface layers, however, the following algal blooms in midsummer were missed by the model. The corresponding DO plot also supports this observation. Overall, the seasonal pH patterns were well simulated. The computed algae shown in figure 4-38 ranges from about 0.5-3.0 mg/l, not much different from that of 1987.

The 1985 computed algae and pH are presented in figures 4-39 and 4-40. Both suggested strong algal growth in early summer. No field data are available to validate these results.

4.2.5 Model Verification

The calibrated model was verified by comparing simulation results of a different year (in this case, 1988) with field data while all model coefficients remained unchanged. Meteorological data (figure 4-41) and inflow concentrations and BOD loadings (figures 4-42 and 4-43) were developed the same manner as that used in the calibration.

Hydrologically, 1988 was similar to 1986 with severely low flows in spring and summer. Watts Bar and Chickamauga Dam releases and the computed water residence time are presented in figure 4-44. The 1988 average spring and summer flows from Chickamauga Reservoir were about 8,500 and 12,700 cfs. These flows represent about 21 percent and 73 percent of the historical spring and summer median flows, respectively. The water residence time for the spring and summer period ranged from about 20-40 days.

In 1988, the biweekly sampling program continued from 1987 was terminated in early May due to a delay in bringing both units back online at SQN. Because of the severe drought conditions in 1988, temperature and DO near SQN were closely monitored during the summer months. Although the locations of these surveys do not coincide with those of the biweekly surveys, they were used in conjunction with the early biweekly surveys for model verification. Stations which are located at the upstream end of the reservoir and in the Hiwassee River arm have only biweekly surveys.

Due to extremely hot weather, a cooling tower at SQN was activated on August 2 and stayed on until Chickamauga Reservoir started its normal turnover at the end of August. Measurements at the intake and discharge locations indicated a net DO increase of 4-5 mg/l across the plant. With a typical 10:1 dilution, the plume would be expected to increase downstream DO by about 0.4-0.5 mg/l (Hauser et al., 1988).

Computed temperature, DO, and pH time-depth contours along with 1988 field data are presented in figures 4-45, 4-46, and 4-47. The seasonal patterns of temperature, DO, and pH were all well reproduced. These matches are further substantiated by the surface and bottom temperatures at Stations 13 and 8 shown in figures 4-48 and 4-49 and Chickamauga Dam release temperature and DO shown in figure 4-50.

As described before, the 1986 field data showed that measured release DO at Chickamauga Dam behaved closely to release DO at Watts Bar Dam. The same behavior was detected in the 1988 data. In both cases, the model was only able to partially reproduce this unique characteristics. When the reservoir is strongly stratified, mixing of bottom

water is driven by the momentum of upstream inflow. Since the time step used by the model was 12 hours, the model inflow was therefore a 12-hour average of Watts Bar Dam releases. This implies that the inflow momentum computed by the model was actually a fraction of that during peaking operation. This was especially true when hydrogeneration was on for only few hours of a day. An adjustment factor which is proportional to the reciprocal of turbine discharge per hour was introduced to the model to augment peaking inflow convective mixing. It is suspected that this adjustment was overdone on low flows in 1986 and 1988 and caused extra mixing of inflow with ambient water.

4.3 Model Simulation

4.3.1 Application of Management Strategies

Management simulations are used to explore reservoir responses to a range of conditions that are difficult to test in the field. In this study, the main concern is the impact of thermal discharge of SQN (TRM 483.7) and WBN (TRM 527.8) on DO in the reservoir. The calibration and validation runs described previously provide base cases for comparing with the effects of nuclear plant operations. The following six scenarios were selected to evaluate the combined effects of SQN and WBN operations under different hydrologies as well as increased release DO at Watts Bar Dam due to surface water pump operation in Watts Bar Dam forebay:

1. Two units operation at SQN and WBN with normal flows,
2. Two units operation at SQN and WBN with low flows,
3. Two units operation at SQN and WBN with high flows,

4. Two units operation at SQN with low flows,
5. Two units operation at SQN and WBN with normal flows and surface water pump operation in Watts Bar forebay,
6. Two units operation at SQN and WBN with low flows and surface water pump operation in Watts Bar forebay.

Two additional model simulations were performed to assist in the evaluation of the assessment on impacts to fisheries: (1) no thermal discharge, and (2) no underwater dam (figures 4-91 through 4-97).

With both units in operation at SQN, the CCW is about 3,000 cfs and the diffuser discharge temperature can be evaluated as a function of intake water temperature as shown in figure 4-51. The relationship between diffuser discharge temperature and CCW intake water temperature can be written as:

$$T_{dis} = 13.506 + 1.0012*T - 1.7703E-3*T^2 + 8.2199E-5*T^3$$

where T_{dis} is the diffuser discharge temperature in °C and T is the intake water temperature in °C. Watts Bar Nuclear Plant is designed to operate in closed cycle cooling mode; the maximum blowdown rate is about 85 cfs. The blowdown temperature is computed as a function of wetbulb temperature (Ungate and Howerton, 1977).

$$T_b = 16.9146 + 0.4915*T_w + 3.8903E-3*T_w^2$$

where T_b is the blowdown temperature in °C and T_w is the wetbulb temperature in °C. The blowdown is discharged into the river via two multiport diffusers. DO in the blowdown was assumed to be the same as the intake (river) DO. In the model, this thermal load is distributed uniformly over the entire water column.

Release DO at Watts Bar Dam can be enhanced by forced mixing of DO rich surface water with DO depressed bottom water in the reservoir

forebay area. The Garton Pump is one device being field tested in TVA's Douglas Reservoir which mechanically mix surface and bottom waters. Preliminary analyses indicate that a 2 mg/l increase in release DO can be realized with the aid of surface water pumps. For management runs 5 and 6, Watts Bar Dam release DO was increased by 2 mg/l to simulate surface water pump operation. It should be noted that the application of surface water pump for release DO enhancement can also cause higher release temperatures. In this study, only DO increase in release water was examined.

4.3.2 Results and Discussions

Results of management simulations are displayed in two types of plots: (1) time-depth-temperature/DO contours and (2) depth-distance-temperature/DO contours (or longitudinal contour). Time-depth contours give an overview of the seasonal variations of the vertical profile of a specified variable at a selected station. Longitudinal contours show a snapshot of the longitudinal variations of a specified variable on a selected day.

A brief discussion of each management run is given below. Due to uncertainties and simplifying assumptions used in modeling and in estimating reservoir nutrients loading and inflow concentrations, emphasis should be placed on relative differences between model runs rather than absolute values.

Run 1. Two Units Operation at SQN and WBN with Normal Flows

Although 1987 annual average flow of 25,230 cfs was somewhat less than the long-term (1903-88) average flow of 33,950 cfs, the 1987 Chickamauga Dam releases showed characteristics of a typical annual flow

distribution and was chosen for this management run to represent normal flow conditions. The only difference between this run and the 1987 calibration was the addition of SQN and WBN heat loads.

Time-depth-temperature and DO contours are given in figures 4-52 and 4-53. Comparing against the 1987 calibration (figures 4-54 and 4-55), the effect of WBN thermal discharge (at TRM 518-523.2) was hardly discernable, if any. The thermal discharge of SQN (at TRM 483-483.7), however, resulted in a temperature increase of about 2°C in the hypolimnion and about 1°C at surface downstream from the diffusers. Thermal stratification in the lower part of Chickamauga Reservoir was, therefore, less pronounced than that of the 1987 calibration. This weakening in thermal stratification was also demonstrated in the longitudinal temperature contour plots shown in figures 4-56 and 4-57 for days 166 and 210, respectively.

The impact of SQN thermal discharge on reservoir DO downstream from the diffusers was significant. Due to strong mixing induced by SQN thermal discharge, reservoir DO immediately below the diffusers remained fully mixed throughout the year. Further downstream, the weakened thermal stratification hampered algal growth and resulted in a DO improvement of about 1 mg/l in the hypolimnion. The surface DO was, however, slightly lower than the 1987 calibration due to mixing with low DO thermal discharge and less algal activity. Comparison of DO patterns up and downstream from SQN in figures 4-58 and 4-59 substantiate the mixing effect of SQN thermal discharge described above. Little effect of WBN thermal discharge on reservoir DO was detected.

Run 2. Two Units Operation at SQN and WBN with Low Flows

The 1986 Chickamauga Dam releases, which had an annual average flow of 18,900 cfs, were chosen for the low flow management runs. As in the normal flow runs, all inputs used in 1986 calibration remained unchanged with the exception of SQN and WBN thermal discharges. Against the 1986 calibration (figure 4-61), the time-depth-temperature contours shown in figure 4-60 indicate an increase of about 4°C in the hypolimnion downstream from the SQN diffusers during the low flow period (day 90-150). The increase was reduced to about 2°C after the low flows were over and riverflow increased to its seasonal norm. During the low flow period, increases in surface temperature were about 1-2°C; thus, reservoir stratification was significantly reduced in areas below the SQN diffusers as demonstrated in figures 4-62 and 4-63. Heating due to WBN thermal discharge was the strongest during the low flow months. A detailed examination of the effect of WBN thermal discharge is given in Run 4. As shown in the time-depth-DO contour in figure 4-64, the improvement in hypolimnetic DO downstream from the SQN diffusers is quite significant. During the low flow period, increases ranging from 2-4 mg/l were observed when compared with the 1986 calibration (figure 4-65). Also noted was a smaller DO increase (1-2 mg/l) in the bottom water upstream from the underwater dam (TRM 483.76). This increase is believed to be the result of SQN cooling water withdrawal which speeds up the bottom water movement and, thereby, reduces the water residence time. As described before, surface DO downstream from the SQN diffusers is lowered due to mixing with low DO diffuser flows (near-field) and less algal activity (far-field). The longitudinal DO contours shown in figures 4-66

and 4-67 provide an overview of the effects. The effect of WBN thermal discharge on reservoir DO is discussed in Run 4.

Run 3. Two Units Operation at SQN and WBN with High Flows

The high flows scenario was constructed by raising 1987 Chickamauga Dam releases to 80 percent rank historical natural flow at Chickamauga Dam (1903-88). The flow adjustment was done on a quarterly basis. In each quarter, a flow adjustment factor (ratio of the sum of 1987 Chickamauga Dam flow to the sum of 80 percent rank historical natural flow at Chickamauga Dam) was determined. This flow adjustment raised the 1987 Chickamauga Dam flow to the 80 percent rank Chickamauga Dam natural flow while still maintaining the original flow pattern. The 80 percent rank Chickamauga Dam natural flow along with the 1987 Chickamauga Dam flow is shown in figure 4-68. A comparison of the time-depth-temperature contours (figure 4-69) and DO contours (figure 4-70) against those of Run 1 (two units operation with normal flows in figures 4-52 and 4-53) revealed that both temperature and DO stratifications were slightly reduced by the increased flows. The mixing effect of SQN thermal discharge can still be seen as the small temperature and DO gradients upstream from the SQN diffusers became fully mixed immediately below the diffusers (figures 4-71 to 4-74). Further downstream, thermal and DO stratification was reestablished. Due to the increased flow, algal activity was reduced which probably contributes to the lower surface DO during the summer months.

Run 4. Two Units Operation at SQN with Low Flows

The purpose of this run is to identify the effect of SQN thermal discharge without the influence of WBN heat load. The 1986 dry hydrology

was used to show the maximum mixing effect induced by the diffuser discharge. Comparing the time-depth-temperature contour (figure 4-75) with the 1986 calibration (figure 4-61) indicated a 2-4°C increase in the hypolimnion downstream from the diffusers and a slight warming (less than 1°C) in the hypolimnion upstream from the underwater dam. Effect on DO (figure 4-76 vs. figure 4-65) was also significant with an increase of 2-4 mg/l in the hypolimnion downstream from the diffusers and 1-2 mg/l in the bottom water upstream from the underwater dam. Effects on surface temperature and DO are essentially the same as those of Run 2.

The effect of WBN thermal discharge can be evaluated by comparing Run 4 (i.e., without WBN thermal discharge) against Run 2 which includes both SQN and WBN heat loads. A comparison of the surface and bottom temperatures immediately below the WBN thermal discharge for the two cases is illustrated in figure 4-77. The difference is very small even under extremely low flow conditions. A close examination shows a maximum increase of about 0.7°C under reverse flow conditions. It should be noted that this reverse flow was computed based on the flat pool assumption and might not actually occur in the field. The small temperature increase dissipates quickly as it flows downstream. With higher river flows, the WBN effect becomes even less pronounced and the temperature increase quickly disappears due to dilution with larger flows (see figures 4-78 vs. 4-62 and 4-79 vs. 4-63). It should be pointed out that the actual local heating immediate below WBN may be higher than that computed by the model. The subject of local heating, however, is beyond the scope of this study.

As shown in figure 4-77, the effect of WBN on reservoir DO is negligibly small with a maximum increase of about 0.6 mg/l in the surface

water near WBN under reverse flow conditions. No effect on downstream DO was observed when comparing figures 4-80 and 4-81 vs. 4-66 and 4-67.

Run 5. Two Units Operation at SQN and WBN with Normal Flows and Surface Water Pump Operation in Watts Bar Reservoir Forebay

In this simulation, Watts Bar Dam release DO was increased by 2 mg/l to account for the operation of surface water pumps in Watts Bar Reservoir forebay. It is conceivable that the operation of surface water pump would also raise Watts Bar Dam release temperature as the warm surface water is forced down and mixed with the cold bottom water. As a sensitivity study, however, 1987 Watts Bar Dam release temperature was used without modification.

To assess the effect of surface water pumps in Watts Bar Reservoir forebay on Chickamauga Reservoir DO, results of the simulation are compared to those of Run 1 which does not have surface water pump operation. Examining the time-depth-DO contour (figure 4-82 vs. figure 4-53) and the longitudinal DO contour (figures 4-83 and 4-84 vs. figures 4-58 and 4-59) show that the 2 mg/l DO increase in Watts Bar Dam release declines as water travels downstream in Chickamauga Reservoir. The decline in added DO is down to 1.0-1.5 mg/l when the water reaches SQN and to about 1 mg/l at Chickamauga Dam.

Run 6. Two Units Operation at SQN and WBN with Low Flows and Surface Water Pump Operation in Watts Bar Dam Forebay

The 1986 dry hydrology was used for this simulation and results are compared to those of Run 2. Based on the analysis of the time-depth-DO contour (figure 4-85 vs. figure 4-64) and the longitudinal DO contour (figures 4-86 and 4-87 vs. figures 4-66 and 4-67), the 2 mg/l DO increase

in Watts Bar Dam release is reduced to 1.0-1.5 mg/l at SQN and about 1.0 mg/l at Chickamauga Dam. Normally one would expect that the reservoir DO increase would be smaller with low flows as the residence time becomes longer. Model simulation indicates, however, that DO increases with low flows are about the same as those of normal flows. The 1986 low flows in spring and summer produced a strong thermal stratification which lasted all summer. This thermal stratification prevented the cool Watts Bar Dam inflow from mixing with surface water and created a fast track for the cool inflow to move downstream. This resulted in a shorter residence time which helped to offset the low flows, possibly explaining why reservoir DO increases with low flows are about the same as those with normal flows.

4.3.3 Conclusions

1. Water quality modeling showed that the discharge from SQN increases the temperature and DO of the release from Chickamauga Reservoir by 1-3°C and 0.5-2.0 mg/l, respectively during the critical spring and summer months (figure 4-88).
2. Water quality modeling showed that the temperature and DO of the release from Chickamauga Dam were the same with or without the discharge from SBN even under extremely low flow conditions (figure 4-88).
3. Water quality modeling showed that the DO in the release from Chickamauga Dam during low flow (19,000 cfs) years was about 2 mg/l lower than that during normal (25,000 cfs) or high flow years (figure 4-89).

4. Model simulations showed that the hypolimnetic DO was above 5 mg/l throughout the summer when flows were normal or higher (figures 4-58 and 4-59). During low flow simulations, the reservoir strongly stratified resulting in hypolimnetic DO less than 3 mg/l (figure 4-67).
5. Water quality modeling showed that the addition of 2 mg/l of DO to the release from Watts Bar Dam by aeration with fore-bay surface water pumps results in an increase of 0.8-1.0 mg/l in the releases from Chickamauga Dam (figure 4-90).
6. The DO concentrations in Chickamauga Reservoir depends greatly on the DO concentration in the release from Watts Bar Dam, which can be in the 2-4 mg/l range in dry summer months.
7. Water quality modeling showed that the DO in the hypolimnion downstream from SQN was increased 2-4 mg/l when both units at SQN are generating (compare figures 4-64 and 4-65). The increase is due to the mixing of the water column induced by the mixing of the heated discharge, the underwater dam, and the bend in the river.
8. Water quality modeling showed that the DO in the hypolimnion downstream from SQN was increased approximately 1 mg/l when SQN is not generating electricity (compare figures 4-91 and 4-93). The increase is due to the mixing of the water column induced by the the underwater dam and the bend in the river.
9. Water quality modeling showed that under low flows, the DO in the hypolimnion near Chickamauga Dam would decrease 2 mg/l if SQN, including the underwater dam, were not present (compare figures 4-67 and 4-97).

10. Water quality modeling showed that the DO in both the epilimnion and the hypolimnion downstream from SQN would increase 1.0-1.5 mg/l if 2 mg/l of DO is added to Watts Bar Dam releases with forebay surface water pumps. This increase is the same under both low and normal flows (compare figures 4-66 and 4-67 with figures 4-86 and 4-87).
11. Water quality modeling showed that the DO in the epilimnion downstream from SQN was decreased approximately 1 mg/l when both units at SQN are generating (compare figures 4-64 and 4-65). The decrease is due to the mixing of the water column induced by the mixing of the heated discharge, the underwater dam, and the bend in the river.
12. Water quality modeling showed that the DO in the epilimnion downstream from SQN was decreased approximately 1 mg/l when SQN is not generating electricity (compare figures 4-91 and 4-93). The decrease is due to the mixing of the water column induced by the the underwater dam and the bend in the river.
13. Water quality modeling showed that under low flows, the DO in the epilimnion near Chickamauga Dam would increase 1 mg/l if SQN, including the underwater dam, were not present (compare figures 4-67 and 4-97).

Table 4-1. Sampling Locations in Chickamauga Reservoir

River mile ^a	No. of horizontal locations	Nutrient sampling	Fluorometry sampling
TRM 529.9	1	yes	yes
TRM 518.0	1	yes	no
TRM 506.6	1	yes	yes
TRM 496.5	1	yes	yes
TRM 490.5	1	no	yes
TRM 484.7	3	yes	yes
TRM 484.1	3	yes	yes
TRM 483.55	3	no	no
TRM 483.4	3	yes	yes
TRM 482.9	3	no	yes
TRM 482.4	3	yes	yes
TRM 481.4	3	no	yes
TRM 480.4	1	yes	yes
TRM 478.2	1	yes	yes
TRM 475.4	1	no	yes
TRM 473.4	1	no	yes
TRM 471.1	1	yes	yes
HRM 20.0	1	yes	no
HRM 7.4	1	yes	no

a. TRM = Tennessee River mile
HRM = Hiwassee River mile

Table 4-2. Field Sampling Dates

<u>April 1, 1987 through September 30, 1989</u>		
1987	1988	1989
April 1	January 19 ^a	April 5
April 16	February 2	April 18 & 19
April 29	February 16	May 1, 3 & 5
May 13	March 1	May 16 & 17
May 27	March 15	May 30 & 31
June 10	March 29	June 13 & 14
June 23	April 5	June 27, 28 & 29
July 7	April 12	July 11 & 12
July 21	April 19	July 25, 26, & 27
August 4	April 26	August 8 & 9
August 18	May 3	August 22
September 1 & 2	May 10	September 5 & 6
September 15		September 19
September 29		
October 13		
October 27		
November 9		
November 23		
December 8		
December 22		

a. No field sampling was conducted on January 5, 1988.

Table 4-3. Sediment Oxygen Demand Results

Test: 1									
Start: 04/06/88									
Stop: 04/18/88		SOD rates (g/m ² /day)				SOD rates (g/m ² /day)			
		0-120 hours			Average		0-48 hours		
							48-144 hours		
Reactor samples	(1)	SOD	R ²	Average SOD	SOD	R ²	SOD	R ²	
1	TRM 473	0.854	0.913	0.854	1.641	0.967	0.510	0.997	
2	TRM 473	n/a	n/a		n/a	n/a	n/a	n/a	
3	TRM 483.4	1.282	0.997		n/a	n/a	n/a	n/a	
4	TRM 483.4	1.114	0.999	1.198	n/a	n/a	n/a	n/a	

Test: 2									
Start: 04/26/88									
Stop: 05/05/88		SOD rates (g/m ² /day)				SOD rates (g/m ² /day)			
		0-120 hours			Average		0-36 hours		
							36-144 hours		
Reactor samples		SOD	R ²	Average SOD	SOD	R ²	SOD	R ²	
1	TRM 490.5	n/a	n/a	n/a	n/a	n/a	n/a	n/a	
2	TRM 490.5	0.573	0.885	0.573	1.485	0.923	0.389	0.995	
3	TRM 498 (2)	0.827	0.975		n/a	n/a	n/a	n/a	
4	TRM 498	0.800	0.998	0.814	n/a	n/a	n/a	n/a	

Test:	3			
Start:	06/07/88			
Stop:	06/22/88	SOD rates (g/m ² /day)		
		0-120 hours		
Reactor samples				Average
		SOD	R ²	SOD
1	TRM519.2	1.039	0.998	
2	TRM519.2	0.640	0.997	0.840
3	TRM506.5	0.758	0.998	
4	TRM506.5 (3)	0.861	0.997	0.809

Test:	4			
Start:	06/28/88			
Stop:	07/12/88	SOD rates (g/m ² /day)		
		0-120 hours		
Reactor samples			Average	
		SOD	R ²	SOD
1	HRM 3.0	0.952	0.998	
2	HRM 3.0	0.932	0.998	0.942
3	HRM 15.0	0.838	0.995	0.838
4	HRM 15.0	n/a	n/a	

Notes:

- (1) Samples identified by river mile number (either Tennessee or Holston).
V/A = 678 l/m² unless otherwise indicated.
- (2) Only 7 core samples were used in this determination.
V/A = 795 l/m².
- (3) Only 6 core samples were used in this determination.
V/A = 951 l/m².

Table 4-4. Watts Bar Dam Release Water Quality

Date	NO ₂ +NO ₃ (mg/l)	NH ₃ +NH ₄ (mg/l)	Org-N (mg/l)	P-dissolved (mg/l)	TOC (mg/l)	BOD ₅ (mg/l)
85/02/20	0.46	0.05	0.23	-	1.7	-
85/05/14	0.33	0.02	0.03	0.01	2.8	-
85/08/20	0.16	0.03	0.23	0.01	3.3	-
85/11/07	0.27	0.02	0.16	0.02	2.9	-
86/02/19	0.38	0.02	0.20	0.01	3.5	-
86/05/06	0.18	0.07	0.21	0.01	2.4	-
86/05/27	0.20	-	-	-	-	-
86/06/10	0.19	-	-	-	-	-
86/07/01	0.20	-	-	-	-	-
86/07/15	0.18	-	-	-	-	-
86/07/28	0.22	-	-	-	-	-
86/08/13	0.23	-	-	-	-	-
86/08/19	0.07	0.03	0.21	0.01	2.8	-
86/09/09	0.13	-	-	-	-	-
86/09/22	0.61	-	-	-	-	-
86/11/18	0.31	0.02	0.13	0.02	3.3	-
87/04/01	0.41	0.03	0.22	0.01	2.3	-
87/05/13	0.29	0.06	0.20	0.01	2.6	-
87/06/10	0.38	0.01	0.17	0.01	2.4	1.5
87/07/07	0.20	0.03	0.41	0.01	4.1	1.7
87/08/04	0.29	0.02	0.30	0.01	2.1	1.0
87/09/01	0.21	0.02	0.18	0.01	1.9	1.0
87/10/13	0.20	0.03	0.15	0.01	1.2	1.1
87/11/09	0.17	0.05	0.21	0.01	1.8	1.7
87/11/09	0.16	0.02	0.24	0.01	1.7	1.6

Table 4-5. Chickamauga Reservoir Inflow Nutrient Concentrations

Parameter	Watts Bar Dam (mg/l)	Hiwassee River (mg/l)	Local runoff (mg/l)
Detritus	1.0	0.7	1.5
Dissolved organics	2.0	2.0	2.0
NH ₃ -N	0.03	0.015	0.01
NO ₃ -N	0.3	0.15	0.3
PO ₄ -P	0.01	0.01	0.01

Table 4-6. Sediment Oxygen Demand Rates Used in the BETTER Model

River mile ^a	SOD (g/m ² -day) (0-120 hours)
TRM 473	0.854
TRM 483.4	1.198
TRM 490.5	0.573
TRM 498.0	0.814
TRM 506.5	0.809
TRM 519.2	0.840
HRM 3.0	0.942
HRM 15.0	0.838

a. TRM = Tennessee River Mile
HRM = Hiwassee River Mile

Sediment Oxygen Demand Test 1 Sediment Core Samples from TRM 473

Figure 4-1. Sediment Oxygen Demand Test 1, Sediment Core Samples from Tennessee River mile 473

Sediment Oxygen Demand Test 1 Sediment Core Samples from TRM 473

Figure A-2. Sediment Oxygen Demand Test 1, Sediment Core Samples from Tennessee River mile 473

Sediment Oxygen Demand Test 1
Sediment Core Samples from TRM 483.4

Figure A-3. Sediment Oxygen Demand Test 1, Sediment Core Samples from Tennessee River mile 483.4

Sediment Oxygen Demand Test 2 Sediment Core Samples from TRM 490.5

Figure 4-4. Sediment Oxygen Demand Test 2, Sediment Core Samples from Tennessee River mile 490.5

Sediment Oxygen Demand Test 2 Sediment Core Samples from TRM 498

Figure 4-5. Sediment Oxygen Demand Test 2, Sediment Core Samples from Tennessee River mile 498

Sediment Oxygen Demand Test 3 Sediment Core Samples from RPM 519.2

Figure A-6. Sediment Oxygen Demand Test 3, Sediment Core Samples from Tennessee River mile 519.2

Sediment Oxygen Demand Test 3 Sediment Core Samples from TRM 506.5

Figure 4-7. Sediment Oxygen Demand Test 3, Sediment Core Samples from Tennessee River mile 506.5

Sediment Oxygen Demand Test 4 Sediment Core Samples from HRM 3.0

Figure 4-8. Sediment Oxygen Demand Test 4, Sediment Core Samples from Hiwassee River mile 3.0

Figure 4-9. Sediment Oxygen Demand Test 4, Sediment Core Samples from Hiwassee River mile 15.0

Figure 4-10. Geometric Representation of Chickamauga Reservoir

ENG LAB 01/04/90

Figure 4-11. 1985 Chickamauga and Watts Bar Discharges and Water Residence Time in Chickamauga Reservoir

ENG LAB 01/04/90
Figure 4-12. 1986 Chickamauga and Watts Bar Discharges and Water Residence Time in Chickamauga Reservoir

ENG LAB 01/04/90

Figure 4-13. 1987 Chickamauga and Watts Bar Discharges and Water Residence Time in Chickamauga Reservoir

Figure 4-14. 1985 Chattanooga Airport Meteorological Data

Figure 4-15. 1986 Chattanooga Airport Meteorological Data

Figure 4-16. 1987 Chattanooga Airport Meteorological Data

Figure 4-17. 1985 Chickamauga Inflow Water Quality

Figure 4-18. 1986 Chickamauga Inflow Water Quality

Figure 4-19. 1987 Chickamauga Inflow Water Quality

Figure 4-20. 1985 Hiwassee Inflow Water Quality

Figure 4-21. 1986 Hiwassee Inflow Water Quality

Figure 4-22. 1987 Hiwassee Inflow Water Quality

Figure 4-23. 1987 Computed and Observed Time-Depth-Temperature Contours in Chickamauga Reservoir

Figure A-23 (Continued)

ENC LAB 65/15/83

Figure 4-23 (Continued)

CHICKAMAUGA TEMPERATURE 1987 TRM 483.7-484.8

ENG LAB 03/10/89

Figure 4-24. 1987 Computed and Observed Surface and Bottom Temperatures at Station 13 (TRM 484.7)

CHICKAMAUGA TEMPERATURE 1987 TRM 483.0-483.7

ENG LAB 08/24/88

Figure 4-25. 1987 Computed and Observed Surface and Bottom Temperatures at Station 8 (TRM 483.4)

Figure 4-26. 1987 Computed and Observed Release Temperature and DO at Chickamauga Dam

COMPUTED TEMPERATURE (°C) AT TRM 471.1-475.1

OBSERVED TEMPERATURE (°C) AT CHICKAMAUGA FOREBAY

COMPUTED DO (MG/L) AT TRM 471.1-475.1

OBSERVED DO (MG/L) AT CHICKAMAUGA FOREBAY

COMPUTED pH AT TRM 471.1-475.1

OBSERVED pH AT CHICKAMAUGA FOREBAY

DLG LWS 05/10/83

Figure 4-27. 1986 Computed and Observed Time-Depth-Temperature/DO/pH Contours in Chickamauga Forebay

ENG LAG 07/13/88

Figure 4-28. 1986 Computed and Observed Surface and Bottom Temperatures at Station 13 (TRM 484.7)

CHICKAMAUGA TEMPERATURE 1986 TRM 483.0-483.7

ENG LAB 05/11/89
Figure 4-29. 1986 Computed and Observed Surface and Bottom Temperatures at Station 8 (TRM 483.4)

Figure 4-30. 1986 Computed and Observed Release Temperature and DO at Chickamauga Dam

CHICKAMAUGA TEMPERATURE 1985 TRM 483.7-484.8

Figure 4-31. 1985 Computed and Observed Surface and Bottom Temperatures at Station 13 (TRM 484.7)

CHICKAMAUGA TEMPERATURE 1985 TRM 483.0-483.7

ENG LAB 08/23/88

Figure 4-32. 1985 Computed and Observed Surface and Bottom Temperatures at Station 8 (TRM 483.4)

Figure 4-33. 1985 Computed and Observed Release Temperature and DO at Chickamauga Dam

Figure 4-34. 1987 Computed and Observed Time-Depth-DO Contours in Chickamauga Reservoir

Figure 4-34 (Continued)

END LOG 05/19/88

ENG LAB 11/21/89 Figure 4-35. 1987 Measured Chlorophyll Concentrations in Chickamauga Reservoir

Figure 4-35 (Continued)

ENG LAB 11/21/89) CHL-AB72

Figure 4-36. 1987 Computed and Observed Time-Depth-Algae Contours in Chickamauga Reservoir

Figure 4-37. 1987 Computed and Observed Time-Depth-pH Contours in Chickamauga Reservoir

Figure 4-37 (Continued)

Figure 4-38. 1986 Computed and Observed Time-Depth-Algae Contours in Chickamauga Reservoir

Figure 4-39. 1985 Computed and Observed Time-Depth-Algae Contours in Chickamauga Reservoir

Figure 4-41. 1988 Chattanooga Airport Meteorological Data

Figure 4-42. 1988 Chickamauga Inflow Water Quality

Figure 4-43. 1988 Hiwassee Inflow Water Quality

ENG LAB 01/04/90

Figure 4-44. 1988 Chickamauga and Watts Bar Discharges and Water Residence Time in Chickamauga Reservoir

ENG LAB 65/17/83

Figure 4-45. 1988 Computed and Observed Time-Depth-Temperature Contours in Chickamauga Reservoir

Figure 4-45 (Continued)

ENG LJS 02/17/03

Figure 4-45 (Continued)

Figure 4-46. 1988 Computed and Observed Time-Depth-DO Contours in Chickamauga Reservoir

Figure 4-46 (Continued)

Figure 4-46 (Continued)

Figure 4-47. 1988 Computed and Observed Time-Depth-pH Contours in Chickamauga Reservoir

Figure 4-47 (Continued)

DEC 1980 05/10/80

Figure 4-47 (Continued)

Figure 4-47 (Continued)

ENG LAB 03/01/89

Figure 4-48. 1988 Computed and Observed Surface and Bottom Temperatures at Station 13 (TRM 484.7)

CHICKAMAUGA TEMPERATURE 1988 TRM 483.0-483.7

ENG LAB 02/28/89

Figure 4-49. 1988 Computed and Observed Surface and Bottom Temperatures at Station 8 (TRM 483.4)

Figure 4-50. 1988 Computed and Observed Release Temperature and DO at Chickamauga Dam

ENG LAB 07/12/89) DIFF-TEMP

Figure 4-51. SQN Intake Temperature vs. Pond Discharge Temperature With Full Loads

Figure 4-52. Time-Depth-Temperature Contours With Full SQN and WEN Loads Under Normal (1987) Flows

Figure 4-52 (Continued)

030 143 03/21/88
 Figure 4-53. Time-Depth-DO Contours With Full SQN and WBN Loads Under Normal (1987) Flows

Figure 4-53 (Continued)

Figure 4-54. 1987 Computed and Observed Time-Depth-Temperature Contours in Chickamauga Reservoir

Figure 4-55. 1987 Computed Time-Depth-DO Contours

END LAB 10/25/88

END LAB 85/21/88

Figure 4-56. Longitudinal Temperature Contours on Day 166 With Full SQN and MBN Loads Under Normal (1987) Flows

ENG LAB 63/21/83

Figure 4-57. Longitudinal Temperature Contours on Day 210 With Full SQW and MBN Loads Under Normal (1987) Flows

END LAB 02/21/89

Figure 4-58. Longitudinal DO Contours on Day 166 With Full SQN and WBN Loads Under Normal (1987) Flows

END LAB 03/21/88

Figure 4-59. Longitudinal DO Contours on Day 210 With Full SQW and WBN Loads Under Normal (1987) Flows

Figure 4-60. Time-Depth-Temperature Contours With Full SQN and WBN Loads Under Low (1986) Flows

Figure 4-61. 1986 Computed Time-Depth-Temperature Contours

ENG LAB 12/18/89
 Figure 4-62. Longitudinal Temperature Contours on Day 166 with Full SQN and MBN Loads Under Low (1986) Flows

END LOG 03/18/79

Figure 4-63. Longitudinal Temperature Contours on Day 210 with Full SQN and WBN Loads Under Low (1986) Flows

Figure 4-64. Time-Depth-DO Contours With Full SQN and WBN Loads Under Low (1986) Flows

ENG LJS 12/18/88

Figure 4-65. 1986 Computed Time-Depth-DO Contours

ENG LAB 12/18/83

Figure 4-66. Longitudinal DO Contours on Day 166 With Full SQN and WBN Loads Under Low (1986) Flows

ENC LAB 05/19/00

Figure 4-67. Longitudinal DO Contours on Day 210 With Full SQN and MBN Loads Under Low (1986) Flows

ENG LAB 12/21/89

Figure 4-68. The 80% Rank Chickamauga Dam Natural Flow

Figure 4-69. Time-Depth-Temperature Contours With Full SQN and WBN Loads Under High (80% Rank) Flows

Figure 4-70. Time-Depth-DO Contours With Full SQN and WBN Loads Under High (80% Rank) Flows

END LAB 12/18/88

ENC LAB 83/14/85

Figure 4-71. Longitudinal Temperature Contours on Day 166 With Full SQW and WBN Loads Under High (80% Rank) Flows

DSG LAB 02/14/78

Figure 4-72. Longitudinal DO Contours on Day 166 With Full SQN and WBN Loads Under High (80% Rank) Flows

ONE LAB 82/14/83

Figure 4-73. Longitudinal Temperature Contours on Day 210 With Full SQN and WBN Load Under High (80% Rank) Flows

Figure 4-75. Time-Depth-Temperature Contours With Full SQN Load Under Low (1986) Flows

Figure 4-76. Time-Depth-DO Contours With Full SQN Load Under Low (1986) Flows

ENG LAB 12/18/89)SBTIME-16

Figure 4-77. Surface and Bottom Temperature and DO at TRM 528 With and Without MBN Thermal Discharge

DIS LAB 10/27/88

Figure 4-78. Longitudinal Temperature Contours on Day 166 With Full SQN load Under Low (1986) Flows

DBS LAB 12/27/88

Figure 4-79. Longitudinal Temperature Contours on Day 210 With Full SQW load Under Low (1986) Flows

END LAR 10/24/88

Figure 4-81. Longitudinal DO Contours on Day 210 With Full SQN load Under Low (1986) Flows

Figure 4-82. Time-Depth-DO Contours With Full SQN and WBN Loads and Increased Watts Bar Release DO (+2 mg/l) Under Normal (1987) Flows

ENC LAB 88/21/78

Figure 4-83. Longitudinal DO Contours on Day 166 With Full SQN and WBN Loads and Increased Watts Bar Release DO (+2 mg/l) Under Normal (1987) Flows

200 LAG 03/21/83

Figure 4-84. Longitudinal DO Contours on Day 210 With Full SQN and WBN Loads and Increased Watts Bar Release DO (+2 mg/L) Under Normal (1987) Flows

Figure 4-85. Time-Depth-DO Contours With Full SQN and WBN Loads and Increased Watts Bar Release DO (+2 mg/l) Under Low (1986) Flows

DOB LAG 12/28/88

Figure 4-86. Longitudinal DO Contours on Day 166 with Full SQW and WBN Loads and Increased Watts Bar Release DO (+2 mg/l) Under Low (1986) Flows

256 L-3 02/12/78

Figure 4-87. Longitudinal DO Contours on Day 210 with Full SQM and WBN Loads and Increase Watts Bar Release DO (+2 mg/l) Under Low (1986) Flows

Figure 4-88. Effects of SQN and WBN Thermal Discharges on Chickamauga Release Temperature and DO

Figure 4-89. Effects of Hydrology on Chickamauga Release Temperature and DO With Full SQN and WBN Loads

Figure 4-90. Effects of Surface Water Pump Operation on Chickamauga Release Temperature and DO Under Normal and Low Flows

ENG LAB 01/03/90

Figure 4-91. Longitudinal Dissolved Oxygen Contours on Day 166 With No Thermal Discharge and With the Underwater Dam Under Normal (1987) Flows

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ENCLOSURE 81/03/78

Figure 4-92. Longitudinal Dissolved Oxygen Contours on Day 166 With No Thermal Discharge and With No Underwater Dam Under Normal (1987) Flows

ES&L 83/21/03

Figure 4-93. Longitudinal Dissolved Oxygen Contours on Day 166 With Full SQN and WBN Loads and With Underwater Dam Under Normal (1987) Flows

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DS 149 12/24/78

Figure 4-94. Longitudinal Dissolved Oxygen Contours on Day 166 With No Thermal Discharge and With the Underwater Dam Under Low (1986) Flows

DS 148 02/12/78

Figure 4-95. Longitudinal Dissolved Oxygen Contours on Day 166 With No Thermal Discharge and With No Underwater Dam Under Low (1986) Flows

Figure 4-96. Longitudinal Dissolved Oxygen Contours on Day 210 With No Thermal Discharge and With the Underwater Dam Under Low (1986) Flows

DS LAB 82/12/78

Figure 4-97. Longitudinal Dissolved Oxygen Contours on Day 210 With No Thermal Discharge and With No Underwater Dam Under Low (1986) Flows

5.0 IMPACTS OF DISSOLVED OXYGEN DISTRIBUTION ON AQUATIC LIFE

Dissolved oxygen is essential, and sometimes even the limiting factor, for maintaining aquatic life (Alabaster and Lloyd, 1980). Depletion or redistribution of life-sustaining DO is a frequent result of hydropower reservoir operations, water pollution or industrial uses of water, and is the most biologically important water quality impact to many river systems. Both large vertical and horizontal spatial expanses of reservoirs and extensive downstream river reaches may suffer low DO levels due to industrial or agricultural discharges in conjunction with stratification and naturally occurring biological reduction of oxygen in reservoir hypolimnia. Whether in a reservoir or regulated river, the degree or severity of biotic effects depends upon; the magnitude and duration of DO reduction, amount of longitudinal and vertical areas disturbed, species of fishes and other biota present, their behavior, and their individual sensitivities to lowered concentrations of DO.

5.1 Phytoplankton

5.1.1 Methods and Materials

Data from collections made in 1987-88 when SQN was not operating have been previously summarized in a progress report and are included with discussion in appendix E. In 1989, samples were collected approximately every two weeks from early April through early October. Samples were collected from midchannel locations at stations identified in table 4-1. In vivo fluorescence profiles were obtained using a low volume pump which routed water to a flow-through cell in a Turner Designs field model fluorometer. Equipment malfunction in early

August required a shift to use of a laboratory model Turner fluorometer. Samples were collected at surface, 1.0, 3.0, and 5.0 m during this period of the operational investigation. Samples for in vivo chlorophyll and phytoplankton counts were obtained from the 1.0-m depth throughout the investigation. Phytoplankton samples were preserved with M-3 fixative and counted using a Palmer cell. Samples for chlorophyll analysis were filtered upon return to the laboratory and sent to TVA's chemical laboratory for analysis.

5.1.2 Results and Discussion

Fluorometry profiles were included in this survey as a low cost method to document that reduced phytoplankton measurements in the upper strata at TRM 483.4 were caused by diffuser mixing. Fluorometry profiles have been used to determine the relative chlorophyll concentration and patterns throughout the euphotic portion of the water column.

Line graphs of chlorophyll concentration and relative fluorescence reading are located in figures E-57 through E-70, algal counts in figures E-71 through E-82, and the isopleths of in vivo fluorescence in figures E-83 through E-96. Phytoplankton production varies depending on nutrient concentrations, light quantity and quality, and flow conditions. Throughout the 1989 sampling period, flows remained high and channel plankton habitat remained fairly constant. As a result, channel conditions (temperature, nutrients, and DO) were greatly influenced by releases from Watts Bar Dam. Dissolved nitrogen and ortho-phosphorus concentrations remained relatively constant with an N:P ratio of 10:1-20:1 throughout the period.

Chlorophyll, fluorometry, and algal counts collected at the 1-m depth showed more variation than chemical and physical measurements made at the same depth, but variation was consistent throughout the sample period. In general, concentrations increased from upstream to downstream until TRM 483.4 (diffuser location) where the water column mixed due to physical action of the diffuser discharge and the underwater dam. Concentrations remained low for 1-2 river miles and then recovered to levels similar to those above the diffuser. An additional increase was often observed at TRM 478.2, where inflows from Wolftever Creek enter the main body of the reservoir. This increase was followed by a slight decrease due to dilution and then concentrations remained fairly constant to the reservoir forebay.

5.1.3 Conclusions

1. Fluorometry values were more sensitive to minor changes in plankton concentrations than chlorophyll concentrations.
2. Both fluorometry and chlorophyll measurements showed that the diffuser discharge and the underwater dam effectively mix the water column in the area of TRM 483.4. The effects of this mixing diminish within 1-2 river miles.

5.2 Fisheries

5.2.1 Fishery Effects from Modeled and Observed Conditions

The following discussion is directed towards evaluating the likelihood and level of effects of low DO on fish production (reproduction, survival, and growth) in Chickamauga Reservoir and the potential contribution of facilities or operational characteristics of the SQN. These

discussions assume daily exposures to predicted or observed DO concentrations are continuous, and do not deal with possible diel cycling or changing exposures. Information on low DO effects on fish are limited at best and are typically based on continuous exposure, laboratory-conducted, short-term studies (although some evidence does suggest that applications to field situations have been reasonable). For a more detailed discussion of particular species and issues relating to applicability of criteria and specific effects of low DO, see appendix F.

Spatio-Temporal Occurrence of Fishes--Life histories and specific habitat used by different life stages of particular fishes strongly influence their likelihood of experiencing low DO effects in reservoirs or regulated rivers. Biological factors which reduce the likelihood of production impacts to fisheries by low summer DO concentrations and SQN-related mixing events to particular fish species in Chickamauga Reservoir include: adult habitat preferences for shallow-water, near-shore habitats with cover; early spawning; spawning by adults in overbank or embayment areas where DO levels are less affected by main-channel events; spawning in epilimnetic rather than in hypolimnetic areas (reduces likelihood of exposure to most severe DO levels); habitat preference of larvae and juveniles of certain fish species for overbank and shallow water habitats (both seasonally and on a diel basis); and lesser species-specific sensitivity to low DO concentration. Characteristics of particular fish species which increase likely exposure to low DO conditions within the reservoir or from plant-related mixing events redistributing DO include: summer spawning; spawning in deep-channel hypolimnetic areas; pelagic epilimnetic spawning if eggs and

larvae are buoyant, transported by currents, and are coincident temporally with occurrence of lowered DO in epilimnetic regions of the SQN mixing-zone; habitat preferences by young of particular fish species for deep-water habitats; and greater sensitivity to low DO concentrations.

Seventy-seven species of fishes and one hybrid have been collected from Chickamauga Reservoir between 1975 and 1985 (table 5-1). Larvae of eleven families have been collected between 1979 and 1985 (table 5-2) indicating a diverse fauna of fishes reproducing in the reservoir or contributed to it through dam passage. Numerically the predominant larval taxa are clupeids, freshwater drum, temperate bass, sunfishes, and crappie.

Early life stages of warmwater fishes are typically the most sensitive to physicochemical environmental impacts, particularly those resulting from low DO (EPA, 1986). Eggs and young fish in Chickamauga Reservoir show definite clusterings into particular habitats (table 5-3) which influence their susceptibility to DO-related production (reproduction, survival, and growth) impacts. For example (tables 5-3 and 5-4 and Buchanan, 1990b ms), data show that young of freshwater drum and catfish are predominantly found in deep-channel areas of the reservoir, whereas sunfishes and crappie are spawned in and mostly remain in overbank and shallow-channel areas, and Morone (temperate bass) are spread fairly evenly across all three gross habitat types. Fishes spawned or spawning in deep-channel areas of the reservoir are most likely to be impacted by low DO, because that is where the magnitude, extent, and duration of low DO concentrations are most severe. Those fish remaining after spawning in overbank areas are least likely to

experience any effects from low deep-channel or redistribution of channel (shallow or deep) DO. The DO in overbank areas is much less affected by mixing that occurs in the main channel. Those species or portions of fish populations occurring in shallow channel areas are likely to experience altered DO levels only in upper reservoir areas affected by low DO releases from Watts Bar Dam or in the mixing zone of SQN.

Fish spawning, presence of susceptible young, and low DO all have definite temporal periods of occurrence in Chickamauga Reservoir. Only their co-occurrence has a large bearing on the likelihood and degree of potential effects from low DO and its redistribution. Perusal of tables 5-5 through 5-11 shows, for example, definite trends to earlier spawning by fishes such as Ictiobus spp., Morone spp., Stizostedion spp., and percids, as well as slightly later, but still relatively early, spawning by Pomoxis spp. This characteristic would tend to eliminate or minimize co-occurrence of impact-susceptible young fish and periods of low DO. Late-spawning (June, July, or August) fish or those whose young are still present in the impacted zones in mid to late summer (e.g., juvenile Ictiobus at greater depths) are much more likely to encounter low DO concentrations in the reservoir. Based strictly on time of occurrence, these species include freshwater drum, some clupeids, several cyprinids, the catfishes, and sunfishes (see above: habitat usage minimizes likely impacts to sunfishes).

Fishes with the least likelihood of DO-related impacts from reservoir releases or facilities-operation of SQN, because of the above-mentioned reasons (table 5-12), are: sunfishes (Lepomis spp.), black basses (Micropterus spp.), cyprinids (including the carp and most

forage minnows, but excluding Notropis volucellus), clupeids (Dorosoma spp.), and the yellow perch (Perca flavescens). Species of intermediate likelihood are: temperate basses (Morone spp.), crappie (Pomoxis spp.), and sauger (Stizostedion canadense). The spawning and earliest stages of these three fish are not likely to be affected by low DO as they spawn before the low DO period. However, juveniles of these species may use deeper water habitats during portions of the day or life cycle. Young of species with the greatest likelihood of experiencing low DO conditions are: the catfishes (Ictalurus spp.), freshwater drum (Aplodinotus grunniens), and juvenile buffalo fish (Ictiobus spp.).

Spatio-Temporal Water Quality Conditions Important To Evaluating Likely Fishery Effects--The dominant factor in determining DO concentrations in the upper and midreaches of Chickamauga Reservoir (above TRM 484) during June, July, and August, is the DO concentration in releases from Watts Bar Dam. The major contributor to determining these DO release levels is flow (Hauser and Shiao, 1989) and its effects on reservoir residence time in Watts Bar Reservoir. As can be seen in figures 5-1 to 5-3 a significant relationship exists between DO concentrations at the tailrace and the preceding 7-day release flow from Watts Bar Dam into Chickamauga Reservoir during June, July, and August. September does not show this relationship (figure 5-4). For example (figures 5-2 and 5-3), during July and August an increase in average flow of 8-10,000 cfs results in an increase of 1 mg/l DO in releases.

Within the range of modeled conditions mimicking low and normal flow year releases from Watts Bar Dam, this translates into a 1 to 2 mg/l difference in DO concentrations between these two modeled examples (1986

and 1987)). Watts Bar Dam release flows thus play a significant driving role in determining DO levels experienced in upper and mid-Chickamauga Reservoir in the vicinity of the SQN.

This relationship allows us to examine flow duration curves (figures 5-5 to 5-8) as indicators of the likely frequency of occurrence for low flows released from Watts Bar Dam (or low flow years) yielding exceptionally poor DO conditions in Chickamauga Reservoir, as occurred in 1986. These occurrences of low DO would be the most detrimental to fishery production in Chickamauga Reservoir. On the average, with 1986 considered a typical dry year and 1987 a typical normal (but still slightly drier than average) flow year; low flows for June would be less than or equal to those producing exceptionally poor DO conditions similar to 1986, once in about 16 years; July low flows would produce similar results once every eleven years; August low flows, about once every 33 years. In those years, low flows similar to 1986 or the extreme case of 1988 (figure 4-46) would strongly contribute to the occurrence of low DO in Chickamauga Reservoir. Normal flow years result in limited occurrence of low DO in the upper tailwater reaches below Watts Bar Dam with occurrence of DO <4 mg/l in the upper reservoir reaches below Watts Bar Dam, and near-bottom areas having <5 mg/l throughout much of the reservoir for as much as 70 days. Frequency of these normal flow years obviously occurs, on the average, a much higher percent of the time. On the average, normal release flows from Watts Bar Dam with moderate DO levels above 4 or 5 mg/l for each summer month are met or exceeded as appears in table 5-13. Depending upon month, flows maintaining 4 mg/l occur 71-89 percent of the time; those maintaining

5 mg/l only 30-63 percent of the time. Flows high enough to completely assure DO levels above 4 or 5 mg/l in the reservoir occur only infrequently (3-19 percent of the time for 5 mg/l; 20-30 percent of the time for 4 mg/l; shown in figures 5-1 through 5-4 and table 5-13). The result is a relatively frequent exposure of fishes (mostly early life history stages) to DO levels below 4 mg/l in large areas of the hypolimnion and metalimnion in Chickamauga Reservoir.

Modeled releases from Watts Bar Dam will be low in DO (<5 mg/l) from about day 150 to around day 250 (figures 4-64 and 5-9). In the area of the SQN (figure 4-64) the occurrence of DO less than 4 mg/l due to releases from Watts Bar Dam will be from about day 160-210. If above those causing direct acute lethality (see appendix F), exposure durations of this length are sufficient to produce chronic growth effects on fish.

Actual field measurements were taken during the summers of 1987 (limited), 1988, and 1989. Data collected in 1989 (figures 5-10 through 5-16) indicate that, under high flows, areas of low DO (<5 mg/l) between TRMs 470 and 530 did not occur in Chickamauga Reservoir during the summer months. Any stratification was very weak (figures 5-15 and 5-16) throughout the summer. However during 1987, a more normal flow year (figures 5-17 through 5-24), when a weak stratification of waters occurred, areas of less than 5 mg/l were observed near the reservoir bottom near SQN below elevations 650 or 660. These low DO areas were temporally confined to about Julian days 170-240 (mid-June to late August). Incursions below 4 mg/l were limited to the most upstream reservoir areas (TRM 518.8). Modeled data for 1987 (normal flow year) corroborate that the lowest DOs should be confined to the upper reservoir

most affected by reservoir releases or below elevation 660 in the area of the SQN (figures 4-59 and 4-53).

Field data for 1988, the extreme low flow year, indicate the occurrence of extremely low (<2 mg/l) DO near the reservoir bottom extending from at least TRM 471.1-TRM 484.5. Large expanses of the near-bottom reservoir areas were experiencing DO levels below 5 mg/l (figure 4-46) from as early as about day 120 to at least day 240 (the longest data collection was maintained in 1988). All these field data (figure 4-46) again indicate that reservoir-wide DO conditions are the result of flow releases from reservoir operations of Watts Bar Dam and the presence or absence of weak natural stratification as year-to-year variation in Chickamauga Reservoir.

Modeling indicates that the proposed enhancement of DO levels (+2 mg/l) in releases from Watts Bar Dam decrease the area, volume, and severity of low DO water existing in upper- and mid-Chickamauga Reservoir (compare figures 4-86 with 4-66 and 4-87 with 4-67). For example, rather than extending the entire distance upstream from the underwater dam to Watts Bar Dam at TRM 529.9, under low flows the areas of water with DO concentrations below 4 mg/l should be confined to that ponded behind the underwater dam up to TRM 501 (compare figures 4-87 and 4-67). Enhancement of DO levels thus directly increases the availability of inhabitable reservoir areas for several fish species by eliminating or reducing habitat quality restrictions imposed by low DO.

Near-Field Factors Resulting from Facilities and Operation of Sequoyah Nuclear Plant with Potential Habitat and Fishery Effects---Under different flow conditions the definable extent of the main channel water ponded extends to between TRMs 504 and 511. Under normal flow conditions

(1987), however, the underwater dam appears to have little or no effect on DO distribution (compare figures 4-91 and 4-92) or levels of DO behind the dam. Normal flows such as occurred in 1987 are apparently sufficient to continuously flush the underwater reservoir and promote a short water residence time behind it. Higher incoming DO levels and short residence time of water behind the underwater dam minimize or eliminate low DO problems with normal flows. Under these conditions the underwater dam does not exacerbate any low DO levels released from Watts Bar Dam and should not have biological consequences in ponded volumes of water.

Under low flow conditions such as occurred in 1986, ponding of low DO water released from Watts Bar Dam (figures 4-66, 4-67, 4-86, and 4-87), is evident under all model management runs. The underwater dam extends vertically to an elevation of 654. At this height, under no flow conditions, the upstream extent of the ponded water could theoretically reach as far as TRM 512 (figure 4-67). However, modeling of a low flow year (1986) without aeration of Watts Bar releases indicates the extent of low DO water (<3 mg/l) associated with ponding may extend upstream as far as TRM 511 (figure 4-67). But comparison of figures 4-92 and 4-93 indicate that the effects of withdrawing water from the ponded areas behind the underwater dam in a normal flow year (1987) extend only as far as TRM 504, just upstream from the Hiwassee River confluence. With the proposed enhancement of DO levels (+2 mg/l) from Watts Bar Dam and normal flows, no areas of significantly low DO (<5 mg/l) should appear (figures 4-83 and 4-84). Under low flow (1986) conditions, areas of low DO (<5 mg/l) will still be apparent but of more limited area (extending only to about TRM 501) and less severity.

Under low flow conditions, operation of the plant actually improves the low DO waters upstream from the underwater dam (compare figures 4-66 and 4-94) by decreasing residence time of low DO water behind the dam. This in turn reduces the total area of reservoir volume above the underwater dam experiencing lowest DO levels. Both the longitudinal and vertical distribution of low DO water would be diminished when compared to likely conditions with the underwater dam in place but without plant operation.

Plant Operation and Diffuser Mixing Effects--The major DO-related effect of thermal discharges during operation of the SQN is to further enhance the mixing of water in the near down-plant area. Some slight mixing was induced by the presence of the underwater dam (figure 4-9). This thermally induced mixing basically lowers surface DO levels while dramatically improving DO levels in lower reservoir strata (see Section 3.0 for a thorough description of mixing effects).

Normal Flows--Under normal flows with full SQN and WBN loads, as modeled for 1987 (Runs 1 and 5), effects from low DO on fishery production (reproduction, survival, and growth) are minimal. Much of the reservoir volume has DO concentrations in excess of 6 mg/l. Most evidence indicates that DO levels in excess of 6 mg/l do not have any significant effects on fish production (e.g., Stewart et al., 1967; Raible, 1975; EPA, 1986). In terms of abundance, diversity, incidence of disease, deformity or parasitization, or sport fish composition in an area, 5 mg/l DO appears adequate for maintenance of healthy warmwater fish faunas (Ellis, 1937; Brinley, 1944; and Coble, 1982). Water with less than 6 mg/l does occur in the upstream reaches of the reservoir.

These DO levels are due to releases of low DO water from Watts Bar Dam. Dissolved oxygen levels below 6 mg/l (but above 4 mg/l) are evident in the tailrace area of Watts Bar Dam and ponded behind the underwater dam. Near-surface areas of the reservoir may theoretically be less than saturated and yet have DO concentrations in excess of 6 mg/l DO. Fishery effects from less-than-saturation DO levels in this range (exceeding 6 mg/l) are highly unlikely.

Of the fish species occurring in the vicinity of the SQN, those whose seasonal and diel habitat preferences (tables 5-3 through 5-12) would make them most likely to be temporally coincident with low DO concentrations in near-bottom areas of the reservoir are catfishes, freshwater drum, the mimic shiner, Notropis volucellus, and larger young of Stizostedion (sauger), Morone spp. (temperate basses) and Ictiobus spp. (buffalo) and yellow perch (Perca flavescens).

Nothing is known of the DO requirements for young or adults of the freshwater drum, the mimic shiner, or the buffalo fishes. However, adult fish surveys and special studies (Buchanan, 1986) circumstantially indicate that population numbers and age class structures are comparable to those of other mainstem TVA reservoirs (TVA, unpublished rotenone data). The yellow perch is exceptionally tolerant of low DO conditions (EPA, 1986) and, as such, is not likely to be affected by the range of concentrations observed.

Dissolved oxygen levels in excess of 4 mg/l do not appear to affect distribution of species such as the channel catfish (Mosher, 1983) so avoidance of these areas by catfish in normal flow years is unlikely. However, when compared to saturation levels, reduction in growth rate

for all DO levels below 6 mg/l has been documented for young of the channel catfish (Andrews et al., 1973; Raible, 1975; Carlson et al., 1980). Extrapolation of these acceptably long-term, but laboratory-based studies, would indicate that, when compared to growth occurring at DO concentrations of 6 mg/l or greater, young catfish within the low DO areas are likely to be experiencing about a 9 percent reduction in growth over the duration of exposure (50 to 70 days). At present we do not know the reservoir-wide contribution from these deep-channel, difficult-to-sample areas of low DO to standing-stocks of adult fishes, reproduction, or strength of year-classes.

Larger young of both temperate basses and sauger are difficult to sample effectively. However, their known habitat preferences, time of occurrence (tables 5-5 through 5-11), and low frequency occurrence in deep-channel larval fish sampling (tables 5-3 and 5-4) indicate that a portion of the young population does at least reside in reservoir areas frequently experiencing reduced DO levels. In terms of survival, temperate basses seem to be relatively tolerant of moderately low DO conditions (EPA, 1986), with the white bass, Morone chrysops, surviving mean DO concentrations in the 2-3 mg/l range (figure F-2). Both field and laboratory evidence indicates that the striped bass, Morone saxatilis, becomes physiologically stressed at 3 mg/l and areas with DO concentrations of 2 mg/l are uninhabitable. These are discussed more fully in the following section on low flow conditions. Growth effects of reduced DO on young temperate basses are unknown. For a general discussion of the range of DO effects on growth of warmwater fishes see appendix F.

Low Flows--The biological significance of the frequency of occurrence of low flows and thus low DO levels, to fish populations is dependent upon the degree and duration of DO reduction, sensitivity of the individual fish species, and the overall life expectancy and years of fertility of fishes. For example, channel catfishes live about 10 years, reproduce initially at age two and every year thereafter. If the population is exposed to a once in 33.3 year occurrence of DO lowered by 1-1.5 mg/l DO, but still within the 4-6 mg/l range, population-level effects are likely to be unmeasurable, if not completely insignificant. Previous experience demonstrates the difficulty in establishing relationships between DO levels and fishery responses. For example, establishing a relationship between DO and fish health measurements for the coldwater trout fishery below Norris Dam (the most intensively studied cold tailwater fishery in the Tennessee River Valley) required eleven years of field investigation, a DO range of 0-13 mg/l and measurement of over 4,000 individual fish of one species (Yeager et al., 1987, et seq.).

However, poor environmental conditions happening with a frequency occurrence less than the life expectancy (life cycle) of a fish should be considered serious. To shorter-lived species, such as those like the sauger, which may live only 4 or 5 years, the effects would be most pronounced, inducing a population alteration in those generations occurring whenever a low flow/DO period occurred. Although the cause is probably related to a number of factors, mainly flow, this situation has been the case for sauger in Watts Bar tailwater over the last several years (Hickman, 1990). For other short-lived species, a frequency of

occurrence of once in 3 years rather than once in 11 years would also obviously have more pronounced effects. But at the frequency of low flow occurrences seen, the likelihood of long-term population effects for most fish species occurring in Chickamauga Reservoir would appear to be more likely related to physical factors other than low DO.

When low flows, such as 1986, producing low DO do occur, the effects on fish production in these areas of Chickamauga Reservoir are likely to be pronounced. The reservoir more strongly stratifies producing areas of <1 mg/l in the lower reservoir (figures 4-94 and 4-95). Most of the reservoir would be below 4 mg/l in DO. Although not related to facilities or operation of the SQN, these conditions are definitely adverse to fisheries. Extensive portions of the reservoir are uninhabitable for several important species of fishes. Under these extreme conditions, the effect of the underwater dam at Sequoyah is beneficial, in that it reduces the amount of reservoir area experiencing the most severely detrimental levels of DO. Late in the seasonal low DO period the areas experiencing DO below 3 mg/l are essentially the same whether the underwater dam is present or not, or the plant is operating or not (figures 4-67, 4-96, and 4-97). By introducing a mixing event to the water column early in the season the underwater dam should act to keep the stratification of lower Chickamauga Reservoir, that would otherwise project above the plant site, to a further downstream river mile (compare figures 4-94 and 4-95). Additionally, upstream areas experiencing DO less than 4 mg/l would be slightly reduced. The effects of operating the plant further enhance the limitation of low DO areas spatially (compare figures 4-66 with 4-94 and 4-95, and 4-67 with 4-96 and 4-97), reducing areas of water with DO less than 2 mg/l in this reach of the reservoir.

Though it does tend to pond low DO water, the overall effect of the underwater dam in this ponded area of the reservoir is to reduce the extent and duration of severe DO levels (<2 mg/l) to which fish are exposed, without increasing or altering the area of lower strata experiencing DO concentrations below 3 mg/l. The most severely DO-depleted areas, those most surely lethal to young fishes or precluding reproduction by adults, are actually reduced by the underwater dam and plant operation when compared to the exposures predicted from releases out of Watts Bar Dam without the underwater dam in place and no plant operation. This is important in that in most cases no mortality of warmwater fishes occurs in acute tests with DO exposures at 3 mg/l (summarized in EPA, 1986) and increasingly greater mortalities occur with lower DO levels. The difference between complete survival and complete mortality for young of one fish species (brook trout) was 0.5 mg/l. At about this 3 mg/l DO concentration, survival of young of species such as the black crappie and white bass are dramatically higher (figure F-2, EPA 1986) than at lower DO concentrations.

Eggs and young fish within the reservoir areas experiencing <3 mg/l in low flow years likely will suffer higher mortalities. For most fish species, acute mortality occurs between 1 and 3 mg/l DO (summarized in Douderoff and Shumway, 1970). Most information is for salmonids and little is known of lethal DO levels for nonsalmonids. However, with the exception of some larval life stages, nonsalmonids do appear to be somewhat less sensitive to lethal effects from low DO (EPA, 1986). Data for evaluating the extended exposures likely in the less than 3 mg/l area of the reservoir are meager, and latent effects to exposures in this low

range are completely unknown. Hypolimnetic DO conditions in Chickamauga Reservoir are improved with the underwater dam in place and with plant operation, but not improved to above the 3 mg/l level where definitive benefits accrue to fish survival for any particular species.

However, even in low flow years, aeration of Watts Bar releases, as proposed in TVA (1990a), would substantially reduce the area and volume of Chickamauga Reservoir experiencing DO concentrations of less than 4 mg/l (compare figures 4-67 and 4-87). As modeled, this improvement could basically eliminate potential problems for survival of young or severe (EPA, 1986) growth effects on fish within low DO areas of the reservoir. With these reservoir release improvements, slight or moderate (EPA, 1986) growth effects on fish production in Chickamauga Reservoir could still occur in the 4-6 mg/l range, but would likely be unmeasurable in field assessments.

Mixing-Zone Events--The major DO-related effect of thermal discharges during operation of the SQN is to further enhance the mixing of water in the near down-plant area. Slight mixing was also induced by the presence of the underwater dam (figure 4-94). This mixing basically lowers surface DO levels while dramatically improving DO levels in lower reservoir strata. The major questions involved are: When are these mixing events most important? Where do they produce better or worse DO conditions for fish in the reservoir or near-plant area? and Where and how significant are any relative DO changes to the fisheries present?

Mixing zone events and their potential for affecting biological responses are greatest under low flow conditions. Under low-flow conditions, large-scale mixing of surface and low-strata waters occurs

with operation of the SQN (figure 4-66). Modeling indicates that this destratification dramatically reduces the deep-reservoir areas experiencing the most severe low DO conditions (compare figure 4-66 with figure 4-94; figure 4-67 with figure 4-96). Again this mixing is beneficial to fishes occurring in the lower reservoir strata by increasing DO levels above those known to be acutely lethal (see general DO effects section and individual species accounts, appendix F), reducing reservoir areas in and downstream from the mixing zone where severe DO-related fish production impacts could occur, and ameliorating potential growth impacts from severe to moderate or slight levels. Young (larvae or juveniles) of catfishes, buffalo, sauger, temperate basses (Morone), freshwater drum, and yellow perch should all benefit in terms of growth and survival from these higher DO levels in the lower reservoir strata.

On the other hand, the DO levels of near-surface waters are lowered by this thermally driven destratification and mixing. Lethality in the range of DO concentrations measured or modeled is highly unlikely even under low flow conditions. In laboratory tests DO-related effects on production have been shown to increase with increasing temperature but acceptable data sets do not presently exist to define, quantify, or assess any likely synergistic temperature-related effects.

Avoidance of lowered epilimnetic DO likely in the range of 4-6 mg/l varies by species. Little information is available regarding fish avoidance of DO levels in this range. The distributions of striped bass (Chittenden, 1971a, and 1971b; Coutant, 1985), largemouth bass (Rinne et al., 1981) and walleye (Scherer, 1971) in reservoirs have been found to be bounded by the 3, 2, and 3 mg/l DO isopleths, respectively. In

laboratory tests striped bass have been reported to avoid DO areas of less than 4.0 mg/l (Meldrim et al., 1974). For the adults of these species, it is unlikely that mixing of waters in the vicinity of the SQN causes any plant-related redistribution of these or closely related fish species such as the white bass or sauger. Sauger appear to be somewhat more tolerant of low DO conditions in reservoirs, reportedly remaining in areas of 1.6-3.0 mg/l DO, whereas a congener, the walleye, avoids areas with less than 3.0 mg/l. In laboratory tests, young of largemouth bass showed slight avoidance of 3.0-4.6 mg/l DO (Whitmore et al., 1960), but definite avoidance only at 1.5 mg/l.

Impacts to growth of largemouth bass occur at virtually any DO concentration below saturation (Carlson and Siefert, 1974). Larval black bass, however, have typically occurred only rarely in either near surface or deep channel samples (table 5-3) near SQN or anywhere else in the Tennessee River Valley. In Sequoyah sampling, too few young black bass have been collected to provide insights into their local distribution. Most Valleywide occurrences are in overbank or near-shore areas where they are not subjected to the channel dynamics involved in DO mixing such as occurs at Sequoyah. Coble (1982) observed centrarchids (sunfishes, black bass, crappie) constituting significantly greater proportions of fish population in areas having mean summer DO concentrations greater than 5 mg/l. But again, these fishes typically occupy near-shore and overbank areas not subject to the mixing events occurring at Sequoyah. Siefert and Herman (1971) have also reported normal centrarchid spawning at DO concentrations as low as 2 mg/l.

Eggs and young of fish likely to occur in the near-surface waters of the reservoir or lying along the thermocline during mid-to-late summer are the freshwater drum, sauger (see two paragraphs previous), and possibly the crappie. Nothing is known of likely effects of DO levels on freshwater drum. Most drum larvae occur in channel-deep samples (tables 5-3 and 5-4) with a significant proportion in channel-shallow areas. Since most eggs or larvae occur in these deep channel areas, overall DO conditions for reproduction or survival, and growth of young drum would seem to be enhanced by the vertical mixing.

Crappie were found in reservoirs at DO concentrations as low as 3.3 mg/l (Grinstead, 1969), but were rarely found at 2.0 mg/l (Gebhart and Summerfelt, 1974). In acute field tests (Moore, 1942) complete 100 percent mortalities of black crappie have been observed for DO levels as high as 4.3 mg/l in summer at 26°C. However, results of all other studies of DO effects on crappie indicate much less sensitivity to low DO conditions. Sigler and Miller (1963) and Moore (1942) reported that DO levels below 1.4 mg/l often cause mortalities in black crappie populations. However, Siefert and Herman (1977) reported no discernable effects on black crappie spawning success, numbers of embryos produced, viability, hatching success, or larval survival in a range of tests from 2.5-7.0 mg/l DO.

By far the greatest number of crappie larvae (tables 5-3 and 5-4) occur in the unaffected overbank areas of Chickamauga Reservoir and in reservoir areas other than the near-field mixing zone (diffuser transect) for Sequoyah (Buchanan, 1989). Since crappie larvae are not transported but remain in the area of spawning until moving out to deeper waters, very little of the reservoir crappie spawn is in the near-plant area

to be affected by moving out into deep-water areas above the thermocline and experiencing lowered DO.

In the vicinity of the SQN, shallow overbank areas (TVA, 1982, et seq.) are located at the plant transect on the opposite side of the river from the plant, at the diffuser transect on the plant side and in the Dallas Bay area on the plant side. Along with many other similar areas of Chickamauga Reservoir these overbanks provide some spawning, hatching, and nursery areas for several important sport and forage fishes, including crappie, sunfishes, black bass, temperate bass, shad, and cyprinids. Temperature and DO conditions for spawning and development of young fish are mostly determined by local factors. Diel investigations (discussed in Section 3.3) show overbank areas to be readily definable by higher DO levels. Overbanks appear sequestered from main-channel events, showing only limited incursion of channel-mixing events into these areas. Fishes such as the sunfishes, basses, most cyprinid species, and the youngest crappie, which remain in these overbanks (tables 5-3 and 5-4), are unlikely to be affected by DO perturbations of the main channel. Tennessee Valley Authority investigations of crappie stocks in Chickamauga Reservoir (Buchanan, 1990a) indicate that larger juvenile crappie do move to deeper water, but still show strong preference for, and remain within, embayments and overbank areas. However, larger young of Morone, shad, and species (freshwater drum, ictiobines, clupeids, and catfishes) which occur predominately in the deep or shallow-channel areas throughout most of their life cycles, may encounter plant-related alterations to DO concentrations and distribution. As discussed elsewhere in this section,

most of these plant-related alterations appear innocuous or beneficial, partially mitigating low DO waters released from Watts Bar Reservoir.

5.2.2 Conclusions

1. Some fish species, such as the channel catfish and possibly the freshwater drum, juvenile ictiobines, and particular cyprinids in Chickamauga Reservoir are likely suffering detrimental effects from low DO levels in the reservoir. Other species (table 5-12) are of varying susceptibility, but are much less likely to experience or be affected by low DO levels than these species.
2. Conditions leading to potential adverse fishery effects are due to low DO in releases from Watts Bar Dam and natural stratification of Chickamauga Reservoir. Potential impacts to fishery production are most pronounced under low flow conditions are minimal under normal or high flow conditions.
3. Mixing events introduced into the water column by both the underwater dam and thermal discharge at Sequoyah are overall beneficial to fisheries in the near-plant area by increasing metalimnetic and hypolimnetic DO levels; by reducing the reservoir volume and areas experiencing the lowest (possibly lethal) DO levels occurring in releases from Watts Bar Dam; and by slightly disrupting stratification of Chickamauga Reservoir. Areas experiencing DO concentrations below 3 mg/l are likely to be avoided by most adult fishes may be lethal to young fish spawned in or remaining in nursery areas subject

to these low DO levels. Under critical low flow conditions, such areas are reduced by the underwater dam and operation of SQN. Normal flows, with higher incoming DO levels from Watts Bar Dam releases and short residence time of water behind the underwater dam, minimize or eliminate low DO problems and should produce no biological consequence.

4. Near-surface DO concentrations are reduced an average of 0.7 mg/l downstream from the mixing zone as compared to upstream from the underwater dam. Impacts to fish distribution (through avoidance of lowered DO), spawning or survival by redistribution of DO are highly unlikely.
5. Temporally or spatially most fish species would not be coincident with lowered DO. For the concentration range within which near-surface DO levels are likely to be reduced, only a small portion of young of fish species coincidentally occurring in the near-surface, deep-water channel area could even potentially experience slightly reduced growth during the lowered DO exposure (when compared to saturation levels). Of these fish, only the young sunfish or crappie (table 5-3) resident in the near-diffuser area may experience slightly lowered DO conditions as they move from overbank areas to shallow channel areas. However, the predominantly productive areas for crappie in Chickamauga Reservoir are in areas other than the Sequoyah near-plant area (Buchanan, 1989).

Table 5-1. Common and Scientific Names^a of Fishes Collected from Chickamauga Reservoir During 1973 to 1985, Preoperational Monitoring for Watts Bar and Operational Monitoring for Sequoyah Nuclear Plant

Species	Common name	Group ^b	Rotenone	Hoop net	Gill net	Electro-fishing	Creal census	Water netting	Seining
<u>ichthyomyzon castaneus</u>	Chestnut lamprey	C	X						
<u>Polyodon spathula</u>	Paddlefish	C	X	X	X				
<u>Lepisosteus oculatus</u>	Spotted gar	C	X	X	X	X			
<u>Lepisosteus osseus</u>	Longnose gar	C	X	X	X	X			
<u>Lepisosteus platostomus</u>	Shortnose gar	C	X	X	X				
<u>Alosa chrysochloris</u>	Skipjack herring	C	X	X	X	X		X	X
<u>Dorosoma cepedianum</u>	Gizzard shad	P	X	X	X	X		X	X
<u>Dorosoma petenense</u>	Threadfin shad	P	X	X	X	X		X	X
<u>Hiodon tergisus</u>	Mooneye	C	X	X	X	X		X	X
<u>Salmo gairdneri</u>	Rainbow trout	G		X	X				
<u>Camostoma anomalum</u>	Stoneroller	P	X						X
<u>Carassius auratus</u>	Goldfish	P	X						
<u>Cyprinus carpio</u>	Carp	C	X	X	X	X	X	X	X
<u>Hybopsis storeriana</u>	Silver chub	P	X		X	X		X	
<u>Notemigonus crysoleucas</u>	Golden shiner	P	X		X	X		X	X
<u>Notropis atherinoides</u>	Emerald shiner	P	X		X	X		X	X
<u>Notropis buchanani</u>	Ghost shiner	P	X		X	X		X	
<u>Notropis chrysoccephalus</u>	Striped shiner	P	X						
<u>Notropis cornutus</u>	Common shiner	P	X						
<u>Notropis emiliae</u>	Pugnose minnow	P	X						
<u>Notropis galacturus</u>	Whitetail shiner	P	X						
<u>Notropis spilopterus</u>	Spottfin shiner	P	X			X			X
<u>Notropis volucellus</u>	Mimic shiner	P	X						
<u>Notropis whipplei</u>	Steelcolor shiner	P	X						X
<u>Pimephales notatus</u>	Bluntnose minnow	P	X						
<u>Pimephales vigilax</u>	Bullhead minnow	P	X			X			

Table 5-1 (Continued)

Species	Common name	Group ^b	Rotenone	Hoop net	Gill net	Electro-fishing	Creel census	Water netting	Sailing
<u>Pimephales promelas</u>	Fathead minnow	P	X						
<u>Carpiodes carpio</u>	River carpsucker	C	X	X	X	X		XC	
<u>Carpiodes cyprinus</u>	Quillback carpsucker	C	X		X				
<u>Carpiodes velifer</u>	Highfin carpsucker	C		X	X				
<u>Catostomus commersoni</u>	White sucker	C	X		X				
<u>Hypentelium nigricans</u>	Northern hogsucker	C	X	X	X		X		
<u>Ictalobus bubalus</u>	Smallmouth buffalo	C	X	X	X	X		XC	
<u>Ictalobus cyprinellus</u>	Bigmouth buffalo	C	X	X					
<u>Ictalobus niger</u>	Black buffalo	C	X						
<u>Minytrema melanops</u>	Spotted sucker	C	X	X	X	X		X	X
<u>Moxostoma anisurum</u>	Silver redhorse	C			X				
<u>Moxostoma carinatum</u>	River redhorse	C	X	X	X	X			
<u>Moxostoma duquesnei</u>	Black redhorse	C	X	X	X				
<u>Moxostoma erythrum</u>	Golden redhorse	C	X	X	X	X			X
<u>Moxostoma macrolepidotum</u>	Shorthead redhorse	C	X		X				
<u>Ictalurus furcatus</u>	Blue catfish	C	X	X	X	X	X	X	
<u>Ictalurus melas</u>	Black bullhead	C	X	X	X			X	
<u>Ictalurus natalis</u>	Yellow bullhead	C	X	X	X			X	
<u>Ictalurus nebulosus</u>	Brown bullhead	C	X	X	X				
<u>Ictalurus punctatus</u>	Channel catfish	C	X	X	X	X	X	X	
<u>Pylodictis olivaris</u>	Fathead catfish	C	X	X	X	X	X	X	
<u>Anguilla rostrata</u>	American eel	C							
<u>Fundulus notatus</u>	Blackstripe topminnow	P	X						
<u>Fundulus olivaceus</u>	Blackspotted topminnow	P	X						
<u>Gambusia affinis</u>	Mosquitofish	P	X						
<u>Labidesthes sicculus</u>	Brook silverside	P	X			X		X	X
<u>Morone chrysops</u>	White bass	G	X	X	X	X	X	X	X
<u>Morone mississippiensis</u>	Yellow bass	G	X	X	X	X	X	X	X

Table 5-1 (Continued)

Species	Common name	Group ^b	Rotenone	Hoop net	Gill net	Electro-fishing	Creel census	Water netting	Sailing
<u>Ambloplites rupestris</u>	Rock bass	G	X	X	X	X	X		
<u>Lepomis auritus</u>	Redbreast sunfish	G	X	X	X	X			
<u>Lepomis cyanellus</u>	Green sunfish	G	X	X	X				
<u>Lepomis gulosus</u>	Warmouth	G	X	X	X	X			
<u>Lepomis humilis</u>	Orangespotted sunfish	P	X						
<u>Lepomis macrochirus</u>	Bluegill	G	X	X	X	X	X		X
<u>Lepomis megalotis</u>	Longear sunfish	G	X	X		X		X	
<u>Lepomis microlophus</u>	Redear sunfish	G	X	X	X	X	X	X	
<u>Micropterus dolomieu</u>	Smallmouth bass	G	X	X	X	X	X	X	X
<u>Micropterus punctulatus</u>	Spotted bass	G	X	X	X	X	X		X
<u>Micropterus salmoides</u>	Largemouth bass	G	X	X	X	X	X		X
<u>Pomoxis annularis</u>	White crappie	G	X	X	X	X	X	X	X
<u>Pomoxis nigromaculatus</u>	Black crappie	G	X	X	X	X	X		
<u>Etheostoma asprigene</u>	Mud darter	P	X						
<u>Etheostoma caeruleum</u>	Rainbow darter	P	X						
<u>Etheostoma kennicotti</u>	Stripetail darter	P	X						
<u>Etheostoma spectabile</u>	Orangethroat darter	P	X						
<u>Perca flavescens</u>	Yellow perch	G	X	X	X	X	X	X	X
<u>Percina caprodes</u>	Logperch	P	X		X	X		X	X
<u>Stizostedion canadense</u>	Sauger	G	X	X	X	X	X		
<u>Stizostedion vitreum</u>	Walleye	G		X	X	X	X		
<u>Aplodinotus grunniens</u>	Freshwater drum	C	X	X	X	X	X	X	
<u>Morone saxatilis</u>	Striped bass	G			X	X	X		
<u>M. chrysops</u> x <u>M. saxatilis</u>	Hybrid bass	G		X	X		X		

a. Taken from Common and Scientific Names of Fishes, American Fisheries Society Special Publication No. 12, Fourth Edition, 1980.

b. Indicates prey (P), commercial (C), or game (G)

c. Unidentified specimens within family or genus.

Table 5-2. List of Scientific and Common Names for Fish Egg and Larval Taxa Collected in Chickamauga Reservoir Near Sequoyah Nuclear Plant in 1979 Through 1985

Taxon	Common name
Eggs	
Unidentifiable fish eggs	Fish eggs
<u>Cyprinus carpio</u> eggs	Carp eggs
<u>Aplodinotus grunniens</u> eggs	Freshwater drum eggs
Larvae	
Unidentifiable fish larvae ^a	
Polyodontidae	
<u>Polyodon spathula</u>	Paddlefish
Clupeidae	
Unidentifiable clupeids	Unidentifiable herrings and shad
<u>Alosa chrysochloris</u>	Skipjack herring
<u>Dorosoma</u> sp.	Mixed shad
<u>Dorosoma cepedianum</u>	Gizzard shad
<u>Dorosoma petenense</u>	Threadfin shad
Hiodontidae	
<u>Hiodon tergisus</u>	Mooneye
Cyprinidae	
Unidentifiable cyprinids	Unidentifiable minnows and carps
<u>Cyprinus carpio</u>	Carp
<u>Hybopsis</u> s.	
<u>oreriana</u>	Silver chub
<u>Notemigonus crysoleucas</u>	Golden shiner
<u>Notropis</u> sp.	Unidentifiable shiners
<u>Notropis atherinoides</u>	Emerald shiner
<u>Notropis buechanani</u>	Ghost shiner
<u>Notropis volucellus</u>	Mimic shiner
<u>Pimephales</u> sp.	Unidentifiable minnow
<u>Pimephales notatus</u>	Bluntnose minnow
<u>Pimephales vigilax</u>	Bullhead minnow
Catostomidae	
Unidentifiable catostomids	Unidentifiable suckers
Ictiobinae	Unidentifiable buffalo and carpsuckers
<u>Ictiobus</u> sp.	Unidentifiable buffalo
Ictaluridae	
<u>Ictalurus furcatus</u>	Blue catfish
<u>Ictalurus punctatus</u>	Channel catfish
<u>Pylodictis olivaris</u>	Flathead catfish
Atherinidae	
<u>Labidesthes sicculus</u>	Brook silverside

Table 5-2 (Continued)

Taxon	Common name
Percichthyidae	
<u>Morone</u> sp.	Unidentifiable temperate bass
<u>Morone</u> (not <u>saxatilis</u>)	Unidentifiable temperate bass (not striped bass)
<u>Morone</u> <u>chrysops</u>	White bass
<u>Morone</u> <u>mississippiensis</u>	Yellow bass
Centrarchidae	
Unidentifiable centrarchids	Unidentifiable sunfish, crappie or black bass
<u>Lepomis</u> or <u>Pomoxis</u>	Unidentifiable sunfish or crappie
<u>Lepomis</u> sp.	Unidentifiable sunfish
<u>Lepomis</u> <u>macrochirus</u>	Bluegill
<u>Lepomis</u> <u>microlophus</u>	Redear sunfish
<u>Micropterus</u> (not <u>dolomieu</u>)	Black bass (not smallmouth bass)
<u>Pomoxis</u> sp.	Unidentifiable crappie
<u>Pomoxis</u> <u>annularis</u>	White crappie
Percidae	
Unidentifiable percid (not	Unidentifiable perch (not
<u>Stizostedion</u> sp.)	<u>Stizostedion</u>)
Unidentifiable darter	Unidentifiable darter
<u>Perca</u> <u>flavescens</u>	Yellow perch
<u>Stizostedion</u> sp.	Unidentifiable sauger or walleye
<u>Stizostedion</u> <u>canadense</u>	Sauger
Sciaenidae	
<u>Aplodinotus</u> <u>grunniens</u>	Freshwater drum

a. Usually mutilated

Table 5-3 Relative Abundance of Larval Fish Taxa at Sequoyah Nuclear Plant (Percent by Habitat and Total Frequencies)

Species	Channel deep	Channel shallow	Overbank	Total frequency
<u>Alosa chrysochloris</u>	10	10	80	10
<u>Aplodinotus grunniens</u>	71	21	8	37810
Centrarchid	100	0	0	1
Clupeid	12	41	47	446474
Cyprinid	12	41	46	6263
<u>Cyprinus carpio</u>	25	41	34	509
<u>Dorosoma cepedianum</u>	25	35	40	6790
<u>D. petenense</u>	14	16	70	17601
<u>Dorosoma</u> sp.	32	28	40	79
<u>Etheostoma</u> sp.	0	0	100	1
<u>Hiodon tergisus</u>	40	43	17	30
<u>Hybopsis storerians</u>	0	0	100	4
<u>Ictalurus furcatus</u>	81	16	3	89
<u>I. punctatus</u>	68	17	15	222
Ictiobinae	35	40	25	719
<u>Ictiobus</u> sp.	60	40	0	5
<u>Labidesthes sicculus</u>	2	31	67	91
<u>Lepomis macrochirus</u>	29	21	50	78
<u>Lepomis microlophus</u>	0	100	0	1
<u>L. or Pomoxis</u>	0	82	18	22
<u>Lepomis</u> sp.	5	39	56	70345
<u>Micropterus</u> (not <u>dolomieu</u>)	0	50	50	4
<u>Morone</u> (not <u>saxatilis</u>)	27	42	31	11956
<u>M. chrysops</u>	80	20	0	5
<u>M. mississippiensis</u>	80	0	20	5
<u>Morone</u> sp.	35	35	30	9203
<u>Notemigonus crysoleucas</u>	20	20	60	5
<u>Notropis atherinoides</u>	4	14	82	77
<u>Notropis</u> sp.	34	6	60	942
<u>N. volucellus</u>	84	3	13	214
<u>Perca flavescens</u>	16	28	56	269
Percidae	0	100	0	3
<u>Pimephales notatus</u>	100	0	0	1
<u>Pimephales</u> sp.	52	9	49	33
<u>P. vigilax</u>	66	17	17	6
<u>Pomoxis annularis</u>	0	0	100	7
<u>Pomoxis</u> sp.	12	30	58	8978
<u>Pylodictis olivaris</u>	100	0	0	1
<u>Stizostedion canadense</u>	29	28	43	7
<u>Stizostedion</u> sp.	25	50	25	8

Table 5-4. Density (No./100 m³) of Larval Fish Taxa at Sequoyah Nuclear Plant 1979-85 (Frequency)

Species	Channel deep	Channel shallow	Overbank
<u>Alosa chrysochloris</u>	.077	.085	1.121
<u>Aplodinotus grunniens</u>	1900.7	670.057	412.498
<u>Centrarchidae</u>	.077	0	0
<u>Clupeidae</u>	4223.38	15335.1	29344.2
<u>Cyprinidae</u>	58.122	220.57	400.589
<u>Cyprinus carpio</u>	9.803	17.544	24.1
<u>Dorosoma cepedianum</u>	128.535	201.918	385.027
<u>Dorosoma petenense</u>	178.297	228.914	1684
<u>Dorosoma</u> sp.	1.93	1.874	4.484
<u>Etheostoma</u> sp.	0	0	0.14
<u>Hiodon tergisus</u>	0.849	1.107	0.701
<u>Hybopsis storerians</u>	0	0	0.560
<u>Ictalurus furcatus</u>	5.48	1.192	0.42
<u>Ictalurus punctatus</u>	10.42	3.066	4.624
<u>Ictiobinae</u>	18.602	24.442	25.641
<u>Ictiobus</u> sp.	0.232	0.17	0
<u>Labidesthes sicculus</u>	0.154	2.299	8.547
<u>Lepomis macrochirus</u>	1.775	1.363	5.464
<u>Lepomis microlophus</u>	0	0.085	0
<u>Lepomis</u> or <u>Pomoxis</u>	0	1.533	0.56
<u>Lepomis</u> sp.	240.05	2318.93	5393.12
<u>Micropterus</u> (not <u>dolomieu</u>)	0	0.17	0.28
<u>Morone</u> (not <u>saxatilis</u>)	243.062	429.22	518.564
<u>Morone chrysops</u>	0.309	0.085	0
<u>Morone mississippiensis</u>	0.309	0	0.14
<u>Morone</u> sp.	242.442	277.455	386.708
<u>Notemigonus crysoleucas</u>	0.077	0.085	0.42
<u>Notropis atherinoides</u>	0.232	0.937	8.827
<u>Notropis</u> sp.	24.7	5.025	78.743
<u>N. volucellus</u>	13.894	0.426	3.923
<u>Perca flavescens</u>	3.319	6.302	21.298
<u>Percidae</u>	0	0.255	0
<u>Pimephales notatus</u>	0.077	0	0
<u>Pimephales</u> sp.	1.081	0.255	2.242
<u>P. vigilax</u>	0.309	0.085	0.14
<u>Pomoxis annularis</u>	0	0	0.981
<u>Pomoxis</u> sp.	81.355	220.657	733.348
<u>Pylodictis olivaris</u>	0.077	0.17	0.42
<u>Stizostedion canadense</u>	0.154	0.17	0.42
<u>Stizostedion</u> sp.	0.154	0.341	0.28

Table 5-5. List of Taxa, Total Number Collected, and Period of Occurrence of Fish Eggs and Larvae Collected at Sequoyah Nuclear Plant, 1979

Taxon	Total collected ^a	Percent composition	Occurrence by sample period														
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
			Mar 14	Mar 21	Mar 28	Apr 3	Apr 9	Apr 23	May 8	May 21	June 4	June 20	July 5	July 17	July 31	Aug 14	Aug 29
<u>Fish Eggs</u>																	
Unidentified fish eggs	8	0.48															
<u>Aplocheilichthys grunniens (eggs)</u>	1,675	99.52															
Total	1,683	100															
<u>Fish Larvae</u>																	
Unidentified fish larvae	101	0.20															
<u>Polyodon spathula</u>	1	Tb															
<u>Clupeidae</u>	41,075	82.24															
<u>Dorosoma sp.</u>	9	0.02															
<u>Dorosoma cepedianum</u>	26	0.05															
<u>Dorosoma petenense</u>	932	1.87															
<u>Hiodon tergisus</u>	5	0.01															
<u>Cyprinidae</u>	528	1.06															
<u>Cyprinus carpio</u>	45	0.09															
<u>Notropis sp.</u>	26	0.05															
<u>Notropis atherinoides</u>	1	T															
<u>Notropis buchanani</u>	1	T															
<u>Pimephales sp.</u>	3	0.01															
<u>Pimephales vigilax</u>	1	T															
<u>Catostomidae</u>	74	0.15															

Table 5-5 (Continued)

Taxon	Total collected ^a	Percent composition	Occurrence by sample period														
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
			Mar 14	Mar 21	Mar 28	Apr 3	Apr 9	Apr 23	May 8	May 21	June 4	June 20	July 5	July 17	July 31	Aug 14	Aug 29
<u>Ictalurus furcatus</u>	9	0.02											+	+			
<u>Ictalurus punctatus</u>	26	0.05										+	+	+	+	+	+
<u>Labidesthes sicculus</u>	3	0.01									+						
<u>Morone</u> sp.	41	0.08							+	+	+	+	+	+			
<u>Morone</u> (not saxatilis)	1,299	2.60				+	+	+	+	+	+	+	+	+			
<u>Lepomis</u> sp.	577	1.16							+	+	+	+	+	+	+	+	+
<u>Micropterus</u> (not dolomieu)	2	T															
<u>Pomoxis</u> sp.	396	0.79						+	+	+	+	+	+				
<u>Pomoxis annularis</u>	1	T									+						
Unidentified darter	6	0.01	+					+			+						
<u>Perca flavescens</u>	2	T															
<u>Stizostedion</u> sp.	3	0.01			+												
<u>Stizostedion canadense</u>	1	T						+									
<u>Aplodinotus grunniens</u>	4,752	9.51							+	+	+	+	+	+	+	+	+
Total	49,946	100															

a. Total number of specimens collected

b. Less than 0.01 percent composition

Table 5-6. List of Taxa, Total Number Collected, and Period of Occurrence of Fish Eggs and Larvae Collected at Sequoyah Nuclear Plant, 1980

Taxon	Total collected ^a	Percent composition	Occurrence by sample period												
			1	2	3	4	5	6	7	8	9	10	11	12	13
			Mar 12	Mar 25	Apr 7	Apr 21	May 7	May 20	June 3	June 18	June 30	July 14	July 29	Aug 11	Aug 27
<u>Fish Eggs</u>															
Unidentified fish eggs	35	0.71													
<u>Cyprinus carpio</u> (eggs)	1	0.02													
<u>Aplocheilichthys grunniens</u> (eggs)	4,869	99.27													
Total	4,905	100													
<u>Fish Larvae</u>															
Unidentified fish larvae	45	0.05													
<u>Clupeidae</u>	65,327	67.69	+	+	+	+	+	+	+	+	+	+	+	+	+
<u>Alosa chrysocloris</u>	2	Tb													
<u>Dorosoma</u> sp.	38	0.04													
<u>Dorosoma cepedianum</u>	1,307	1.35													
<u>Dorosoma petenense</u>	12,702	13.16													
<u>Hiodon tergisus</u>	11	0.01	+	+											
<u>Cyprinidae</u>	645	0.67													
<u>Cyprinus carpio</u>	74	0.08													
<u>Notropis</u> sp.	565	0.59													
<u>Notropis atherinoides</u>	17	0.02													
<u>Pimephales</u> sp.	24	0.02													
<u>Ictiobinae</u>	140	0.15													
<u>Ictiobus</u> sp.	3	T	+	+											
<u>Ictalurus furcatus</u>	23	0.02													
<u>Ictalurus punctatus</u>	108	0.11													

Table 5-6 (Continued)

Taxon	Total collected ^a	Percent composition	Occurrence by sample period												
			1	2	3	4	5	6	7	8	9	10	11	12	13
			Mar 12	Mar 25	Apr 7	Apr 21	May 7	May 20	June 3	June 18	June 30	July 14	July 29	Aug 11	Aug 27
<u>Fish Larvae</u>															
<u><i>Pylodictis olivaris</i></u>	1	T								+					
<u><i>Labidesthes sicculus</i></u>	17	0.02							+	+		+			+
<u><i>Morone</i> sp.</u>	218	0.23					+		+	+	+	+			
<u><i>Morone chrysops</i></u>	1	T								+					
<u><i>Morone mississippiensis</i></u>	1	T										+			
<u><i>Morone</i> (not <i>saxatilis</i>)</u>	1,219	1.26		+	+	+	+	+	+	+					
<u><i>Lepomis</i> or <i>Pomoxis</i></u>	9	0.01							+						
<u><i>Lepomis</i> sp.</u>	2,429	2.52							+	+	+	+	+	+	+
<u><i>Lepomis macrochirus</i></u>	11	0.01										+	+	+	+
<u><i>Pomoxis</i> sp.</u>	635	0.66					+	+	+	+	+	+			
Unidentified percid (not <i>stizostedion</i>)	1	T													
Unidentified darter	12	0.01		+	+	+	+	+							
<u><i>Perca flavescens</i></u>	5	0.01		+	+	+	+	+							
<u><i>Stizostedion</i> sp.</u>	11	0.01					+								
<u><i>Stizostedion canadense</i></u>	1	T					+								
<u><i>Aplodinotus grunniens</i></u>	10,906	11.30					+	+	+	+	+	+	+	+	+
Total	96,508	100													

a. Total number of specimens collected

b. Less than 0.01 percent composition

Table 5-7. List of Taxa, Total Number Collected, and Period of Occurrence of Fish Eggs and Larvae Collected at Sequoyah Nuclear Plant, 1981

Taxon	Total collected ^a	Percent composition	Occurrence by sample period										
			1	2	3	4	5	6	7	8	9	10	11
			Apr 6	Apr 13	May 4	May 12	May 26	Jun 1	Jun 16	July 1	July 15	July 29	Aug 27
<u>Fish Eggs</u>													
Unidentified fish eggs	670	6.35		+	+		+	+				+	
<u>Aplodinotus grunniens (eggs)</u>	<u>9,887</u>	<u>93.65</u>		+	+	+	+	+	+	+	+	+	+
Total	10,557	100											
<u>Fish Larvae</u>													
Unidentified fish larvae	47	0.05			+	+	+	+	+	+	+	+	+
<u>Clupeidae</u>	<u>63,445</u>	<u>65.25</u>	+	+	+	+	+	+	+	+	+	+	
<u>Dorosoma sp.</u>	<u>7</u>	<u>0.01</u>											
<u>Dorosoma cepedianum</u>	<u>126</u>	<u>0.13</u>					+		+	+	+	+	
<u>Dorosoma petenense</u>	<u>3,439</u>	<u>3.54</u>					+	+	+	+	+	+	+
<u>Hiodon tergisus</u>	<u>3</u>	<u>Tb</u>							+				
<u>Cyprinidae</u>	<u>652</u>	<u>0.67</u>			+	+	+	+	+	+	+	+	+
<u>Cyprinus carpio</u>	<u>23</u>	<u>0.02</u>		+			+	+	+				
<u>Hybopsis storeriana</u>	<u>4</u>	<u>T</u>										+	+
<u>Notropis sp.</u>	<u>34</u>	<u>0.03</u>							+	+	+	+	
<u>Notropis atherinoides</u>	<u>3</u>	<u>T</u>											
<u>Notropis volucellus</u>	<u>36</u>	<u>0.04</u>									+	+	+
<u>Pimephales sp.</u>	<u>7</u>	<u>0.01</u>								+			
<u>Pimephales vigilax</u>	<u>4</u>	<u>T</u>											+
<u>Ictiobinae</u>	<u>48</u>	<u>0.05</u>			+	+		+	+				

Table 5-7 (Continued)

Taxon	Total collected ^a	Percent composition	Occurrence by sample period										
			1	2	3	4	5	6	7	8	9	10	11
			Apr 6	Apr 13	May 4	May 12	May 26	Jun 1	Jun 16	July 1	July 15	July 29	Aug 27
<u>Ictalurus furcatus</u>	17	0.02								+		+	+
<u>Ictalurus punctatus</u>	75	0.08							+	+	+	+	+
<u>Labidesthes sicculus</u>	24	0.02					+			+			
<u>Morone</u> sp.	2,293	2.36		+	+	+	+	+	+			+	
<u>Morone</u> (not <u>saxatilis</u>)	876	0.90	+	+	+	+	+	+	+				
<u>Centrarchidae</u>	3	T									+		
<u>Lepomis</u> or <u>Pomoxis</u>	1	T								+			
<u>Lepomis</u> sp.	13,143	13.52				+	+	+	+	+	+	+	+
<u>Lepomis macrochirus</u>	10	0.01										+	
<u>Lepomis microlophus</u>	1	T											+
<u>Pomoxis</u> sp.	4,055	4.17	+	+	+	+	+	+	+				
Unidentified darter	4	T	+	+					+				
<u>Etheostoma</u> sp.	1	T			+								
<u>Perca flavescens</u>	59	0.06											
<u>Stizostedion canadense</u>	1	T	+				+						
<u>Aplodinotus grunniens</u>	8,786	9.04			+	+	+	+	+	+	+	+	+
Total	97,228	100											

a. Total number of specimens collected

b. Less than 0.01 percent composition

Table 5-8. List of Taxa, Total Number Collected, and Period of Occurrence of Fish Eggs and Larvae Collected at Sequoyah Nuclear Plant, 1982

Taxon	Total collected ^a	Percent composition	Occurrence by sample period											
			1	2	3	4	5	6	7	8	9	10	11	12
			Mar 18	Mar 31	Apr 14	Apr 28	May 12	May 26	Jun 9	Jun 23	July 6	July 20	Aug 3	Aug 17
<u>Fish Eggs</u>														
Unidentifiable fish eggs	69	0.42												
<u>Aplodinotus grunniens (eggs)</u>	<u>16439</u>	<u>99.58</u>	+	+	+	+	+	+	+	+	+	+	+	+
Total	16508	100												
<u>Fish Larvae</u>														
Unidentifiable fish larvae	61	0.07	+											
Unidentifiable Clupeids	59512	68.10	+	+	+	+	+	+	+	+	+	+	+	+
<u>Alosa chrysochloris</u>	1	T ^b												
<u>Dorosoma sp.</u>	41	0.05												
<u>Dorosoma cepedianum</u>	5192	5.94												
<u>Dorosoma petenense</u>	705	0.81												
Unidentifiable Cyprinids	1218	1.39												
<u>Cyprinus carpio</u>	9	0.01												
<u>Notropis sp.</u>	39	0.04												
<u>Notropis atherinoides</u>	11	0.01												
<u>Notropis volucellus</u>	164	0.19												
<u>Pimephales sp.</u>	1	T												
<u>Pimephales notatus</u>	1	T												
<u>Pimephales vigilax</u>	2	T												
Unidentifiable Ictiobinae	16	0.02												
<u>Ictiobus sp.</u>	1	T												

Table 5-8 (Continued)

Taxon	Total collected ^a	Percent composition	Occurrence by sample period											
			1	2	3	4	5	6	7	8	9	10	11	12
			Mar 18	Mar 31	Apr 14	Apr 28	May 12	May 26	Jun 9	Jun 23	July 6	July 20	Aug 3	Aug 17
<u>Ictalurus furcatus</u>	19	0.02								+	+	+	+	+
<u>Ictalurus punctatus</u>	49	0.06							+	+	+	+	+	+
<u>Pylodictis olivaris</u>	1	T									+			
<u>Labidesthes sicculus</u>	35	0.04					+	+	+	+				
<u>Morone</u> sp.	1935	2.21				+	+	+	+	+				
<u>Morone chrysops</u>	1	T								+				
<u>Morone mississippiensis</u>	5	0.01							+					+
<u>Morone</u> sp. (not <u>saxatilis</u>)	1693	1.94		+	+	+	+	+	+	+				
<u>Lepomis</u> sp.	11243	12.87		+	+	+	+	+	+	+	+	+	+	+
<u>Lepomis macrochirus</u>	66	0.08						+		+	+	+	+	+
<u>Micropterus</u> sp. (not <u>dolomieu</u>)	1	T												
<u>Pomoxis</u> sp.	2698	3.09				+	+	+	+	+	+	+		+
<u>Pomoxis annularis</u>	7	0.01												
Unidentified Percids	9	0.01				+	+							
<u>Perca flavescens</u>	64	0.07		+	+	+								
<u>Stizostedion canadense</u>	4	0.01		+		+								
<u>Aplodinotus grunniens</u>	2581	2.95				+	+	+	+	+	+	+	+	+
	87385	100												

a. Total number of specimens collected

b. Less than 0.01 percent composition

Table 5-9. List of Taxa, Total Number Collected, and Period of Occurrence of Fish Eggs and Larvae Collected at Sequoyah Nuclear Plant, 1983

Taxon	Total collected ^a	Percent composition	Occurrence by sample period												
			1	2	3	4	5	6	7	8	9	10	11	12	13
			Mar 9	Mar 22	Apr 6	Apr 20	May 5	May 18	Jun 1	Jun 15	Jun 28	July 13	July 27	Aug 10	Aug 22
<u>Fish Eggs</u>															
Unidentifiable fish eggs	56	0.42					+	+	+	+	+	+	+	+	+
Aplodinotus grunniens eggs	13,214	99.58			+		+	+	+	+	+	+	+	+	+
Total	13,270	100.00													
<u>Fish Larvae</u>															
Unidentifiable fish larvae	653	0.54			+	+	+	+	+	+	+	+	+	+	+
Clupeidae	89,887	74.12			+	+	+	+	+	+	+	+	+	+	+
Alosa chrysochloris	3	T ^b								+					
Dorosoma sp.	1	T									+				
Lorosoma cepedianum	20	0.02								+	+	+	+	+	+
Dorosoma petenense	375	0.31								+	+	+	+	+	+
Hiodon tergisus	17	0.01									+	+	+	+	+
Cyprinidae	1,432	1.18						+	+	+	+	+	+	+	+
Cyprinus carpio	106	0.09			+	+	+	+	+	+	+	+	+	+	+
Notemigonus crysoleucas	2	T					+								
Notropis sp.	239	0.20								+	+	+	+	+	+
Notropis atherinoides	31	0.03								+	+	+	+	+	+
Notropis volucellus	47	0.04													+
Ictiobinae	203	0.17													
+					+	+	+	+	+						
Ictiobus sp.	1	T				+									
Ictalurus furcatus	23	0.02								+	+	+	+	+	+
Ictalurus punctatus	37	0.03								+	+	+	+	+	+
Labidesthes sicculus	11	0.01													
Morone sp.	194	0.16													
Morone chrysops	1	T			+	+	+	+	+	+	+	+	+	+	+
Morone (not saxatilis)	4,342	3.48			+	+	+	+	+	+	+	+	+	+	+

Table 5-9 (Continued)

Taxon	Total collected ^a	Percent composition	Occurrence by sample period														
			1	2	3	4	5	6	7	8	9	10	11	12	13		
			Mar 9	Mar 22	Apr 6	Apr 20	May 5	May 18	Jun 1	Jun 15	Jun 28	July 13	July 27	Aug 10	Aug 22		
Lepomis or Pomoxis	15	0.01								+	+						
Lepomis sp.	10,370	8.55					+		+	+	+	+	+	+	+	+	+
Micropterus (not dolomieu)	2	T						+									
Pomoxis sp.	734	0.61					+		+	+	+	+					
Pomoxis annularis	1	T															+
Percidae	2	T				+											
Unidentifiable darter	2	T							+								
Perca flavescens	52	0.04		+		+	+										
Stizostedion canadense	3	T		+						+	+						
Aplodinotus grunniens	12,463	10.28								+	+	+	+	+	+	+	+
Total	121,269	100.00															

a. Total number of specimens collected

b. Less than 0.01 percent composition

Table 5-10. List of Taxa, Total Number Collected, and Period of Occurrence of Fish Eggs and Larvae Collected at Sequoyah Nuclear Plant, 1984

Taxon	Total collected ^a	Percent composition	Occurrence by sample period												
			1	2	3	4	5	6	7	8	9	10	11	12	13
			Mar 7	Mar 21	Apr 4	Apr 17	May 1	May 15	May 30	Jun 12	Jun 26	July 10	July 24	Aug 7	Aug 21
<u>Fish Eggs</u>															
Unidentifiable fish eggs	247	3.03													
Aplodinotus grunniens eggs	7,900	96.97													
Total	8,147	100.00													
<u>Fish Larvae</u>															
Unidentifiable fish larvae	115	0.08													
Clupeidae	115,735	78.54													
Alosa chrysochloris	2	Tb													
Dorosoma sp.	1	T													
Dorosoma cepedianum	208	0.14													
Dorosoma petenense	308	0.21													
Hiodon tergisus	18	0.01													
Cyprinidae	2,289	1.55													
Cyprinus carpio	154	0.10													
Notemigonus crysoleucas	1	T													
Notropis sp.	413	0.28													
Notropis atherinoides	20	0.01													
Pimephales sp.	2	T													
Ictiobinae	397	0.27													
Ictalurus furcatus	12	0.01													
Ictalurus punctatus	37	0.03													
Morone sp.	119	0.08													

Table 5-10 (Continued)

Taxon	Total collected ^a	Percent composition	Occurrence by sample period													
			1	2	3	4	5	6	7	8	9	10	11	12	13	
			Mar 7	Mar 21	Apr 4	Apr 17	May 1	May 15	May 30	Jun 12	Jun 26	July 10	July 24	Aug 7	Aug 21	
Morone (not saxatilis)	2,471	1.68					+	+	+	+						
Lepomis sp.	14,388	9.76						+	+	+	+	+	+	+	+	
Pomoxis sp.	622	0.42					+	+	+	+	+					
Unidentifiable darter	2	T							+							
Perca flavescens	64	0.04					+	+								
Stizostedion canadense	1	T														
Aplodinotus grunniens	9,986	6.78							+	+	+	+	+	+	+	
Labidesthes sicculus	1	T														
Total	147,366	100.00														

a. Total number of specimens collected

b. Less than 0.01 percent composition.

Table 5-11. List of Taxa, Total Number Collected, and Period of Occurrence of Fish Eggs and Larvae Collected at Sequoyah Nuclear Plant, 1985

Taxon	Total collected ^a	Percent composition	Occurrence by sample period													
			1	2	3	4	5	6	7	8	9	10	11	12	13	
			Mar 11	Mar 26	Apr 8	Apr 22	May 6	May 20	Jun 3	Jun 17	Jul 1	Jul 15	Jul 31	Aug 12	Aug 27	
<u>Fish Eggs</u>																
Unidentifiable fish eggs	162	0.46														
	1	Tb														
Aplodinotus grunniens eggs	35,094	99.54														
Total	35,257	100.00														
<u>Fish Larvae</u>																
Unidentifiable fish larvae	12	0.01														
Clupeidae	72,837	60.01														
	2	T														
Alosa chrysochloris	2	T														
Dorosoma sp.	230	0.19														
Dorosoma cepedianum	580	0.48														
Dorosoma petenense	822	0.68														
Cyprinidae	194	0.16														
Cyprinus carpio	2	T														
Notemigonus crysoleucas	164	0.14														
Notropis sp.	21	0.02														
Notropis atherinoides	24	0.02														
Ictiolabes	12	0.01														
Ictalurus furcatus	28	0.02														
Ictalurus punctatus	4,870	4.01														
Morone sp.	2	T														
Morone chrysops	2	T														
Morone mississippiensis																

Table 5-11 (Collected)

Taxon	Total collected ^a	Percent composition	Occurrence by sample period												
			1	2	3	4	5	6	7	8	9	10	11	12	13
			Mar 11	Mar 26	Apr 8	Apr 22	May 6	May 20	Jun 3	Jun 17	July 1	July 15	July 31	Aug 12	Aug 27
Morone (not saxatilis)	2,252	1.86			+	+	+	+	+	+					
Lepomis sp.	20,653	17.02				+	+	+	+	+	+	+	+	+	+
Lepomis macrochirus	23	0.02													
Micropterus (not dolomieu)	4	T					+								
Pomoxis sp.	558	0.46				+	+	+	+	+	+				
Percidae	2	T			+										
Unidentifiable darter	7	0.01			+	+	+								
Perca flavescens	55	0.05			+	+	+								
Aplodinotus grunniens	18,009	14.84	+			+	+	+	+	+	+	+	+	+	+
Labidesthes sicculus	3	T							+						
Total	121,370	100.00													

a. Total number of specimens collected

b. Less than 0.01 percent composition

Table 5-12. Potential Susceptibility of Selected Fish Species Occurring in Chickamauga Reservoir to Impacts from Low Concentrations of Dissolved Oxygen

Fish taxa	Relative susceptibility			Reasons
	High	Mid	Low	
<u>Dorosoma</u> spp. (gizzard and threadfin shad)			X	Broad habitat usage
<u>Cyprinus carpio</u> (carp)			X	Use overbank habitats
<u>Notropis</u> spp. (shines)			X	Use overbank habitats
<u>Notropis volucellus</u> (mimic shiner)	X			Summer spawn, young prefer deep channels, DO sensitivity unknown
<u>Ictiobus</u> spp. (buffalo fish)	X			Early spawners but larger young inhabit deep channels in summer, DO sensitivity unknown
<u>Ictalurus</u> spp. (catfish)	X			Some deep spawning, young predominately in deep channels, young sensitive to low DO
<u>Morone</u> spp. (white bass, striped bass)		X		Larger young inhabit deep channels in summer, moderately tolerant of low DO
<u>Lepomis</u> spp. (sunfishes)			X	Spawn and predominately remain in overbank
<u>Micropterus</u> (not dolomieu) (largemouth and spotted bass)			X	Spawn and predominately remain in overbank or near-shore habitat
<u>Pomoxis</u> spp. (white and black crappie)			X	Spawn and predominately remain in overbank and embayment habitats, but older young sometimes found on channel slopes, sensitivity to low DO in question

Table 5-12 (Continued)

Fish taxa	Relative susceptibility			Reasons
	High	Mid	Low	
<u>Perca flavescens</u> (yellow perch)			X	Young inhabit channels, but are tolerant of low DO
<u>Stizostedion canadense</u> (sauger)		X		Early spawner, but older young strongly prefer deep waters during day, sensitivity to low DO not well-defined
<u>Aplodinotus grunniens</u> (freshwater drum)		X		Summer deep-water spawner, young prefer deep-water channel, sensitivity to low DO unknown

Table 5-13. Flows (cfs) and Flow Frequencies (% of Time Flow Is Met or Exceeded in Parentheses), Which on the Average Maintain or Assure 4 or 5 mg/l DO in Releases from Watts Bar Dam Into Chickamauga Reservoir

	June	July	August
4 mg/l DO			
Average	11,000 (89)	20,000 (71)	19,000 (81)
Assure	30,000 (20)	28,000 (30)	33,000 (20)
5 mg/l DO			
Average	20,000 (63)	28,000 (30)	29,000 (40)
Assure	31,000 (19)	35,000 (19)	35,000 (3)

Figure 5-1. Relationship Between June Dissolved Oxygen Measurements and the Preceding 7-day Mean Flow for Watts Bar Dam Releases

Figure 5-2. Relationship Between July Dissolved Oxygen Measurements and the Preceding 7-day Mean Flow for Watts Bar Dam Releases

Figure 5-3. Relationship Between August Dissolved Oxygen Measurements and the Preceding 7-day Mean Flow for Watts Bar Dam Releases

Figure 5-4. Relationship Between September Dissolved Oxygen Measurements and the Preceding 7-day Mean Flow for Watts Bar Dam Releases

Figure 5-5. June Flow Duration Curves for Watts Bar Dam Releases

Figure 5-6. July Flow Duration Curves for Watts Bar Dam Releases

WATTS BAR FLOW DURATION
1960 - 1988 (AUGUST)

Figure 5-7. August Flow Duration Curves for Watts Bar Dam Releases

WATTS BAR FLOW DURATION
1968 - 1988 (SEPTEMBER)

Figure 5-8. September Flow Duration Curves for Watts Bar Dam Releases

ENG LAB 12/18/89)SBTIME-DO
Figure 5-9. Surface and Bottom Dissolved Oxygen With Full SQN and WBN Loads Under Low (1986) Flows

Figure 5-10. Longitudinal Dissolved Oxygen Contours from Measurements in April and May 1989

Figure 5-11. Longitudinal Dissolved Oxygen Contours from Measurements in May and June 1989

Figure 5-12. Longitudinal Dissolved Oxygen Contours from Measurements in June and July 1989

Figure 5-13. Longitudinal Dissolved Oxygen Contours from Measurements in August and September 1989

Figure 5-14. Longitudinal DO contours from Measurements in September 1989

ENG LUG 12/11/89

Figure 5-15. Time-Elevation Dissolved Oxygen Contours Measured from Six Tennessee River Miles During 1989

ENG LAB 12/11/89
Figure 5-16. Time-Elevation Dissolved Oxygen Contours Measured from Two Tennessee River and Two Hiwassee River Miles During 1989

Figure 5-17. Time-Elevation Dissolved Oxygen Contours from TRM 478.19 and 471.1 During 1987

Figure 5-18. Time-Elevation Dissolved Oxygen Contours from TRM 480.4 and 479.4 During 1987

Figure 5-19. Time-Elevation Dissolved Oxygen Contours
from TRM 482.4 and 481.4 During 1987

Figure 5-20. Time-Elevation Dissolved Oxygen Contours from TRM 483.4 and 482.9 During 1987

Figure 5-21. Time-Elevation Dissolved Oxygen Contours Measured from TRM 474.7 and 484.1 During 1987

Figure 5-22. Time-Elevation Dissolved Oxygen Contours Measured from TRM 496.5 and 490.47 During 1987

Figure 5-23. Time-Elevation Dissolved Oxygen Contours Measured from TRM 518.0 and 506.6 During 1987

Figure 5-24. Time-Elevation Dissolved Oxygen Contours Measured from Hiwassee River miles 20.0 and 7.4 During 1987

6.0 CONCLUSIONS

6.1 Inplant Effects on Dissolved Oxygen

1. The temperature of the cooling water at SQN is increased approximately 14°C when both units are operating in open mode. This change in water temperature causes a shift in the gas transfer equilibrium with the atmosphere resulting in a reduction in the DO concentration in the cooling water discharge averaging 0.8 mg/l.
2. The percent DO saturation increased due to the oxygen not recovering equilibrium with the atmosphere under the higher temperature.
3. The reduction of DO in the cooling water discharge is estimated to cause a reduction of less than 0.1 mg/l in the DO concentration throughout the reservoir water column during normal flows. Such a reduction would be unmeasurable within the reservoir. In the extreme case of maximum DO loss in the cooling water under low flow conditions, the mean water column DO of the reservoir would be reduced by approximately 0.5 mg/l.
4. No detectable increase in ultimate oxygen demands due to entrainment of plankton or fish larvae was detected as was described in the environmental impact statement for SQN (TVA, 1974).
5. The short-term oxygen demand of the cooling water at SQN is decreased slightly. On the average, chemical oxygen demand was reduced 0.8 mg/l and the 5-day BOD was reduced by 0.1 mg/l.

6.2 Dissolved Oxygen Distribution in the Vicinity of SQN

1. The underwater dam produces significant upwelling with increased vertical mixing, especially in the layers between the top of the dam and the water surface.
2. Both the underwater dam and diffuser structures provide significant perturbations in the flow patterns of the lower layers of the reservoir.
3. The natural bend in the main channel may have a significant effect on vertical circulation patterns in the vicinity of SQN.
4. A statistically significant decrease in DO measured at 5 ft during three consecutive springs averaging 0.9 mg/l was observed downstream from the mixing zone as compared to upstream from the underwater dam.
5. No statistically significant change in mean water column DO was observed between the upstream and downstream locations tested.
6. SQN does not change the mass of DO in the reservoir, but does redistribute the DO into a mixed water column.
7. The distribution patterns of DO and temperature near SQN were extremely dynamic over a diel period.
8. During the daytime, overbank areas showed higher DO and temperature levels compared to the adjacent main channel. These higher levels resulted from shallower depths and higher photosynthetic activity.

9. The surface water upstream from the underwater dam contained relatively more daytime DO from photosynthesis. Mixing of the water column downstream from the submerged dam distributed algae to depths where light limits productivity, suppressing the relative daytime DO.
10. A strong thermal thermal gradient was observed at the diffuser discharge for most to the diel period. When low or reverse flows caused by Chickamauga Dam operations were encountered at SQN, the thermal discharge spread upstream from the underwater dam. During these periods of low and reverse flow, the DO became uniformly distributed throughout the reservoir reach.

6.3 Dissolved Oxygen Distribution in Reservoir

1. Water quality modeling showed that the discharge from SQN increases the temperature and DO of the release from Chickamauga Reservoir by 1-3°C and 0.5-2.0 mg/l, respectively during the critical spring and summer months.
2. Water quality modeling showed that the temperature and DO of the release from Chickamauga Dam were the same with or without the discharge from SQN even under extremely low flow conditions.
3. Water quality modeling showed that the DO in the release from Chickamauga Dam during low flow (19,000 cfs) years was about 2 mg/l lower than that during normal (25,000 cfs) or high flow years.

4. Model simulations showed that the hypolimnetic DO was above 5 mg/l throughout the summer when flow were normal or higher. During low flow simulations, the reservoir strongly stratified resulting in hypolimnetic DO less than 3 mg/l.
5. Water quality modeling showed that the addition of 2 mg/l of DO to the release from Watts Bar Dam by aeration with forebay surface water pumps results in an increase of 0.8-1.0 mg/l in the releases from Chickamauga Dam.
6. The DO concentrations in Chickamauga Reservoir depends greatly on the DO concentration in the release from Watts Bar Dam, which can be in the 2 to 4 mg/l range in dry summer months.
7. Water quality modeling showed that the DO in the hypolimnion downstream from SQN was increased 2-4 mg/l when both units at SQN are generating. The increase is due to the mixing of the water column induced by the mixing of the heated discharge, the underwater dam, and the bend in the river.
8. Water quality modeling showed that the DO in the hypolimnion downstream from SQN was increased approximately 1 mg/l when SQN is not generating electricity. The increase is due to the mixing of the water column induced by the the underwater dam and the bend in the river.
9. Water quality modeling showed that under low flows, the DO in the hypolimnion near Chickamauga Dam would decrease 2 mg/l if SQN, including the underwater dam, were not present.

10. Water quality modeling showed that the DO in both the epilimnion and the hypolimnion downstream from SQN would increase 1.0-1.5 mg/l if 2 mg/l of DO is added to Watts Bar Dam releases with forebay surface water pumps. This increase is the same under both low and normal flows.
11. Water quality modeling showed that the DO in the epilimnion downstream from SQN was decreased approximately 1 mg/l when both units at SQN are generating. The decrease is due to the mixing of the water column induced by the mixing of the heated discharge, the underwater dam, and the bend in the river.
12. Water quality modeling showed that the DO in the epilimnion downstream from SQN was decreased approximately 1 mg/l when SQN is not generating electricity. The decrease is due to the mixing of the water column induced by the the underwater dam and the bend in the river.
13. Water quality modeling showed that under low flows, the DO in the epilimnion near Chickamauga Dam would increase 1 mg/l if SQN, including the underwater dam, were not present.

6.4 Aquatic Life Responses to Dissolved Oxygen Distribution

1. Fluorometry values were more sensitive to minor changes in plankton concentrations than chlorophyll concentrations.
2. Both fluorometry and chlorophyll measurements showed that the diffuser discharge and the underwater dam effectively mix the water column in the area of TRM 483.4. The effects of this mixing diminish within 1-2 river miles.
3. Some fish species, such as the channel catfish and possibly the freshwater drum, juvenile ictiobines, and particular cyprinids in Chickamauga Reservoir are likely suffering detrimental effects from low DO levels in the reservoir. Other species (table 5-12) are of varying susceptibility, but are much less likely to experience or be affected by low DO levels than these species.
4. Conditions leading to potential adverse fishery effects are due to low DO in releases from Watts Bar Dam and natural stratification of Chickamauga Reservoir. Potential impacts to fishery production are most pronounced under low flow conditions and are minimal under normal or high flow conditions.
5. Mixing events introduced into the water column by both the underwater dam and thermal discharge at Sequoyah are overall beneficial to fisheries in the near-plant area by increasing metalimnetic and hypolimnetic DO levels; by reducing the reservoir volume and areas experiencing the lowest (possibly lethal) DO levels occurring in releases from Watts Bar Dam; and by slightly disrupting

stratification of Chickamauga Reservoir. Areas experiencing DO concentrations below 3 mg/l are likely to be avoided by most adult fishes may be lethal to young fish spawned in or remaining in nursery areas subject to these low DO levels. Under critical low flow conditions, such areas are reduced by the underwater dam and operation of SQN. Normal flows, with higher incoming DO levels from Watts Bar Dam releases and short residence time of water behind the underwater dam, minimize or eliminate low DO problems and should produce no biological consequence.

6. Near-surface DO concentrations are reduced an average of 0.7 mg/l downstream from the mixing zone as compared to upstream from the underwater dam. Impacts to fish distribution (through avoidance of lowered DO), spawning or survival by redistribution of DO are highly unlikely.
7. Temporally or spatially most fish species would not be coincident with lowered DO. For the concentration range within which near-surface DO levels are likely to be reduced, only a small portion of young of fish species coincidentally occurring in the near-surface, deep-water channel area could even potentially experience slightly reduced growth during the lowered DO exposure (when compared to saturation levels). Of these fish, only the young sunfish or crappie (table 5-3) resident in the near-diffuser area may experience slightly lowered DO conditions as they move from overbank areas to shallow channel areas. However, the predominantly productive areas for crappie in Chickamauga Reservoir are in areas other than the Sequoyah near-plant area (Buchanan, 1989).

7.0 RECOMMENDATIONS

1. No operational or facilities modifications are recommended for SQN to alter present DO dynamics or conditions in Chickamauga Reservoir.
2. Water quality criteria and methods of measurement should be modified to reflect more biologically significant DO characteristics of reservoirs.

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APPENDIX A

ANALYTICAL METHODS FOR CHEMICAL PARAMETERS
OPERATIONAL WATER QUALITY MONITORING
SEQUOYAH NUCLEAR PLANT
CHICKAMAUGA RESERVOIR

Table A1. Analytical Methods for Chemical Parameters

Parameter	STORET Code Number	Method	Detection Limit	Reference
Alkalinity, total	00410	Potentiometric Titration	none	TVA NRS-LB-AP-30.337.2
Carbon, total organic	00680	Oxidation-Infrared	0.2 mg/l	TVA NRS-LB-AP-30.502.1
Chlorophyll	32211	Trichromatic	1 µg/l	TVA NRS-LB-AP-41.501.1
Conductance, specific	00095	In situ Wheatstone Bridge	10 µmhos/cm	TVA NR OPS-FO-NRE-42.3
Nitrogen, total ammonia	00610	Auto Colorimetric Phenate	0.01 mg/l	TVA NRS-LB-AP-30.356.1
Nitrogen, total nitrate plus nitrite	00630	Auto Cadmium Reduction	0.01 mg/l	TVA NRS-LB-AP-30.356.4
Nitrogen, organic	00605	Kjeldahl-N minus Inorganic-N	0.01 mg/l	TVA NRS-LB-AP-30.360.2
Oxygen, dissolved	00300	In situ Electrode	0.1 mg/l	TVA NR OPS-FO-NRE-42.4
Oxygen demand, chemical	00335	Oxidation-Titration	1 mg/l	TVA NRS-LB-AP-30.503
Oxygen demand, biochemical	00310	Incubation	1 mg/l	TVA NRS-LB-AP-30.501
Oxygen demand, carbonaceous	80276	Incubation with Inhibitor	1 mg/l	TVA NRS-LB-AP-30.501
pH	00400	Electrometric	Not applicable	TVA NR OPS-FO-NRE-42.8
Phosphorus, total	00665	Auto Colorimetric Ascorbic Acid	0.01 mg/l	TVA NRS-LB-AP-30.360.3
Phosphorus, dissolved	00666	Auto Colorimetric Ascorbic Acid	0.01 mg/l	TVA NRS-LB-AP-30.360.3
Phosphorus, ortho-	70507	Auto Colorimetric Ascorbic Acid	0.01 mg/l	TVA NRS-LB-AP-30.360.3
Suspended solids, total	00530	Residue, Nonfilterable	1 mg/l	TVA NRS-LB-AP-30.1.4.2
Suspended solids, volatile	00535	Residue, Volatile	1 mg/l	TVA NRS-LB-AP-30.1.4.4
Temperature	00010	In situ Thermister	0.1°C	TVA NR OPS-FO-NRE-42.11
Turbidity	00070	Nephelometric	0.1 NTU	TVA NRS-LB-AP-30.1.6

STORET is the acronym for the Environmental Protection Agency's data storage and retrieval system.

Reference abbreviations refer to the following:

TVA NRS -Laboratory Branch Manual, 1980, Tennessee Valley Authority.

TVA NR OPS-Field Operations NRE Procedures Manual, Volume 1, 1983, Tennessee Valley Authority.

APPENDIX B

**INPLANT MEASUREMENTS OF TEMPERATURE, DISSOLVED OXYGEN
CONCENTRATIONS, AND SATURATION**

Figure B-1. Temperature Measured at SQN During May 1988

Figure B-2. Temperature Measured at SQN During May 1989

Figure B-3. Temperature Measured at SQN During June 1989

Figure B-4. Temperature Measured at SQN During July 1989

TEMPERATURE (C)

Figure B-5. Temperature Measured at SQN During August 1989

Figure B-6. Temperature Measured at SQN During September 1989

Figure B-7. Dissolved Oxygen Measured at SQN During May 1988

Figure B-8. Dissolved Oxygen Measured at SQN During May 1989

Figure B-9. Dissolved Oxygen Measured at SQN During June 1989

Figure B-10. Dissolved Oxygen Measured at SQF During July 1989

Figure B-11. Dissolved Oxygen Measured at SQN During August 1989

Figure B-12. Dissolved Oxygen Measured at SQN During September 1989

Figure B-13. Dissolved Oxygen Saturation (%) Measured at SQN During May 1988

Figure B-14. Dissolved Oxygen Saturation (%) Measured at SQN During May 1989

Figure B-15. Dissolved Oxygen Saturation (%) Measured at SQN During June 1989

Figure B-16. Dissolved Oxygen Saturation (%) Measured at SQN During July 1989

Figure B-17. Dissolved Oxygen Saturation (%) Measured at SQN During August 1989

Figure B-18. Dissolved Oxygen Saturation (%) Measured at SQN During September 1989

Figure B-19. SQW Power Load and Changes in Temperature, Dissolved Oxygen, and Saturation During May 1988

Figure B-20. SQM Power Load and Changes in Temperature, Dissolved Oxygen, and Saturation During May 1989

Figure B-21. SQN Power Load and Changes in Temperature, Dissolved Oxygen, and Saturation During June 1989

Figure B-22. SQN Power Load and Changes in Temperature, Dissolved Oxygen, and Saturation During July 1989

Figure B-23. SQN Power Load and Changes In Temperature, Dissolved Oxygen, and Saturation During August 1989

Figure B-24. SQN Power Load and Changes in Temperature, Dissolved Oxygen, and Saturation During September 1989

APPENDIX C

NEAR-FIELD RESERVOIR MEASUREMENTS OF TEMPERATURE,
DISSOLVED OXYGEN CONCENTRATIONS, AND pH

Figure C-1. Dissolved Oxygen and Temperature Measured Near SQN on April 1, 1987

Figure C-2. Percent Oxygen Saturation and pH Measured Near SQN on April 1, 1987

Figure C-3. Dissolved Oxygen and Temperature Measured Near SQN on April 16, 1987

Figure C-4. Percent Oxygen Saturation and pH Measured Near SQN on April 16, 1987

Figure C-5. Dissolved Oxygen and Temperature Measured Near SQN on April 29, 1987

Figure C-6. Percent Oxygen Saturation and pH Measured Near SQN on April 29, 1987

Figure C-7. Dissolved Oxygen and Temperature Measured Near SQN on May 13, 1987

Figure C-8. Percent Oxygen Saturation and pH Measured Near SQN on May 13, 1987

Figure C-9. Dissolved Oxygen and Temperature Measured Near SQN on May 27, 1987

Figure C-10. Percent Oxygen Saturation and pH Measured Near SQN on May 27, 1987

Figure C-11. Dissolved Oxygen and Temperature Measured Near SQN on June 10, 1987

Figure C-12. Percent Oxygen Saturation and pH Measured Near SQN on June 10, 1987

Figure C-13. Dissolved Oxygen and Temperature Measured Near SQN on June 23, 1987

Figure C-14. Percent Oxygen Saturation and pH Measured Near SQN on June 23, 1987

Figure C-15. Dissolved Oxygen and Temperature Measured Near SQN on July 1, 1987

Figure C-16. Percent Oxygen Saturation and pH Measured Near SQN on July 1, 1987.

Figure C-17. Dissolved Oxygen and Temperature Measured Near SQN on July 7, 1987

Figure C-18. Percent Oxygen Saturation and pH Measured Near SQN on July 7, 1987

Figure C-19. Dissolved Oxygen and Temperature Measured Near SQN on July 14, 1987

Figure C-20. Percent Oxygen Saturation and pH Measured Near SQN on July 14, 1987

Figure C-21. Dissolved Oxygen and Temperature Measured Near SQN on July 21, 1987

Figure C-22. Percent Oxygen Saturation and pH Measured Near SQW on July 21, 1987

Figure C-23. Dissolved Oxygen and Temperature Measured Near SQN on July 28, 1987

Figure C-24. Percent Oxygen Saturation and pH Measured Near SQN on July 28, 1987

Figure C-25. Dissolved Oxygen and Temperature Measured Near SQN on July 28, 1987

Figure C-26. Percent Oxygen Saturation and pH Measured Near SQN on July 28, 1987

Figure C-27. Dissolved Oxygen and Temperature Measured Near SQN on August 11, 1987

Figure C-28. Percent Oxygen Saturation and pH Measured Near SQN on August 11, 1987

Figure C-29. Dissolved Oxygen and Temperature Measured Near SQN on August 18, 1987

Figure C-30. Percent Oxygen Saturation and pH Measured Near SQN on August 18, 1987

Figure C-31. Dissolved Oxygen and Temperature Measured Near SQN on August 25, 1987

Figure C-32. Percent Oxygen Saturation and pH Measured Near SQN on August 25, 1987

Figure C-33. Dissolved Oxygen and Temperature Measured Near SQN on September 1, 1987

Figure C-34. Percent Oxygen Saturation and pH Measured Near SQN on September 1, 1987

Figure C-35. Dissolved Oxygen and Temperature Measured Near SQN on September 8, 1987

Figure C-36. Percent Oxygen Saturation and pH Measured Near SQN on September 8, 1987

Figure C-38. Percent Oxygen Saturation and pH Measured Near SQN on September 15, 1987

Figure C-39. Dissolved Oxygen and Temperature Measured Near SQN on September 22, 1987

Figure C-40. Percent Oxygen Saturation and pH Measured Near SQN on September 22, 1987

Figure C-41. Dissolved Oxygen and Temperature Measured Near SQN on March 1, 1988

Figure C-42. Percent Oxygen Saturation and pH Measured Near SQN on March 1, 1988

Figure C-43. Dissolved Oxygen and Temperature Measured Near SQN on March 15, 1988

Figure C-44. Percent Oxygen Saturation and pH Measured Near SQN on March 15, 1988

Figure C-45. Dissolved Oxygen and Temperature Measured Near SQN on March 29, 1988

Figure C-47. Dissolved Oxygen and Temperature Measured Near SQN on April 5, 1988

Figure C-48. Percent Oxygen Saturation and pH Measured Near SQN on April 5, 1988

Figure C-49. Dissolved Oxygen and Temperature Measured Near SQN on April 12, 1988

Figure C-50. Percent Oxygen Saturation and pH Measured Near SQN on April 12, 1988

Figure C-51. Dissolved Oxygen and Temperature Measured Near SQN on April 19, 1988

Figure C-52. Percent Oxygen Saturation and pH Measured Near SQN on April 19, 1988

Figure C-53. Dissolved Oxygen and Temperature Measured Near SQN on April 26, 1988

Figure C-54. Percent Oxygen Saturation and pH Measured Near SQN on April 26, 1988

Figure C-55. Dissolved Oxygen and Temperature Measured Near SQN on May 3, 1988

Figure C-56. Percent Oxygen Saturation and pH Measured Near SQN on May 3, 1988

Figure C-57. Dissolved Oxygen and Temperature Measured Near SQN on May 10, 1988

Figure C-58. Percent Oxygen Saturation and pH Measured Near SQN on May 10, 1988

Figure C-59. Dissolved Oxygen and Temperature Measured Near SQN on April 5, 1989

Figure C-60. Percent Oxygen Saturation and pH Measured Near SQN on April 5, 1989

Figure C-61. Dissolved Oxygen and Temperature Measured Near SQN on April 19, 1989

Figure C-62. Percent Oxygen Saturation and pH Measured Near SQN on April 19, 1989

Figure C-63. Dissolved Oxygen and Temperature Measured Near SQN on May 3, 1989

Figure C-64. Percent Oxygen Saturation and pH Measured Near SQN on May 3, 1989

Figure C-65. Dissolved Oxygen and Temperature Measured Near SQN on May 17, 1989

Figure C-66. Percent Oxygen Saturation and pH Measured Near SQN on May 17, 1989

Figure C-67. Dissolved Oxygen and Temperature Measured Near SQN on May 31, 1989

Figure C-68. Percent Oxygen Saturation and pH Measured Near SQW on May 31, 1989

Figure C-69. Dissolved Oxygen and Temperature Measured Near SQN on June 14, 1989

Figure C-71. Dissolved Oxygen and Temperature Measured Near SQN on June 28, 1989

Figure C-72. Percent Oxygen Saturation and pH Measured Near SQN on June 28, 1989

Figure C-73. Dissolved Oxygen and Temperature Measured Near SQN on July 12, 1989

Figure C-74. Percent Oxygen Saturation and pH Measured Near SQN on July 12, 1989

Figure C-75. Dissolved Oxygen and Temperature Measured Near SQN on July 26, 1989

Figure C-76. Percent Oxygen Saturation and pH Measured Near SQN on July 26, 1989

Figure C-77. Dissolved Oxygen and Temperature Measured Near SQN on August 9, 1989

Figure C-78. Percent Oxygen Saturation and pH Measured Near SQN on August 9, 1989

Figure C-79. Dissolved Oxygen and Temperature Measured Near SQN on August 22, 1989

Figure C-80. Percent Oxygen Saturation and pH Measured Near SQN on August 22, 1989

Figure C-81. Dissolved Oxygen and Temperature Measured Near SQN on September 5, 1989

Figure B-11. Dissolved Oxygen Measured at SQN During August 1989

Figure B-12. Dissolved Oxygen Measured at SQN During September 1989

Figure B-13. Dissolved Oxygen Saturation (%) Measured at SQN During May 1988

Figure B-14. Dissolved Oxygen Saturation (%) Measured at SQN During May 1989

Figure B-15. Dissolved Oxygen Saturation (%) Measured at SQN During June 1989

Figure B-16. Dissolved Oxygen Saturation (%) Measured at SQN During July 1989

Figure B-17. Dissolved Oxygen Saturation (%) Measured at SQN During August 1989

Figure B-18. Dissolved Oxygen Saturation (%) Measured at SQN During September 1989

Figure B-19. SQW Power Load and Changes in Temperature, Dissolved Oxygen, and Saturation During May 1988

Figure B-20. SQN Power Load and Changes in Temperature, Dissolved Oxygen, and Saturation During May 1989

Figure B-21. SQN Power Load and Changes in Temperature, Dissolved Oxygen, and Saturation During June 1989

Figure B-22. SQN Power Load and Changes in Temperature, Dissolved Oxygen, and Saturation During July 1989

Figure B-23. SQN Power Load and Changes in Temperature, Dissolved Oxygen, and Saturation During August 1989

Figure B-24. SQN Power Load and Changes in Temperature, Dissolved Oxygen, and Saturation During September 1989

APPENDIX C

NEAR-FIELD RESERVOIR MEASUREMENTS OF TEMPERATURE,
DISSOLVED OXYGEN CONCENTRATIONS, AND pH

Figure C-1. Dissolved Oxygen and Temperature Measured Near SQN on April 1, 1987

Figure C-2. Percent Oxygen Saturation and pH Measured Near SQN on April 1, 1987

Figure C-3. Dissolved Oxygen and Temperature Measured Near SQN on April 16, 1987

Figure C-4. Percent Oxygen Saturation and pH Measured Near SQN on April 16, 1987

Figure C-5. Dissolved Oxygen and Temperature Measured Near SQN on April 29, 1987

Figure C-6. Percent Oxygen Saturation and pH Measured Near SQM on April 29, 1987

Figure C-7. Dissolved Oxygen and Temperature Measured Near SQN on May 13, 1987

Figure C-8. Percent Oxygen Saturation and pH Measured Near SQN on May 13 1987

Figure C-9. Dissolved Oxygen and Temperature Measured Near SQN on May 27, 1987

Figure C-10. Percent Oxygen Saturation and pH Measured Near SQN on May 27, 1987

Figure C-11. Dissolved Oxygen and Temperature Measured Near SQN on June 10, 1987

Figure C-12. Percent Oxygen Saturation and pH Measured Near SQN on June 10, 1987

Figure C-13. Dissolved Oxygen and Temperature Measured Near SQN on June 23, 1987

Figure C-14. Percent Oxygen Saturation and pH Measured Near SQN on June 23, 1987

Figure C-15. Dissolved Oxygen and Temperature Measured Near SQN on July 1, 1987

Figure C-16. Percent Oxygen Saturation and pH Measured Near SQN on July 1, 1987.

Figure C-17. Dissolved Oxygen and Temperature Measured Near SQN on July 7, 1987

Figure C-18. Percent Oxygen Saturation and pH Measured Near SQN on July 7, 1987.

Figure C-19. Dissolved Oxygen and Temperature Measured Near SQN on July 14, 1987

Figure C-20. Percent Oxygen Saturation and pH Measured Near SQN on July 14, 1987

Figure C-21. Dissolved Oxygen and Temperature Measured Near SQN on July 21, 1987

Figure C-22. Percent Oxygen Saturation and pH Measured Near SQN on July 21, 1987

Figure C-23. Dissolved Oxygen and Temperature Measured Near SQW on July 28, 1987

Figure C-24. Percent Oxygen Saturation and pH Measured Near SQN on July 28, 1987

Figure C-25. Dissolved Oxygen and Temperature Measured Near SQN on July 28, 1987

Figure C-26. Percent Oxygen Saturation and pH Measured Near SQH on July 28, 1987

Figure C-27. Dissolved Oxygen and Temperature Measured Near SQN on August 11, 1987

Figure C-28. Percent Oxygen Saturation and pH Measured Near SQN on August 11, 1987

Figure C-29. Dissolved Oxygen and Temperature Measured Near SQN on August 18, 1987

Figure C-30. Percent Oxygen Saturation and pH Measured Near SQN on August 18, 1987

Figure C-31. Dissolved Oxygen and Temperature Measured Near ON on August 25, 1987

Figure C-32. Percent Oxygen Saturation and pH Measured Near SQN on August 25, 1987

Figure C-33. Dissolved Oxygen and Temperature Measured Near SQN on September 1, 1987

Figure C-34. Percent Oxygen Saturation and pH Measured Near SQN on September 1, 1987

Figure C-35. Dissolved Oxygen and Temperature Measured Near SQN on September 8, 1987

Figure C-36. Percent Oxygen Saturation and pH Measured Near SQN on September 8, 1987

Figure C-37. Dissolved Oxygen and Temperature Measured Near SQN on September 15, 1987

Figure C-38. Percent Oxygen Saturation and pH Measured Near SQW on September 15, 1987

Figure C-39. Dissolved Oxygen and Temperature Measured Near SQN on September 22, 1987

Figure C-40. Percent Oxygen Saturation and pH Measured Near SQN on September 22, 1987

Figure C-41. Dissolved Oxygen and Temperature Measured Near SQN on March 1, 1988

Figure C-42. Percent Oxygen Saturation and pH Measured Near SQN on March 1, 1988

Figure C-43. Dissolved Oxygen and Temperature Measured Near SQN on March 15, 1988

Figure C-44. Percent Oxygen Saturation and pH Measured Near SQN on March 15, 1988

Figure C-45. Dissolved Oxygen and Temperature Measured Near SQN on March 29, 1988

Figure C-46. Percent Oxygen Saturation and pH Measured Near SQN on March 29, 1988

Figure C-47. Dissolved Oxygen and Temperature Measured Near SQN on April 5, 1988

Figure C-48. Percent Oxygen Saturation and pH Measured Near SQN on April 5, 1988

Figure C-49. Dissolved Oxygen and Temperature Measured Near SQN on April 12, 1988

Figure C-51. Dissolved Oxygen and Temperature Measured Near SQN on April 19, 1988

Figure C-52. Percent Oxygen Saturation and pH Measured Near SQN on April 19, 1988

Figure C-53. Dissolved Oxygen and Temperature Measured Near SQN on April 26, 1988

Figure C-54. Percent Oxygen Saturation and pH Measured Near SQN on April 26, 1988

Figure C-55. Dissolved Oxygen and Temperature Measured Near SQN on May 3, 1988

Figure C-56. Percent Oxygen Saturation and pH Measured Near SQN on May 3, 1988

Figure C-57. Dissolved Oxygen and Temperature Measured Near SQN on May 10, 1988

Figure C-58. Percent Oxygen Saturation and pH Measured Near SQN on May 10, 1988

Figure C-59. Dissolved Oxygen and Temperature Measured Near SQN on April 5, 1989

Figure C-60. Percent Oxygen Saturation and pH Measured Near SQN on April 5, 1989

Figure C-61. Dissolved Oxygen and Temperature Measured Near SQN on April 19, 1989

Figure C-62. Percent Oxygen Saturation and pH Measured Near SQN on April 19, 1989

Figure C-63. Dissolved Oxygen and Temperature Measured Near SQN on May 3, 1989

Figure C-64. Percent Oxygen Saturation and pH Measured Near SQN on May 3, 1989

Figure C-65. Dissolved Oxygen and Temperature Measured Near SQN on May 17, 1989

Figure C-66. Percent Oxygen Saturation and pH Measured Near SQN on May 17, 1989

Figure C-67. Dissolved Oxygen and Temperature Measured Near SQN on May 31, 1989

Figure C-68. Percent Oxygen Saturation and pH Measured Near SQW on May 31, 1989

Figure C-69. Dissolved Oxygen and Temperature Measured Near SQN on June 14, 1989

Figure C-70. Percent Oxygen Saturation and pH Measured Near SQN on June 14, 1989

Figure C-71. Dissolved Oxygen and Temperature Measured Near SQN on June 28, 1989

Figure C-72. Percent Oxygen Saturation and pH Measured Near SQN on June 28, 1989

Figure C-73. Dissolved Oxygen and Temperature Measured Near SQN on July 12, 1989

Figure C-74. Percent Oxygen Saturation and pH Measured Near SQN on July 12, 1989

Figure C-75. Dissolved Oxygen and Temperature Measured Near SQN on July 26, 1989

Figure C-76. Percent Oxygen Saturation and pH Measured Near SQN on July 26, 1989

Figure C-77. Dissolved Oxygen and Temperature Measured Near SQN on August 9, 1989

Figure C-78. Percent Oxygen Saturation and pH Measured Near SQN on August 9, 1989

Figure C-79. Dissolved Oxygen and Temperature Measured Near SQN on August 22, 1989

Figure C-80. Percent Oxygen Saturation and pH Measured Near SQN on August 22, 1989

Figure C-81. Dissolved Oxygen and Temperature Measured Near SQN on September 5, 1989

Figure C-82. Percent Oxygen Saturation and pH Measured Near SQN on September 5, 1989

Figure C-83. Dissolved Oxygen and Temperature Measured Near SQN on September 19, 1989

Figure C-84. Percent Oxygen Saturation and pH Measured Near SQN on September 19, 1989

Figure C-85. Temperature Isotherms of Cross-Sections Near SQN Measured on April 1, 1987

Figure C-86. Temperature Isotherms of Cross-Sections Near SQN Measured on April 16, 1987

Figure C-87. Temperature Isotherms of Cross-Sections Near SQN Measured on April 29, 1987

Figure C-88. Temperature Isotherms of Cross-Sections Near SQN Measured on May 13, 1987

Figure C-89. Temperature Isotherms of Cross-Sections Near SQN Measured on May 27, 1987

Figure C-90. Temperature Isotherms of Cross-Sections Near SQN Measured on June 23, 1987

Figure C-91. Temperature Isotherms of Cross-Sections Near SQN Measured on July 1, 1987

Figure C-92. Temperature Isotherms of Cross-Sections Near SQN Measured on July 7, 1987

Figure C-93. Temperature Isotherms of Cross-Sections Near SQN Measured on July 07, 1987

Figure C-94. Temperature Isotherms of Cross-Sections Near SQN Measured on July 14, 1987

Figure C-95. Temperature Isotherms of Cross-Sections Near SQN Measured on July 21, 1987

Figure C-96. Temperature Isotherms of Cross-Sections Near SQN Measured on July 28, 1987

Figure C-97. Temperature Isotherms of Cross-Sections Near SQN Measured on August 4, 1987

Figure C-98. Temperature Isotherms of Cross-Sections Near SQN Measured on August 11, 1987

Figure C-99. Temperature Isotherms of Cross-Sections Near SQN Measured on August 18, 1987

Figure C-100. Temperature Isotherms of Cross-Sections Near SQN Measured on August 25, 1987

Figure C-101. Temperature Isotherms of Cross-Sections Near SQN Measured on September 1, 1987

Figure C-102. Temperature Isotherms of Cross-Sections Near SQN Measured on September 8, 1987

Figure C-103. Temperature Isotherms of Cross-Sections Near SQN Measured on September 15, 1987

Figure C-104. Temperature Isotherms of Cross-Sections Near SQN Measured on September 22, 1987

Figure C-105. Temperature Isotherms of Cross-Sections Near SQW Measured on March 1, 1988

Figure C-106. Temperature Isotherms of Cross-Sections Near SQN Measured on March 15, 1988

Figure C-107. Temperature Isotherms of Cross-Sections Near SQN Measured on March 29, 1988

Figure C-108. Temperature Isotherms of Cross-Sections Near SQN Measured on April 5, 1988

Figure C-109. Temperature Isotherms of Cross-Sections Near SQN Measured on April 12, 1988

Figure C-110. Temperature Isotherms of Cross-Sections Near SQN Measured on April 19, 1988

Figure C-111. Temperature Isotherms of Cross-Sections Near SQN Measured on April 26, 1988

Figure C-112. Temperature Isotherms of Cross-Sections Near SQN Measured on May 3, 1988

Figure C-113. Temperature Isotherms of Cross-Sections Near SQN Measured on May 10, 1988

Figure C-114. Temperature Isotherms of Cross-Sections Near SQN Measured on April 5, 1989

Figure C-115. Temperature Isotherms of Cross-Sections Near SQN Measured on April 19, 1989

Figure C-116. Temperature Isotherms of Cross-Sections Near SQN Measured on May 3, 1989

Figure C-117. Temperature Isotherms of Cross-Sections Near SQW Measured on May 17, 1989

Figure C-118. Temperature Isotherms of Cross-Sections Near SQN Measured on May 31, 1989

Figure C-119. Temperature Isotherms of Cross-Sections Near SQN Measured on June 14, 1989

Figure C-120. Temperature Isotherms of Cross-Sections Near SQN Measured on June 28, 1989

Figure C-121. Temperature Isotherms of Cross-Sections Near SQN Measured on July 12, 1989

Figure C-122. Temperature Isotherms of Cross-Sections Near SQN Measured on July 26, 1989

Figure C-123. Temperature Isotherms of Cross-Sections Near SQN Measured on August 9, 1989

Figure C-124. Temperature Isotherms of Cross-Sections Near SQN Measured on August 22, 1989

Figure C-125. Temperature Isotherms of Cross-Sections Near SQN Measured on September 5, 1989

Figure C-126. Temperature Isotherms of Cross-Sections Near SQN Measured on September 19, 1989

Figure C-127. Dissolved Oxygen Isopleths of Cross-Sections Near SQN Measured on April 1, 1987

Figure C-128. Dissolved Oxygen Isoleths of Cross-Sections Near SQN Measured on April 16, 1987

Figure C-129. Dissolved Oxygen Isopleths of Cross-Sections Near SQN Measured on April 29, 1987

Figure C-130. Dissolved Oxygen Isopleths of Cross-Sections Near SQN Measured on May 13, 1987

Figure C-131. Dissolved Oxygen Isopleths of Cross-Sections Near SQN Measured on May 27, 1987

Figure C-132. Dissolved Oxygen Isopleths of Cross-Sections Near SQN Measured on June 10, 1987

Figure C-133. Dissolved Oxygen Isopleths of Cross-Sections Near SQN Measured on June 23, 1987

Figure C-134. Dissolved Oxygen Isopleths of Cross-Sections Near SQN Measured on July 1, 1987

Figure C-135. Dissolved Oxygen Isopleths of Cross-Sections Near SQN Measured on July 7, 1987

Figure C-136. Dissolved Oxygen Isopleths of Cross-Sections Near SQW Measured on July 14, 1987

Figure C-137. Dissolved Oxygen Isopleths of Cross-Sections Near SQN Measured on July 21, 1987

Figure C-138. Dissolved Oxygen Isopleths of Cross-Sections Near SQN Measured on July 28, 1987

Figure C-139. Dissolved Oxygen Isopleths of Cross-Sections Near SQN Measured on August 4, 1987

Figure C-140. Dissolved Oxygen Isopleths of Cross-Sections Near SQN Measured on August 11, 1987

Figure C-141. Dissolved Oxygen Isopleths of Cross-Sections Near SQN Measured on August 18, 1987

Figure C-142. Dissolved Oxygen Isopleths of Cross-Sections Near SQN Measured on August 25, 1987

Figure C-143. Dissolved Oxygen Isopleths of Cross-Sections Near SQN Measured on September 1, 1987

Figure C-144. Dissolved Oxygen Isopleths of Cross-Sections Near SQN Measured on September 8, 1987

Figure C-145. Dissolved Oxygen Isopleths of Cross-Sections Near SQN Measured on September 15, 1987

Figure C-146. Dissolved Oxygen Isopleths of Cross-Sections Near SQM Measured on September 22, 1987

Figure C-147. Dissolved Oxygen Isopleths of Cross-Sections Near SQN Measured on March 1, 1988

Figure C-148. Dissolved Oxygen Isopleths of Cross-Sections Near SQN Measured on March 15, 1988

Figure C-149. Dissolved Oxygen Isopleths of Cross-Sections Near SQN Measured on March 29, 1988

Figure C-150. Dissolved Oxygen Isopleths of Cross-Sections Near SQW Measured on April 5, 1988

Figure C-151. Dissolved Oxygen Isopleths of Cross-Sections Near SQN Measured on April 12, 1988

Figure C-152. Dissolved Oxygen Isopleths of Cross-Sections Near SQN Measured on April 19, 1988

Figure C-153. Dissolved Oxygen Isopleths of Cross-Sections Near SQN Measured on April 26, 1988

Figure C-154. Dissolved Oxygen Isopleths of Cross-Sections Near SQN Measured on May 3, 1988

Figure C-155. Dissolved Oxygen Isopleths of Cross-Sections Near SQN Measured on May 10, 1988

Figure C-156. Dissolved Oxygen Isopleths of Cross-Sections Near SQN Measured on April 5, 1989

Figure C-157. Dissolved Oxygen Isopleths of Cross-Sections Near SQN Measured on April 19, 1989

Figure C-158. Dissolved Oxygen Isopleths of Cross-Sections Near SQN Measured on May 3, 1989

Figure C-159. Dissolved Oxygen Isopleths of Cross-Sections Near SQN Measured on May 17, 1989

Figure C-160. Dissolved Oxygen Isopleths of Cross-Sections Near SQN Measured on May 31, 1989

Figure C-161. Dissolved Oxygen Isopleths of Cross-Sections Near SQN Measured on June 14, 1989

Figure C-162. Dissolved Oxygen Isopleths of Cross-Sections Near SQN Measured on June 28, 1989

Figure C-163. Dissolved Oxygen Isopleths of Cross-Sections Near SQN Measured on July 12, 1989

Figure C-164. Dissolved Oxygen Isopleths of Cross-Sections Near SQN Measured on July 26, 1989

Figure C-165. Dissolved Oxygen Isopleths of Cross-Sections Near SQN Measured on August 9, 1989

Figure C-166. Dissolved Oxygen Isopleths of Cross-Sections Near SQN Measured on August 22, 1989

Figure C-167. Dissolved Oxygen Isopleths of Cross-Sections Near SQN Measured on September 5, 1989

Figure C-168. Dissolved Oxygen Isopleths of Cross-Sections Near SQN Measured on September 19, 1989

Figure C-169. pH Isopleths of Cross-Sections Near SQN Measured on April 1, 1987

Figure C-170. pH Isopleths of Cross-Sections Near SQN Measured on April 16, 1987

Figure C-171. pH Isopleths of Cross-Sections Near SQN Measured on April 29, 1987

Figure C-172. pH Isopleths of Cross-Sections Near SQN Measured on May 13, 1987

Figure C-173. pH Isopleths of Cross-Sections Near SQN Measured on May 27, 1987

Figure C-174. pH Isopleths of Cross-Sections Near SQN Measured on June 10, 1987

Figure C-175. pH Isopleths of Cross-Sections Near SQN Measured on June 23, 1987

Figure C-176. pH Isopleths of Cross-Sections Near SQN Measured on July 1, 1987

Figure C-177. pH Isopleths of Cross-Sections Near SQN Measured on July 7, 1987

Figure C-178. pH Isopleths of Cross-Sections Near SQN Measured on July 14, 1987

Figure C-179. pH Isopleths of Cross-Sections Near SQN Measured on July 21, 1987

Figure C-180. pH Isopleths of Cross-Sections Near SQN Measured on July 28, 1987

Figure C-181. pH Isopleths of Cross-Sections Near SQN Measured on August 4, 1987

Figure C-182. pH Isopleths of Cross-Sections Near SQN Measured on August 11, 1987

Figure C-183. pH Isopleths of Cross-Sections Near SQN Measured on August 18, 1987

Figure C-184. pH Isopleths of Cross-Sections Near SQN Measured on August 25, 1987

Figure C-185. pH Isopleths of Cross-Sections Near SQN Measured on September 1, 1987

Figure C-186. pH Isopleths of Cross-Sections Near SQN Measured on September 8, 1987

Figure C-187. pH Isopleths of Cross-Sections Near SQN Measured on September 15, 1987

Figure C-188. pH Isopleths of Cross-Sections Near SQN Measured on September 22, 1987

Figure C-189. pH Isopleths of Cross-Sections Near SQN Measured on March 1, 1988

Figure C-190. pH Isopleths of Cross-Sections Near SQN Measured on March 10, 1988

Figure C-191. pH Isopleths of Cross-Sections Near SQN Measured on March 29, 1988

Figure C-192. pH Isopleths of Cross-Sections Near SQN Measured on April 5, 1988

Figure C-193. pH Isopleths of Cross-Sections Near SQN Measured on April 12, 1988

Figure C-194. pH Isopleths of Cross-Sections Near SQN Measured on April 19, 1988

Figure C-195. pH Isopleths of Cross-Sections Near SQN Measured on April 26, 1988

Figure C-196. pH Isopleths of Cross-Sections Near SQN Measured on May 3, 1988

Figure C-197. pH Isopleths of Cross-Sections Near SQN Measured on May 10, 1988

Figure C-198. pH Isopleths of Cross-Sections Near SQN Measured on April 5, 1989

Figure C-199. pH Isopleths of Cross-Sections Near SQW Measured on April 19, 1989

Figure C-200. pH Isopleths of Cross-Sections Near SQN Measured on May 3, 1989

Figure C-201. pH Isopleths of Cross-Sections Near SQN Measured on May 17, 1989

Figure C-202. pH Isopleths of Cross-Sections Near SQN Measured on May 31, 1989

Figure C-203. pH Isopleths of Cross-Sections Near SQN Measured on June 14, 1989

Figure C-204. pH Isopleths of Cross-Sections Near SQN Measured on June 28, 1989

Figure C-205. pH Isopleths of Cross-Sections Near SQN Measured on July 12, 1989

Figure C-206. pH Isopleths of Cross-Sections Near SQN Measured on July 26, 1989

Figure C-207. pH Isopleths of Cross-Sections Near SQN Measured on August 9, 1989

Figure C-208. pH Isopleths of Cross-Sections Near SQN Measured on August 22, 1989

Figure C-209. pH Isopleths of Cross-Sections Near SQN Measured on September 5, 1989

Figure C-210. pH Isopleths of Cross-Sections Near SQN Measured on September 19, 1989

Dissolved Oxygen (mg/l)

Dissolved Oxygen (mg/l)

Delta Temperature (deg. C)

Figure C-211. Summary of DO Concentrations and Temperature Differentials Near SQN on April 1, 1987

Figure C-112. Summary of DO Concentrations and Temperature Differentials Near SQN on April 16, 1987

Dissolved Oxygen (mg/l)

Dissolved Oxygen (mg/l)

Delta Temperature (deg. C)

Figure C-213. Summary of DO Concentrations and Temperature Differentials Near SQN on April 29, 1987

Figure C-214. Summary of DO Concentrations and Temperature Differentials Near SQN on May 13, 1987

Dissolved Oxygen (mg/l)

Dissolved Oxygen (mg/l)

Delta Temperature (deg. C)

Figure C-215. Summary of DO Concentrations and Temperature Differentials Near SQN on May 27, 1987

Figure C-216. Summary of DO Concentrations and Temperature Differentials Near SQN on June 10, 1987

Figure C-217. Summary of DO Concentrations and Temperature Differentials Near SQN on June 23, 1987

Figure C-218. Summary of DO Concentrations and Temperature Differentials Near SQN on July 1, 1987

Figure C-219. Summary of DO Concentrations and Temperature Differentials Near SQN on July 7, 1987

Figure C-220. Summary of DO Concentrations and Temperature Differentials Near SQN on July 14, 1987

Dissolved Oxygen (mg/l)

Dissolved Oxygen (mg/l)

Delta Temperature (deg. C)

Figure C-221. Summary of DO Concentrations and Temperature Differentials Near SQN on July 21, 1987

Figure C-222. Summary of DO Concentrations and Temperature Differentials Near SQN on July 28, 1987

Figure C-223. Summary of DO Concentrations and Temperature Differentials Near SQN on August 4, 1987

Dissolved Oxygen (mg/l)

Dissolved Oxygen (mg/l)

Delta Temperature (deg. C)

Figure C-225. Summary of DO Concentrations and Temperature Differentials Near SQN on August 18, 1987

Figure C-226. Summary of DO Concentrations and Temperature Differentials Near SQN on August 25, 1987

Dissolved Oxygen (mg/l)

Dissolved Oxygen (mg/l)

Delta Temperature (deg. C)

Figure C-227. Summary of DO Concentrations and Temperature Differentials Near SQN on September 1, 1987

Figure C-228. Summary of DO Concentrations and Temperature Differentials Near SQN on September 8, 1987

Dissolved Oxygen (mg/l)

Dissolved Oxygen (mg/l)

Delta Temperature (deg. C)

Figure C-229. Summary of DO Concentrations and Temperature Differentials Near SQN on September 15, 1987

Figure C-230. Summary of DO Concentrations and Temperature Differentials Near SQN on September 22, 1987

Dissolved Oxygen (mg/l)

Dissolved Oxygen (mg/l)

Delta Temperature (deg. C)

Figure C-231. Summary of DO Concentrations and Temperature Differentials Near SQN on March 1, 1988

Figure C-232. Summary of DO Concentrations and Temperature Differentials Near SQN on March 15, 1988

Figure C-233. Summary of DO Concentrations and Temperature Differentials Near SQN on March 29, 1988

Figure C-234. Summary of DO Concentrations and Temperature Differentials Near SQN on April 5, 1988

Figure C-235. Summary of DO Concentrations and Temperature Differentials Near SQN on April 12, 1988

Figure C-236. Summary of DO Concentrations and Temperature Differentials Near SQN on April 19, 1988

Figure C-237. Summary of DO Concentrations and Temperature Differentials Near SQN on April 26, 1988

Figure C-238. Summary of DO Concentrations and Temperature Differentials Near SQN on May 3, 1988

Figure C-239. Summary of DO Concentrations and Temperature Differentials Near SQN on May 10, 1988

Figure C-240. Summary of DO Concentrations and Temperature Differentials Near SQN on April 5, 1988

Dissolved Oxygen (mg/l)

Dissolved Oxygen (mg/l)

Delta Temperature (deg. C)

Figure C-241. Summary of DO Concentrations and Temperature Differentials Near SQN on April 19, 1989

Figure C-242. Summary of DO Concentrations and Temperature Differentials Near SQN on May 3, 1989

Disolved Oxygen (mg/l)

Disolved Oxygen (mg/l)

Delta Temperature (deg. C)

Figure C-243. Summary of DO Concentrations and Temperature Differentials Near SQN on May 17, 1989

Figure C-244. Summary of DO Concentrations and Temperature Differentials Near SQN on May 31, 1989

Disolved Oxygen (mg/l)

Disolved Oxygen (mg/l)

Delta Temperature (deg. C)

Figure C-245. Summary of DO Concentrations and Temperature Differentials Near SQN on June 14, 1989

Figure C-246. Summary of DO Concentrations and Temperature Differentials Near SQN on June 28, 1989

Figure C-247. Summary of DO Concentrations and Temperature Differentials Near SQN on July 12, 1989

Figure C-248. Summary of DO Concentrations and Temperature Differentials Near SQN on July 26, 1989

Figure C-249. Summary of DO Concentrations and Temperature Differentials Near SQN on August 9, 1989

Figure C-250. Summary of DO Concentrations and Temperature Differentials Near SQN on August 22, 1989

Figure C-251. Summary of DO Concentrations and Temperature Differentials Near SQN on September 5, 1989

Figure C-252. Summary of DO Concentrations and Temperature Differentials Near SQN on September 19, 1989

APPENDIX D

DIEL RESERVOIR MEASUREMENTS OF TEMPERATURE,
DISSOLVED OXYGEN CONCENTRATIONS
AND pH

Figure D-1. Schedule of Sampling During the First Diel Survey

TRANSECT SAMPLING PERIODS

Figure D-2. Schedule of Sampling During the Second Diel Survey

IDEALIZED BATHYMETRY OF CHICKAMAUGA RESERVOIR NEAR SQN

SAMPLING LOCATIONS AND APPROXIMATE NAVIGATION CHANNEL

Figure D-3. Reservoir Bathymetry and Sampling Locations Near SQN

TEMPERATURE (C) IN MAIN CHANNEL

DISSOLVED OXYGEN (MG/L) IN MAIN CHANNEL

Figure D-4. Temperature and DO Isopleths from Main Channel for 8 a.m. to 4 p.m. on August 25, 1989

DISSOLVED OXYGEN (MG/L) AT 5 FT DEPTH

Figure D-5. Temperature and D0 Isopleths at 5 feet for 8 a.m. to 4 p.m. on August 25, 1989

TEMPERATURE (C) IN MAIN CHANNEL

DISSOLVED OXYGEN (MG/L) IN MAIN CHANNEL

Figure D-6. Temperature and DO Isopleths from Main Channel for 4 p.m. to 9 p.m. on August 25, 1989

TEMPERATURE (C) AT 5 FT DEPTH

DISSOLVED OXYGEN (MG/L) AT 5 FT DEPTH

Figure D-7. Temperature and DO Isopleths at 5 feet for 4 p.m. to 9 p.m. on August 25, 1989

TEMPERATURE (C) IN MAIN CHANNEL

DISSOLVED OXYGEN (MG/L) IN MAIN CHANNEL

Figure D-8. Temperature and DO Isopleths from Main Channel for 9 p.m. to 12 midnight on August 25, 1989

TEMPERATURE (C) AT 5 FT DEPTH

DISSOLVED OXYGEN (MG/L) AT 5 FT DEPTH

Figure D-9. Temperature and DO Isopleths at 5 feet for 9 p.m. to 12 midnight on August 25, 1989

TEMPERATURE (C) IN MAIN CHANNEL

DISSOLVED OXYGEN (MG/L) IN MAIN CHANNEL

Figure D-10. Temperature and DO Isotherms from Main Channel for 12 midnight to 4 a.m. on August 26, 1989

DISSOLVED OXYGEN (MG/L) AT 5 FT DEPTH

Figure D-11. Temperature and D0 Isopleths at 5 feet for 12 midnight to 4 a.m. on August 26, 1989

TEMPERATURE (C) IN MAIN CHANNEL

DISSOLVED OXYGEN (MG/L) IN MAIN CHANNEL

Figure D-12. Temperature and DO Isoleths from Main Channel for 4 a.m. to 8 a.m. on August 26, 1989.

TEMPERATURE (C) AT 5 FT DEPTH

DISSOLVED OXYGEN (MG/L) AT 5 FT DEPTH

Figure D-13. Temperature and DO Isopleths at 5 feet for 4 a.m. to 8 a.m. on August 26, 1989

TEMPERATURE (C) IN MAIN CHANNEL

DISSOLVED OXYGEN (MG/L) IN MAIN CHANNEL

Figure D-14. Temperature and DO Isopleths in Main Channel for 8 a.m. to 12 noon on August 26, 1989

TEMPERATURE (C) AT 5 FT DEPTH

DISSOLVED OXYGEN (MG/L) AT 5 FT DEPTH

Figure D-15. Temperature and DO Isopleths at 5 feet for 8 a.m. to 12 noon on August 26, 1989

TEMPERATURE (C) IN MAIN CHANNEL

DISSOLVED OXYGEN (MG/L) IN MAIN CHANNEL

Figure D-16. Temperature and DO Isopleths from Main Channel for 12 noon to 3 p.m. on August 26, 1989

TEMPERATURE (C) AT 5 FT DEPTH

DISSOLVED OXYGEN (MG/L) AT 5 FT DEPTH

Figure D-17. Temperature and DO Isopleths at 5 feet for 12 noon to 3 p.m. on August 26, 1989

TEMPERATURE (C) IN MAIN CHANNEL

DISSOLVED OXYGEN (MG/L) IN MAIN CHANNEL

Figure D-18. Temperature and DO Isopleths from Main Channel for 12 midnight to 4 a.m. on August 27, 1989

TEMPERATURE (C) AT 5 FT DEPTH

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DISSOLVED OXYGEN (MG/L) AT 5 FT DEPTH

Figure 3-280. Temperature and DO Isoleths at 5 feet for 4 a.m. to 8 a.m. on August 27, 1989

TEMPERATURE (C) IN MAIN CHANNEL

DISSOLVED OXYGEN (MG/L) IN MAIN CHANNEL

Figure D-20. Temperature and DO Isopleths from Main Channel for 4 a.m. to 8 a.m. on August 27, 1989

TEMPERATURE (C) AT 5 FT DEPTH

DISSOLVED OXYGEN (MG/L) AT 5 FT DEPTH

Figure D-21. Temperature and DO Isopleths at 5 feet for 4 a.m. to 8 a.m. on August 27, 1989

TEMPERATURE (C) IN MAIN CHANNEL

DISSOLVED OXYGEN (MG/L) IN MAIN CHANNEL

Figure D-22. Temperature and DO Isopleths from Main Channel for 8 a.m. to 12 noon on September 8, 1989

TEMPERATURE (C) AT 5 FT DEPTH

DISSOLVED OXYGEN (MG/L) AT 5 FT DEPTH

Figure D-23. Temperature and DO Isopleths at 5 feet for 8 a.m. to 12 noon on September 8, 1989

TEMPERATURE (C) IN MAIN CHANNEL

DISSOLVED OXYGEN (MG/L) IN MAIN CHANNEL

Figure D-24. Temperature and DO Isoleths from Main Channel for 12 noon to 4 p.m. on September 8, 1989

TEMPERATURE (C) AT 5 FT DEPTH

DISSOLVED OXYGEN (MG/L) AT 5 FT DEPTH

Figure D-25. Temperature and DO Isopleths at 5 feet for 12 noon to 4 p.m. on September 8, 1989

TEMPERATURE (C) IN MAIN CHANNEL

DISSOLVED OXYGEN (MG/L) IN MAIN CHANNEL

Figure D-26. Temperature and DO Isopleths from Main Channel for 4 p.m. to 8 p.m. on September 8, 1989

TEMPERATURE (C) AT 5 FT DEPTH

DISSOLVED OXYGEN (MG/L) AT 5 FT DEPTH

Figure D-27. Temperature and DO Isopleths at 5 feet for 4 p.m. to 8 p.m. on September 8, 1989

TEMPERATURE (C) IN MAIN CHANNEL

DISSOLVED OXYGEN (MG/L) IN MAIN CHANNEL

Figure D-28. Temperature and DO Isopleths from Main Channel for 8 p.m. to 12 midnight on September 8, 1989

TEMPERATURE (C) AT 5 FT DEPTH

DISSOLVED OXYGEN (MG/L) AT 5 FT DEPTH

Figure D-29. Temperature and DO Isopleths at 5 feet for 8 p.m. to 12 midnight on September 8, 1989

TEMPERATURE (C) IN MAIN CHANNEL

DISSOLVED OXYGEN (MG/L) IN MAIN CHANNEL

Figure D-30. Temperature and DO Isopleths from Main Channel for 12 midnight to 4 a.m. on September 9, 1989

TEMPERATURE (C) AT 5 FT DEPTH

DISSOLVED OXYGEN (MG/L) AT 5 FT DEPTH

Figure D-31. Temperature and DO Isopleths at 5 feet for 12 midnight to 4 a.m. on September 9, 1989

TEMPERATURE (C) IN MAIN CHANNEL

DISSOLVED OXYGEN (MG/L) IN MAIN CHANNEL

Figure D-32. Temperature and DO Isopleths from Main Channel for 4 a.m. to 8 a.m. on September 9, 1989

TEMPERATURE (C) AT 5 FT DEPTH

DISSOLVED OXYGEN (MG/L) AT 5 FT DEPTH

Figure D-33. Temperature and DO Isopleths at 5 feet for 4 a.m. to 8 a.m. on September 9, 1989

TEMPERATURE (C) IN MAIN CHANNEL

DISSOLVED OXYGEN (MG/L) IN MAIN CHANNEL

Figure D-34. Temperature and DO Isoleths from Main Channel for 8 a.m. to 12 noon on September 9, 1989

TEMPERATURE (C) AT 5 FT DEPTH

DISSOLVED OXYGEN (MG/L) AT 5 FT DEPTH

Figure D-35. Temperature and DO Isopleths at 5 feet for 8 a.m. to 12 noon on September 9, 1989

TEMPERATURE (C) IN MAIN CHANNEL

DISSOLVED OXYGEN (MG/L) IN MAIN CHANNEL

Figure D-36. Temperature and DO Isopleths from Main Channel for 12 noon to 4 p.m. on September 9, 1989

TEMPERATURE (C) AT 5 FT DEPTH

DISSOLVED OXYGEN (MG/L) AT 5 FT DEPTH

Figure D-37. Temperature and DO Isopleths at 5 feet for 12 noon to 4 p.m. on September 9, 1989

TEMPERATURE (C) IN MAIN CHANNEL

DISSOLVED OXYGEN (MG/L) IN MAIN CHANNEL

Figure D-38. Temperature and DO Isopleths from Main Channel for 4 p.m. to 8 p.m. on September 9, 1989

TEMPERATURE (C) AT 5 FT DEPTH

DISSOLVED OXYGEN (MG/L) AT 5 FT DEPTH

Figure D-39. Temperature and DO Isopleths at 5 feet for 4 p.m. to 8 p.m. on September 9, 1989

TEMPERATURE (C) IN MAIN CHANNEL

DISSOLVED OXYGEN (MG/L) IN MAIN CHANNEL

Figure D-40. Temperature and DO Isopleths from Main Channel for 8 p.m. to 12 midnight on September 9, 1989

TEMPERATURE (C) AT 5 FT DEPTH

DISSOLVED OXYGEN (MG/L) AT 5 FT DEPTH

Figure D-41. Temperature and DO Isopleths at 5 feet for 8 p.m. to 12 midnight on September 9, 1989

TEMPERATURE (C) IN MAIN CHANNEL

DISSOLVED OXYGEN (MG/L) IN MAIN CHANNEL

Figure D-42. Temperature and DO Isoleths from Main Channel for 12 midnight to 4 a.m. on September 10, 1989

TEMPERATURE (C) AT 5 FT DEPTH

DISSOLVED OXYGEN (MG/L) AT 5 FT DEPTH

Figure D-43. Temperature and DO Isopleths at 5 feet for 12 midnight to 4 a.m. on September 10, 1989

TEMPERATURE (C) IN MAIN CHANNEL

DISSOLVED OXYGEN (MG/L) IN MAIN CHANNEL

Figure D-44. Temperature and DO Isopleths from Main Channel for 4 a.m. to 8 a.m. on September 10, 1989

TEMPERATURE (C) AT 5 FT DEPTH

DISSOLVED OXYGEN (MG/L) AT 5 FT DEPTH

Figure D-45. Temperature and DO Isopleths at 5 feet for 4 a.m. to 8 a.m. on September 10, 1989

TRM 481.4 - 25% HORIZONTAL LOCATION

TRM 481.4 - 50% HORIZONTAL LOCATION

TRM 481.4 - 75% HORIZONTAL LOCATION

Figure D-46. Temperature Isotherms at TRM 481.4 of Survey 1

TRM 481.4 - 25% HORIZONTAL LOCATION

TRM 481.4 - 50% HORIZONTAL LOCATION

TRM 481.4 - 75% HORIZONTAL LOCATION

Figure D-47. Temperature Isotherms at TRM 481.4 of Survey 2

TRM 482.4 - 30% HORIZONTAL LOCATION

TRM 482.4 - 55% HORIZONTAL LOCATION

TRM 482.4 - 80% HORIZONTAL LOCATION

Figure D-48. Temperature Isotherms at TRM 482.4 of Survey 1

TRM 482.4 - 30% HORIZONTAL LOCATION

TRM 482.4 - 55% HORIZONTAL LOCATION

TRM 482.4 - 80% HORIZONTAL LOCATION

Figure D-49. Temperature Isotherms at TRM 482.4 of Survey 2

TRM 482.9 - 20% HORIZONTAL LOCATION

TRM 482.9 - 50% HORIZONTAL LOCATION

TRM 482.9 - 80% HORIZONTAL LOCATION

Figure D-50. Temperature Isotherms at TRM 482.9 of Survey 1

TRM 482.9 - 20% HORIZONTAL LOCATION

TRM 482.9 - 50% HORIZONTAL LOCATION

TRM 482.9 - 80% HORIZONTAL LOCATION

Figure D-51. Temperature Isotherms at TRM 482.9 of Survey 2

TRM 483.4 - 17% HORIZONTAL LOCATION

TRM 483.4 - 40% HORIZONTAL LOCATION

TRM 483.4 - 75% HORIZONTAL LOCATION

Figure D-52. Temperature Isotherms at TRM 483.4 of Survey 1

TRM 483.4 - 17% HORIZONTAL LOCATION

TRM 483.4 - 40% HORIZONTAL LOCATION

TRM 483.4 - 75% HORIZONTAL LOCATION

Figure D-3. Temperature Isotherms at TRM 483.4 of Survey 2

TRM 483.55 - 30% HORIZONTAL LOCATION

TRM 483.55 - 60% HORIZONTAL LOCATION

TRM 483.55 - 90% HORIZONTAL LOCATION

Figure D-54. Temperature Isotherms at TRM 483.55 of Survey 1

TRM 483.55 - 30% HORIZONTAL LOCATION

TRM 483.55 - 60% HORIZONTAL LOCATION

TRM 483.55 - 90% HORIZONTAL LOCATION

Figure D-55. Temperature Isotherms at TRM 483.55 of Survey 2

TRM 483.65 - 30% HORIZONTAL LOCATION

TRM 483.55 - 30% HORIZONTAL LOCATION

TRM 483.65 - 90% HORIZONTAL LOCATION

Figure D-56. Temperature Isotherms at TRM 483.65 of Survey 1

TRM 483.65 - 30% HORIZONTAL LOCATION

TRM 483.65 - 60% HORIZONTAL LOCATION

TRM 483.65 - 90% HORIZONTAL LOCATION

Figure D-57. Temperature Isotherms at TRM 483.65 of Survey 2

TRM 484.1 - 25% HORIZONTAL LOCATION

TRM 484.1 - 50% HORIZONTAL LOCATION

TRM 484.1 - 75% HORIZONTAL LOCATION

Figure D-58. Temperature Isotherms at TRM 484.1 of Survey 1

TRM 484.1 - 25% HORIZONTAL LOCATION

TRM 484.1 - 50% HORIZONTAL LOCATION

TRM 484.1 - 75% HORIZONTAL LOCATION

Figure D-59. Temperature Isotherms at TRM 484.1 of Survey 2

TRM 484.7 - 30% HORIZONTAL LOCATION

TRM 484.7 - 60% HORIZONTAL LOCATION

TRM 484.7 - 80% HORIZONTAL LOCATION

Figure D-60. Temperature Isotherms at TRM 484.7 of Survey 1

TRM 484.7 - 30% HORIZONTAL LOCATION

TRM 484.7 - 60% HORIZONTAL LOCATION

TRM 484.7 - 80% HORIZONTAL LOCATION

Figure D-61. Temperature Isotherms at TRM 484.7 of Survey 2

TRM 481.4 - 25% HORIZONTAL LOCATION

TRM 481.4 - 50% HORIZONTAL LOCATION

TRM 481.4 - 75% HORIZONTAL LOCATION

Figure D-62. Dissolved Oxygen Isopleths at TRM 481.4 of Survey 1

TRM 481.4 - 25% HORIZONTAL LOCATION

TRM 481.4 - 50% HORIZONTAL LOCATION

TRM 481.4 - 75% HORIZONTAL LOCATION

Figure D-63. Dissolved Oxygen Isopleths at TRM 481.4 of Survey 2

TRM 482.4 - 30% HORIZONTAL LOCATION

TRM 482.4 - 55% HORIZONTAL LOCATION

TRM 482.4 - 80% HORIZONTAL LOCATION

Figure D-64. Dissolved Oxygen Isopleths at TRM 482.4 of Survey 1

TRM 482.4 - 30% HORIZONTAL LOCATION

TRM 482.4 - 55% HORIZONTAL LOCATION

TRM 482.4 - 80% HORIZONTAL LOCATION

Figure D-65. Dissolved Oxygen Isopleths at TRM 482.4 of Survey 2

TRM 482.9 - 20% HORIZONTAL LOCATION

TRM 482.9 - 50% HORIZONTAL LOCATION

TRM 482.9 - 80% HORIZONTAL LOCATION

Figure D-66. Dissolved Oxygen Isopleths at TRM 482.9 of Survey 1

TRM 482.9 - 20% HORIZONTAL LOCATION

TRM 482.9 - 50% HORIZONTAL LOCATION

TRM 482.9 - 80% HORIZONTAL LOCATION

Figure D-67. Dissolved Oxygen Isopleths at TRM 482.9 of Survey 2

TRM 483.4 - 17% HORIZONTAL LOCATION

TRM 483.4 - 40% HORIZONTAL LOCATION

TRM 483.4 - 75% HORIZONTAL LOCATION

Figure D-68. Dissolved Oxygen Isopleths at TRM 483.4 of Survey 1

TRM 483.4 - 17% HORIZONTAL LOCATION

TRM 483.4 - 40% HORIZONTAL LOCATION

TRM 483.4 - 75% HORIZONTAL LOCATION

Figure D-69. Dissolved Oxygen Isopleths at TRM 483.4 of Survey 2

TRM 483.55 - 30% HORIZONTAL LOCATION

TRM 483.55 - 60% HORIZONTAL LOCATION

TRM 483.55 - 90% HORIZONTAL LOCATION

Figure D-70. Dissolved Oxygen Isopleths at TRM 483.55 of Survey 1

TRM 483.55 - 30% HORIZONTAL LOCATION

TRM 483.55 - 60% HORIZONTAL LOCATION

TRM 483.55 - 90% HORIZONTAL LOCATION

Figure D-71. Dissolved Oxygen Isopleths at TRM 483.55 of Survey 2

TRM 483.65 - 30% HORIZONTAL LOCATION

TRM 483.65 - 60% HORIZONTAL LOCATION

TRM 483.65 - 90% HORIZONTAL LOCATION

Figure D-72. Dissolved Oxygen Isopleths at TRM 483.65 of Survey 1

TRM 483.65 - 30% HORIZONTAL LOCATION

TRM 483.65 - 60% HORIZONTAL LOCATION

TRM 483.65 - 90% HORIZONTAL LOCATION

Figure D-73. Dissolved Oxygen Isopleths at TRM 483.65 of Survey 2

TRM 484.1 - 25% HORIZONTAL LOCATION

TRM 484.1 - 50% HORIZONTAL LOCATION

TRM 484.1 - 75% HORIZONTAL LOCATION

Figure D-74. Dissolved Oxygen Isopleths at TRM 484.1 of Survey 1

TRM 484.1 - 25% HORIZONTAL LOCATION

TRM 484.1 - 50% HORIZONTAL LOCATION

TRM 484.1 - 75% HORIZONTAL LOCATION

Figure D-75. Dissolved Oxygen Isopleths at TRM 484.1 of Survey 2

TRM 484.7 - 30% HORIZONTAL LOCATION

TRM 484.7 - 60% HORIZONTAL LOCATION

TRM 484.7 - 80% HORIZONTAL LOCATION

Figure D-76. Dissolved Oxygen Isopleths at TRM 484.7 of Survey 1

TRM 484.7 - 30% HORIZONTAL LOCATION

TRM 484.7 - 60% HORIZONTAL LOCATION

TRM 484.7 - 80% HORIZONTAL LOCATION

Figure D-77. Dissolved Oxygen Isopleths at TRM 484.7 of Survey 2

TRM 481.4 - 25% HORIZONTAL LOCATION

TRM 481.4 - 50% HORIZONTAL LOCATION

TRM 481.4 - 75% HORIZONTAL LOCATION

Figure D-78. pH Isopleths at TRM 481.4 of Survey 1

TRM 481.4 - 25% HORIZONTAL LOCATION

TRM 481.4 - 50% HORIZONTAL LOCATION

TRM 481.4 - 75% HORIZONTAL LOCATION

Figure D-79. pH Isopleths at TRM 481.4 of Survey 2

TRM 482.4 - 30% HORIZONTAL LOCATION

TRM 482.4 - 55% HORIZONTAL LOCATION

TRM 482.4 - 80% HORIZONTAL LOCATION

Figure D-80. pH Isopleths at TRM 482.4 of Survey 1

TRM 482.4 - 30% HORIZONTAL LOCATION

TRM 482.4 - 55% HORIZONTAL LOCATION

TRM 482.4 - 80% HORIZONTAL LOCATION

Figure D-81. pH Isopleths at TRM 482.4 of Survey 2

TRM 482.9 - 20% HORIZONTAL LOCATION

TRM 482.9 - 50% HORIZONTAL LOCATION

TRM 482.9 - 80% HORIZONTAL LOCATION

Figure D-82. pH Isopleths at TRM 482.9 of Survey 1

TRM 482.9 - 20% HORIZONTAL LOCATION

TRM 482.9 - 50% HORIZONTAL LOCATION

TRM 482.9 - 80% HORIZONTAL LOCATION

Figure D-83. pH Isopleths at TRM 482.9 of Survey 2

TRM 483.4 - 17% HORIZONTAL LOCATION

TRM 483.4 - 40% HORIZONTAL LOCATION

TRM 483.4 - 75% HORIZONTAL LOCATION

Figure D-84. pH Isopleths at TRM 483.4 of Survey 1

TRM 483.4 - 17% HORIZONTAL LOCATION

TRM 483.4 - 40% HORIZONTAL LOCATION

TRM 483.4 - 75% HORIZONTAL LOCATION

Figure D-85. pH Isopleths at TRM 483.4 of Survey 2

TRM 483.55 - 30% HORIZONTAL LOCATION

TRM 483.55 - 60% HORIZONTAL LOCATION

TRM 483.55 - 90% HORIZONTAL LOCATION

Figure D-86. pH Isopleths at TRM 483.55 of Survey 1

TRM 483.55 - 30% HORIZONTAL LOCATION

TRM 483.55 - 60% HORIZONTAL LOCATION

TRM 483.55 - 90% HORIZONTAL LOCATION

Figure D-87. pH Isopleths at TRM 483.55 of Survey 2

TRM 483.65 - 30% HORIZONTAL LOCATION

TRM 483.65 - 60% HORIZONTAL LOCATION

TRM 483.65 - 80% HORIZONTAL LOCATION

Figure D-88. pH Isopleths at TRM 483.65 of Survey 1

TRM 483.65 - 30% HORIZONTAL LOCATION

TRM 483.65 - 60% HORIZONTAL LOCATION

TRM 483.65 - 90% HORIZONTAL LOCATION

Figure D-89. pH Isopleths at TRM 483.65 of Survey 2

TRM 484.1 - 25% HORIZONTAL LOCATION

TRM 484.1 - 50% HORIZONTAL LOCATION

TRM 484.1 - 75% HORIZONTAL LOCATION

Figure D-90. pH Isopleths at TRM 484.1 of Survey 1

TRM 484.1 - 25% HORIZONTAL LOCATION

TRM 484.1 - 50% HORIZONTAL LOCATION

TRM 484.1 - 75% HORIZONTAL LOCATION

Figure D-91. pH Isopleths at TRM 484.1 of Survey 2

TRM 484.7 - 30% HORIZONTAL LOCATION

TRM 484.7 - 60% HORIZONTAL LOCATION

TRM 484.7 - 80% HORIZONTAL LOCATION

Figure D-92. pH Isopleths at TRM 484.7 of Survey 1

TRM 484.7 - 30% HORIZONTAL LOCATION

TRM 484.7 - 60% HORIZONTAL LOCATION

TRM 484.7 - 80% HORIZONTAL LOCATION

Figure D-93. pH Isopleths at TRM 484.7 of Survey 2

APPENDIX E

CHICKAMAUGA RESERVOIR FLUOROMETRY MEASUREMENTS

CHICKAMAUGA RESERVOIR FLUOROMETRY STUDIES
APRIL 1987-MAY 1988

1.0 Introduction

Two of the objectives of the investigation of the impact of SQN on DO levels in Chickamauga Reservoir ("the DO Study") were (1) to better define the extent and duration of the redistribution of DO in the reservoir below the SQN discharge, and (2) to better understand the role of the underwater dam in the mixing process. To achieve these objectives, the DO in the vicinity of SQN is being evaluated in terms of the overall DO regime in Chickamauga Reservoir. An important factor in the oxygen dynamics of any reservoir is the amount and distribution of phytoplankton. Measurements of algal chlorophyll fluorescence were included in the DO study workplan as a relatively quick and easily accomplished estimate of phytoplankton abundance, horizontal and vertical distribution, and (through use of the Fluorescence Response Index [FRI]) physiological condition. This information is useful from the overall reservoir perspective and for the determination of mixing patterns in the vicinity of the SQN diffuser discharge. It will also be useful as an indicator of the effects of plant heat load in altering the rates of temperature-dependent biochemical processes that affect DO (photosynthesis and respiration).

2.0 Materials and Methods

Samples for analysis of chlorophyll fluorescence were collected every two weeks beginning April 1, 1987, from midchannel at the stations shown in table 4-1. Samples were taken from the surface, 1 m, 1.5 m, 3.0 m, and at subsequent 2-m intervals to

the bottom, corresponding to the the depth intervals for Hydrolab measurements taken at these same stations each day. One middepth sample only was collected from the TRM 529.9 station just below Watts Bar Dam.

The samples were taken with a nonmetallic Kemmerer water sampler. All samples were collected between 8 a.m. and 12 noon EDT. Immediately after collection, the samples were placed in dark boxes (ice chests without ice) for dark adaptation. A sample for spectrophotometric analysis of chlorophyll was collected with every tenth sample. Samples were picked up by couriers at various points along the length of the reservoir and transported back to the Wrinkle Building where they were analyzed in the same order as they were collected. In general, all samples were analyzed within 2-5 hr of collection.

Fluorometric analysis was performed using a Turner Designs Model 10 Fluorometer equipped with the 10-040 chlorophyll accessory kit, which includes the proper light source and optical filters for in vivo measurement of chlorophyll fluorescence.

A portion of the first sample in each station set was filtered through a Whatman GF/C glass microfiber filter, and the filtrate was used to zero the fluorometer to account for dissolved fluorescence. Fluorescence was then measured on two 25 ml aliquots from each sample. The first (F) was untreated, the second (F_D) was treated with 1 ml of a 10^{-4} M solution of 1 (3, 4-dichlorophenyl)-1, 1-dimethylurea (DCMU), an inhibitor of noncyclic photosynthetic

election transport. Readings were taken for F_D after two minutes contact time. This treatment results in maximal chlorophyll emission. An FRI, $FRI = \frac{F_D - F}{F_D}$, was calculated for each sample (Cullen and Renger, 1979).

3.0 Results and Discussion

This report covers the 32 biweekly surveys conducted between April 1, 1987 and May 10, 1988. Plots of raw fluorescence showing the spread between maximum and minimum fluorescence readings at each station are given in figures E-1 through E-64. These show at a glance relative amounts and stratification patterns of phytoplankton throughout the reservoir during the entire year. The general pattern through time is quite consistent and conforms with expectations. There are generally high fluorescence readings throughout the water column in April, indicating high productivity and complete vertical mixing. In May, stratification begins to develop, with higher fluorescence near the surface and decreasing amounts toward the bottom. This pattern remained essentially unchanged through early August but, by the beginning of September, fluorescence levels dropped to uniformly low levels throughout the reservoir. This may be a reflection of low nutrient input because of the lack of rainfall and runoff in the watershed. With a few scattered exceptions, that pattern of very low fluorescence persisted through December.

In early January, a bloom occurred that resulted in high fluorescence levels throughout the water column particularly in the

downstream reaches of the reservoir. Stratification of fluorescence occurred in late March and persisted albeit with considerable fluctuation in the fluorescence maxima through the last survey in early May 1988. The diffuser and underwater dam at SQN did not appear to have a significant effect on the vertical distribution of phytoplankton in the absence of a heated discharge. Certainly the Sequoyah discharge did not result in a breakdown of stratification. However, during the May through August 1987 and March through May 1988 periods, the spread between maximum and minimum chlorophyll fluorescence at the station just downstream from the diffusers did appear to be consistently less than the spread at the stations just upstream.

FRI is theoretically a biomass-independent indicator of the average physiological state of a phytoplankton population. However, since FRI expresses the difference between the fluorescence readings of the treated and untreated samples as a percentage of the treated sample, at very low fluorescence levels even small inconsistencies in readings can affect the values dramatically. Therefore, at low levels of raw fluorescence, FRI values should be interpreted more cautiously than at higher levels.

The patterns of FRI observed in this study were for the most part quite consistent except when fluorescence levels were very low (even numbered figures E-2 through E-64). The first survey showed mean FRI values between 0.57 and 0.66, indicating a population perhaps in transition from cold to warmer water species. The second

showed FRI values between 0.67 and 0.74, indicating high levels of vigorously growing phytoplankton throughout the reservoir. Mean FRI gradually decreased as stratification set in and remained quite stable at 0.58 to 0.62 throughout the period of stratification. The error bars (plus or minus one standard deviation from the mean) on the graphs generally widened during stratification. In this case, these bars do not indicate error, but reflect the fact that the variation in FRI in the water column was greater during stratification, when vigorously growing algae are in the photic zone and those at greater depths are generally senescent cells.

Overall, the lowest FRI values (0.56-0.60) were seen in August when phytoplankton levels in the reservoir declined dramatically. From September 1 through December 22, FRI values tended to be quite erratic, coincident with very low fluorescence readings.

The FRI values observed in Chickamauga Reservoir compare favorably with those observed by other investigators. Blasco and Dexter (1972) reported FRI values from near zero in severely nitrogen-depleted algal cultures to above 0.70 in actively growing cultures. Kimmel and White (undated) observed an FRI range of 0.11 to 0.68 in southern Oklahoma reservoirs and ponds.

Studies reported in the literature (summarized by Cox, 1984) show that in vivo fluorescence is not a reliable indicator of extractable chlorophyll a concentration. The ratio of fluorescence to chlorophyll varies with species composition, previous light history, nutrient stress, toxicity, and temperature and shows a diel rhythm.

Some workers (Kimmel, personal communication) have shown that extraction and spectrophotometric analysis of a portion of the samples collected from a given water body on a given day can provide the basis for using fluorescence to estimate chlorophyll concentrations on that day. Attempts to correlate extractable chlorophyll a with fluorescence measurements during this study met with mixed results (table E-1). Correlation coefficients varied from -0.16 to 0.95. There does not seem to be any easy explanation for these results. However, the fact that fair to excellent correlations were found in a majority of the surveys (11 of 16) at least supports the notion that fluorescence is often a reasonably good indicator of absolute chlorophyll concentration. The two surveys showing the lowest correlations (June 23 and July 9) were bracketed by surveys showing very good correlations. Yet, through that entire period, the abundance and distribution patterns shown by the fluorescence data were very consistent. This suggests that the lack of correlation could be merely apparent and caused by problems in the chlorophyll extraction and analysis or other unknown factors.

The data provided by this study reveal other interesting and possibly significant facts. For example, during May, when the algal distribution patterns began showing significant stratification, the fluorescence maxima measured at all but the most upstream stations were at a depth of 3 to 7 m. After stratification was firmly established, the maxima were near the surface (0.3 to 1.5 m).

Fluorescence measurements, even if there is some question about their use as an absolute biomass indicator, are particularly well suited for studies such as this where information is needed on vertical and horizontal patterns over time. The extent of vertical mixing is immediately apparent and after restart at SQN the data should be very useful in showing the effects of the heated discharge on the vertical distribution of the phytoplankton.

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Table E-1. Correlation Coefficients (r) for Raw Fluorescence
Extractable Chlorophyll a, Chickamauga Reservoir,
April-October, 1987^a

Sample date	Correlation coefficients (r)
04-01-87	0.75
04-16-87	0.07
04-29	0.76
05-13	0.70
05-27	0.88
06-10	0.92
06-23	-0.05
07-07	-0.16
07-21	0.95
08-04	0.34
08-18	0.92
09-01	0.84
09-15	0.92
09-29	0.62
10-13	0.48
10-27	0.27

a. Based on spectrophotometric analysis of approximately 10 percent of total samples collected (14 of 130-140 samples each survey).

Appendix Figure E-2
Mean Algal Fluorescence Response
Indices in Chickamauga Reservoir
April 1, 1987

Appendix Figure E-1
Distribution of Chlorophyll
Fluorescence in Chickamauga
Reservoir April 1, 1987

Appendix Figure E-3
Distribution of Chlorophyll
Fluorescence in Chickamauga
Reservoir April 16, 1987

Appendix Figure E-4
Mean Algal Fluorescence Response
Indices in Chickamauga Reservoir
April 16, 1987

Appendix Figure E-6
 Mean Algal Fluorescence Response
 Indices in Chickamauga Reservoir
 April 29, 1987

Appendix Figure E-5
 Distribution of Chlorophyll
 Fluorescence in Chickamauga
 Reservoir April 29, 1987

Appendix Figure E-7
Distribution of Chlorophyll
Fluorescence in Chickamauga
Reservoir May 13, 1987

Appendix Figure E-8
Mean Algal Fluorescence Response
Indices in Chickamauga Reservoir
May 13, 1987

Appendix Figure E-10
 Mean Algal Fluorescence Response
 Indices in Chickamauga Reservoir
 May 27, 1987

Appendix Figure E-9
 Distribution of Chlorophyll
 Fluorescence in Chickamauga
 Reservoir May 27, 1987

Appendix Figure E-11
Distribution of Chlorophyll
Fluorescence in Chickamauga
Reservoir June 10, 1987

Appendix Figure E-12
Mean Algal Fluorescence Response
Indices in Chickamauga Reservoir
June 10, 1987

Appendix Figure E-14
 Mean Algal Fluorescence Response
 Indices in Chickamauga Reservoir
 June 23, 1987

Appendix Figure E-13
 Distribution of Chlorophyll
 Fluorescence in Chickamauga
 Reservoir June 23, 1987

Appendix Figure E-15
Distribution of Chlorophyll
Fluorescence in Chickamauga
Reservoir July 7, 1987

Appendix Figure E-16
Mean Algal Fluorescence Response
Indices in Chickamauga Reservoir
July 7, 1987

Appendix Figure E-13
 Mean Algal Fluorescence Response
 Indices in Chickamauga Reservoir
 July 21, 1987

Appendix Figure E-17
 Distribution of Chlorophyll
 Fluorescence in Chickamauga
 Reservoir July 21, 1987

Appendix Figure E-19
Distribution of Chlorophyll
Fluorescence in Chickamauga
Reservoir August 4, 1987

Appendix Figure E-20
Mean Algal Fluorescence Response
Indices in Chickamauga Reservoir
August 4, 1987

Appendix Figure E-22
 Mean Algal Fluorescence Response
 Indices in Chickamauga Reservoir
 August 18, 1987

Appendix Figure E-21
 Distribution of Chlorophyll
 Fluorescence in Chickamauga
 Reservoir August 18, 1987

Appendix Figure E-23
 Distribution of Chlorophyll
 Fluorescence in Chickamauga
 Reservoir September 1, 1987

Appendix Figure E-24
 Mean Algal Fluorescence Response
 Indices in Chickamauga Reservoir
 September 1, 1987

Appendix Figure E-26
Mean Algal Fluorescence Response
Indices in Chickamauga Reservoir
September 15, 1987

Appendix Figure E-25
Distribution of Chlorophyll
Fluorescence in Chickamauga
Reservoir September 15, 1987

Appendix Figure E-28
 Mean Algal Fluorescence Response
 Indices in Chickamauga Reservoir
 September 29, 1987

Appendix Figure E-27
 Distribution of Chlorophyll
 Fluorescence in Chickamauga
 Reservoir September 29, 1987

Appendix Figure E-30
 Mean Algal Fluorescence Response
 Indices in Chickamauga Reservoir
 October 13, 1987

Appendix Figure E-29
 Distribution of Chlorophyll
 Fluorescence in Chickamauga
 Reservoir October 13, 1987

Appendix Figure E-31
Distribution of Chlorophyll
Fluorescence in Chickamauga
Reservoir October 27, 1987

Appendix Figure E-32
Mean Algal Fluorescence Response
Indices in Chickamauga Reservoir
October 27, 1987

Appendix Figure E-33

Distribution of Chlorophyll
Fluorescence in Chickamauga
Reservoir November 9, 1987

Appendix Figure E-34

Mean Algal Fluorescence Response
Indices in Chickamauga Reservoir
November 9, 1987

Appendix Figure E-35

Distribution of Chlorophyll
Fluorescence in Chickamauga
Reservoir November 23, 1987

Appendix Figure E-36

Mean Algal Fluorescence Response
Indices in Chickamauga Reservoir
November 23, 1987

Appendix Figure E-38
 Mean Algal Fluorescence Response
 Indices in Chickamauga Reservoir
 December 8, 1987

Appendix Figure E-37
 Distribution of Chlorophyll
 Fluorescence in Chickamauga
 Reservoir December 8, 1987

Appendix Figure E-39

Distribution of Chlorophyll
Fluorescence in Chickamauga
Reservoir December 22, 1987

Appendix Figure E-40

Mean Algal Fluorescence Response
Indices in Chickamauga Reservoir
December 22, 1987

Appendix Figure E-42
 Mean Algal Fluorescence Response
 Indices in Chickamauga Reservoir
 January 1, 1988

Appendix Figure E-41
 Distribution of Chlorophyll
 Fluorescence in Chickamauga
 Reservoir January 1, 1988

Appendix Figure E-43
 Distribution of Chlorophyll
 Fluorescence in Chickamauga
 Reservoir February 2, 1988

Appendix Figure E-44
 Mean Algal Fluorescence Response
 Indices in Chickamauga Reservoir
 February 2, 1988

Appendix Figure E-45

Distribution of Chlorophyll
Fluorescence in Chickamauga
Reservoir February 16, 1988

Appendix Figure E-46

Mean Algal Fluorescence Response
Indices in Chickamauga Reservoir
February 16, 1988

Appendix Figure E-47

Distribution of Chlorophyll
Fluorescence in Chickamauga
Reservoir March 1, 1988

Appendix Figure E-48

Mean Algal Fluorescence Response
Indices in Chickamauga Reservoir
March 1, 1988

Appendix Figure E-50
 Mean Algal Fluorescence Response
 Indices in Chickamauga Reservoir
 March 15, 1988

Appendix Figure E-49
 Distribution of Chlorophyll
 Fluorescence in Chickamauga
 Reservoir March 15, 1988

Appendix Figure E-51

Distribution of Chlorophyll
Fluorescence in Chickamauga
Reservoir March 29, 1988

Appendix Figure E-52

Mean Algal Fluorescence Response
Indices in Chickamauga Reservoir
March 29, 1988

Appendix Figure E-53

Distribution of Chlorophyll
Fluorescence in Chickamauga
Reservoir April 5, 1988

Appendix Figure E-54

Mean Algal Fluorescence Response
Indices in Chickamauga Reservoir
April 5, 1988

Appendix Figure E-55

Distribution of Chlorophyll
Fluorescence in Chickamauga
Reservoir April 12, 1988

Appendix Figure E-56

Mean Algal Fluorescence Response
Indices in Chickamauga Reservoir
April 12, 1988

Appendix Figure E-57

Distribution of Chlorophyll
Fluorescence in Chickamauga
Reservoir April 19, 1988

Appendix Figure E-58

Mean Algal Fluorescence Response
Indices in Chickamauga Reservoir
April 19, 1988

Appendix Figure E-60

Mean Algal Fluorescence Response
Indices in Chickamauga Reservoir
April 26, 1988

Appendix Figure E-59

Distribution of Chlorophyll
Fluorescence in Chickamauga
Reservoir April 26, 1988

Appendix Figure E-62
 Mean Algal Fluorescence Response
 Indices in Chickamauga Reservoir
 May 3, 1988

Appendix Figure E-61
 Distribution of Chlorophyll
 Fluorescence in Chickamauga
 Reservoir May 3, 1988

Appendix Figure E-63

Distribution of Chlorophyll
Fluorescence in Chickamauga
Reservoir May 10, 1988

Appendix Figure E-64

Mean Algal Fluorescence Response
Indices in Chickamauga Reservoir
May 10, 1988

CHICKAMAUGA RESERVOIR

APRIL 5, 1989

Figure E-65. Chlorophyll Concentrations and Relative Fluorescence, Chickamauga Reservoir, April 5, 1989

CHICKAMAUGA RESERVOIR

APRIL 19, 1989

Figure E-66. Chlorophyll concentrations and Relative Fluorescence, Chickamauga Reservoir, April 19, 1989

CHICKAMAUGA RESERVOIR

MAY 3, 1989

Figure E-67. Chlorophyll Concentrations and Relative Fluorescence, Chickamauga Reservoir, May 3, 1989

CHICKAMAUGA RESERVOIR

MAY 17, 1989

Figure E-68. Chlorophyll Concentrations and Relative Fluorescence, Chickamauga Reservoir, May 17, 1989

CHICKAMAUGA RESERVOIR

MAY 30, 1989

Figure E-69. Chlorophyll Concentrations and Relative Fluorescence, Chickamauga Reservoir, May 30, 1989

CHICKAMAUGA RESERVOIR

JUNE 20, 1989

Figure E-70. Chlorophyll Concentrations and Relative Fluorescence, Chickamauga Reservoir, June 20, 1989

CHICKAMAUGA RESERVOIR

JUNE 28, 1989

Figure E-71. Chlorophyll Concentrations and Relative Fluorescence, Chickamauga Reservoir, June 28, 1989

CHICKAMAUGA RESERVOIR

JULY 12, - 1989

Figure E-72. Chlorophyll Concentrations and Relative Fluorescence, Chickamauga Reservoir, July 12, 1989

CHICKAMAUGA RESERVOIR

JULY 26, 1989

Figure E-73. Chlorophyll Concentrations and Relative Fluorescence, Chickamauga Reservoir, July 26, 1989

CHICKAMAUGA RESERVOIR

AUGUST 1, 1989

Figure E-74. Chlorophyll Concentrations and Relative Fluorescence, Chickamauga Reservoir, August 1, 1989

CHICKAMAUGA RESERVOIR

AUGUST 9, 1989

Figure E-75. Chlorophyll Concentrations and Relative Fluorescence, Chickamauga Reservoir, August 9, 1989

CHICKAMAUGA RESERVOIR

AUGUST 16, 1989

Figure E-76. Chlorophyll concentrations and Relative Fluorescence, Chickamauga Reservoir, August 16, 1989

CHICKAMAUGA RESERVOIR

SEPTEMBER 20, -1989

KEY +---+ CHLOR. A (MG/M3)
 □---□ F(1) ACTUAL

Figure E-77. Chlorophyll Concentrations and Relative Fluorescence, Chickamauga Reservoir, September 20, 1989

CHICKAMAUGA RESERVOIR

OCTOBER 6, 1989

Figure E-78. Chlorophyll Concentrations and Relative Fluorescence, Chickamauga Reservoir, October 6, 1989

CHICKAMAUGA RESERVOIR

APRIL 5, 1989

TENNESSEE RIVER MILE

Figure E-79. Algal Counts (cells/liter), Chickamauga Reservoir. April 5, 1989

CHICKAMAUGA RESERVOIR

APRIL 19, 1989

TENNESSEE RIVER MILE

Figure E-8C. Algal Counts (cells/liter), Chickamauga Reservoir, April 19, 1989

CHICKAMAUGA RESERVOIR

MAY 3, 1989

TENNESSEE RIVER MILE

Figure E-81. Algal Counts (cells/liter), Chickamauga Reservoir, May 3, 1989

CHICKAMAUGA RESERVOIR

MAY 17, -1989

TENNESSEE RIVER MILE

Figure E-82. Algal Counts (cells/liter), Chickamauga Reservoir, May 17, 1989

CHICKAMAUGA RESERVOIR

MAY 30, 1989

TENNESSEE RIVER MILE

Figure E-83. Algal Counts (cells/liter), Chickamauga Reservoir, May 30, 1989

CHICKAMAUGA RESERVOIR

JUNE 20, 1989

TENNESSEE RIVER MILE

Figure E-84. Algal Counts (cells/liter), Chickamauga Reservoir, June 20, 1989

CHICKAMAUGA RESERVOIR

JUNE 28, 1989

TENNESSEE RIVER MILE

Figure E-85. Algal Counts (cells/liter), Chickamauga Reservoir, June 28, 1989

CHICKAMAUGA RESERVOIR

JULY 12, 1989

TENNESSEE RIVER MILE

Figure E-86. Algal Counts (cells/liter), Chickamauga Reservoir, July 12, 1989

CHICKAMAUGA RESERVOIR

JULY 26, 1989

TENNESSEE RIVER MILE

Figure E-87. Algal Counts (cells/liter), Chickamauga Reservoir, July 26, 1989

CHICKAMAUGA RESERVOIR

AUGUST 9, 1989

TENNESSEE RIVER MILE

Figure E-88. Algal Counts (cells/liter), Chickamauga Reservoir, August 9, 1989

CHICKAMAUGA RESERVOIR
AUGUST 16, 1989

TENNESSEE RIVER MILE

Figure E-89. Algal Counts (cells/liter), Chickamauga Reservoir, August 16, 1989

CHICKAMAUGA RESERVOIR

OCTOBER 6, 1989

TENNESSEE RIVER MILE

Figure E-90. Algal Counts (cells/liter), Chickamauga Reservoir, October 6, 1989

Fluorometry - April 4-5, 1989

Figure E-91. Fluorescence Profiles, Chickamuga Reservoir, April 4-5, 1989

Fluorometry — April 19–20, 1989

Figure E-92. Fluorescence Profiles, Chickamugua Reservoir, April 19–20, 1989

Fluorometry - May 3, 1989

Figure E-93. Fluorescence Profiles, Chickamugua Reservoir, May 3, 1989

Fluorometry - May 17-18, 1989

Figure E-94. Fluorescence Profiles, Chickamugua Reservoir, May 17-18, 1989

Fluorometry - May 30-31, 1989

Figure E-95. Fluorescence Profiles, Chickamugua Reservoir, May 30-31, 1989

Fluorometry - June 20, 1989

Figure E-96. Fluorescence Profiles, Chickamauga Reservoir, June 20, 1989

Fluorometry - June 28-29, 1989

Figure E-97. Fluorescence Profiles, Chickamuga Reservoir, June 28-29, 1989

Fluorometry - July 11-12, 1989

Figure E-98. Fluorescence Profiles, Chickamauga Reservoir, July 11-12, 1989

Fluorometry - July 26, 1989

Figure E-99. Fluorescence Profiles, Chickamugua Reservoir, July 26, 1989

Fluorometry -- August 1, 1989

Figure E-100. Fluorescence Profiles, Chickamauga Reservoir, August 1, 1989

Fluorometry - August 9-10, 1989

Figure E-101. Fluorescence Profiles, Chickamuga Reservoir, August 9-10, 1989

Fluorometry - August 16, 1989

Figure E-102. Fluorescence Profiles, Chickamuga Reservoir, August 16, 1989

Fluorometry - September 20, 1989

Figure E-103. Fluorescence Profiles, Chickamugua Reservoir, September 20, 1989

Fluorometry - October 6, 1989

Figure E-104. Fluorescence Profiles, Chickamuga Reservoir, October 6, 1989

APPENDIX F

**BACKGROUND FOR BIOLOGICAL EVALUATION OF LOW DISSOLVED OXYGEN
OCCURRING IN CHICKAHAUGA RESERVOIR**

APPENDIX F

BACKGROUND FOR BIOLOGICAL EVALUATION OF LOW DISSOLVED OXYGEN OCCURRING IN CHICKAMAUGA RESERVOIR

Physical Factors Affecting the Magnitude of Biological Responses

As conditions become seasonally more anoxic, due to stratification, and widespread spatially within a reservoir (figure F-1), there is a loss of available habitat with DO levels acceptable to fishes. Many fish species and life stages sense low DO concentrations and attempt to avoid them by entering shallower shoreline areas; by passing above the thermocline; or moving upstream, downstream, or into oxygenated tributaries. This emigration may allow increased predation upon them by other fishes; concentrate them, increasing angler harvest; or put some species in suboptimal habitat where they are subjected to physiological stresses from higher than acceptable temperatures leading to increased incidences of disease and mortality. Early life stages, such as embryos or larvae developing in nursery areas, are often unable to leave the area and simply die; or if DO levels are not below completely lethal concentration, do suffer higher rates of mortality, delayed development, smaller hatching sizes, and reduced growth. Laboratory investigations suggest those young of some species which do survive exposure to low concentrations of DO during early development, may be weak and suffer significant delayed mortalities.

Seasonally, as temperatures rise, stratification strengthens, and DO-depletion worsens, deep-release reservoirs discharge waters of increasingly poorer quality to the downstream regulated river. Biological impacts of low DO (table F-1) are typically localized to some degree by natural reaeration occurring in the river. The downstream distances required for reaeration in rivers may, however, be

quite significant (as much as 40-70 km in the southeastern U.S.). Within this area the severity of biological DO-related impacts are greatest in the near-dam tailwater. Here the most severe depression of fish and benthic diversity and numbers, growth, and reproduction occurs. As DO conditions ameliorate downstream, a variable biological "recovery zone" occurs in which benthic and fishery diversity increases and depression of growth or survival of young fish should be attenuated. This DO-related recovery zone is pushed further downstream by greater dam discharges of DO-depleted waters, increased severity of DO-depletion, or limited natural stream reaeration because of stream geometry or gradient. Temperature and flow-related recovery zones may also occur, which makes cause-and-effect attribution of impacts solely to low DO concentrations complex, but sometimes not impossible (Yeager et al., 1987; McDonough et al., 1990 M.S.).

These low DO zones may also act as effective barriers or delays to either upstream passage of fish in spawning migrations, and possibly (not as yet documented) young anadromous fish passing downstream. The severity of a physicochemical barrier, such as low concentrations of DO, depends upon the magnitude of the DO depression, its longitudinal distance in the river, reservoir, or estuary, seasonal timing and duration of the DO-depression, the DO sensitivity of the fish species involved, their species-specific behavior, and DO effects on swimming performance.

Current National (EPA) Criteria for Dissolved Oxygen and Rationale

Under authorization of Section 304(a)(1) of the Clean Water Act of 1977 (PL 95-217), the EPA reviewed then-current DO criteria (EPA,

1976) for protection of aquatic life and following a nonregulatory scientific reassessment, issued newly revised biological criteria (EPA, 1986). EPA revised single-number DO criteria (EPA, 1976), previously based solely on mean DO concentrations, in favor of a two-number criteria based on both minimum and mean concentrations. This two-concentration criteria and revised methods were adopted in recognition of several concerns: the greater complexity of biological effects from low DO than can be communicated by a single-number criteria; the limited ability of mean DO criteria to provide protection from acutely lethal DO concentrations; to avoid underprotection of aquatic organisms exposed to extended periods of DO concentrations below 5 mg/l; to minimize the cost to developers and action agencies of overly stringent criteria that could be exceeded for short periods of time without significant effects on fishes; and to provide more guidance to users in judging applicability and appropriateness of modifying criteria.

Historically, two basic approaches to establishment of DO criteria have been implemented. The first was a dynamic approach in which DO criteria varied with ambient natural DO minimums (Douderooff and Shumway, 1970), or with DO needs of fish, expressed as percent saturation (Davis, 1975). The second approach (EPA, 1976) maintained that a single minimum allowable concentration adequately protected the diversity of freshwater aquatic life. Both relied on minimum DO concentrations as the basis for criteria. Lack of data for naturally occurring, site-specific minimum DO concentrations made application of the first approach extremely difficult. A more sophisticated, but still relatively simple, two-tiered approach, including a minimum and average DO concentration, evolved from a review of DO criteria for the Great Lakes (Magnuson et al., 1979).

Present EPA criteria for DO is based upon this two-number method and is similar to national criteria used for toxicants (Federal Register, 45 FR 79318).

These new criteria were presented based on the dichotomous distinction between cold and warmwater species, life history stages and lengths of exposure to low DO concentrations (table F-2). Application of coldwater criteria is intended for waters with salmonid populations or fish species having comparably greater sensitivity than most warmwater species. Determining the appropriateness of applying coldwater criteria to nonsalmonid species is left to the discretion and judgment of the States or other recommending agencies. Most States whose use-classification for a particular stream is for protection of fish and other aquatic life have adopted a 5 mg/l minimum concentration for nonsalmonid waters and 6 mg/l DO minimum for salmonid streams. In some localities where species have been transplanted to warmer waters, maintenance of coldwater criteria may be unattainable. Transplanted populations would certainly be better off if the higher DO were met, but constraints on nonnative fish management and put-and-take fisheries by failure to attain coldwater criteria were not intended by criteria developers. Criteria for life history stages was deemed necessary to address their often drastically differing sensitivities, as described in the following sections, and are to apply only where and when those life stages occur.

Concentration criteria for nonsalmonid species were basically established to protect early life stages as sensitive as those of the channel catfish and other life stages as sensitive as those of the largemouth bass from production impairment. Impairment of fish

production is essentially any reduction of fish growth rates (increase in biomass over time) or their attained weights when compared to that expected for fish growing under local ambient conditions for DO. The DO requirements of invertebrates were discussed, but for purposes of establishing new criteria, it was again "de facto" assumed that as long as lethal concentrations were avoided, protection of invertebrates would be afforded by maintenance of DO concentrations adequate to avoid impairment of fish production.

The selection of fishery impairment, though not the only possibility, as the "parameter of choice" for developing DO criteria has many advantages, major ones being that: though limited in many cases, data is available, i.e., the three measurements affecting production (reproduction, survival and growth) are commonly investigated; the parameters are measurable under both field and laboratory conditions; assumptions relating laboratory and field data appear reasonable based on currently available data and knowledge; and this measure has economic and social ramifications.

Recommended ambient DO criteria were established to protect the more sensitive fishes and appropriate life stages from damaging production impairment under annual "worst case" DO-high temperature conditions. These conditions typically occur for only a limited portion of the year at some hydroelectric sites. However, the criteria are not considered as entirely assuring "no production impairment," particularly when minimal criteria are maintained for extended periods of time. In areas where natural DO concentrations are less than 110 percent of applicable criteria means, minimal or both, minimum acceptable DO concentration is 90 percent of the natural concentration (EPA, 1986).

Unless the degree of tolerance to low DO is known to be different for organisms present, no man-induced depression of DO concentrations below the 1-day minimum should be allowed to occur. Concentrations below that level are in the identified, potentially lethal ranges for the applicable life stage or fishery (warmwater or coldwater).

For site-specific situations where DO patterns are extremely erratic, (i.e., where the 1-day minimum DO is appreciably less than the acceptable 7-day mean minimum or where significantly lower daily minimums occur in more than one or two weeks per year) it was recommended that either the occurrence of daily minimums below the 7-day mean minimum be limited to three weeks per year, or that acceptable 1-day minimum for warmwater fisheries be increased to 3.5 mg/l and that for coldwater fisheries to 4.5 mg/l. Sample methods for calculations of appropriate mean DO concentrations were included in EPA (1986). The biological significance of failure to maintain these recommended criteria depends upon (EPA, 1986): duration of the event, magnitude of the depression, frequency of recurrence, proportional area of the site failing to meet criteria, and biological importance of the site, life stages, and species present.

Considerations in Evaluating Potential DO Effects on Biota

The objectives of this section are to identify the important physical and biological parameters to be considered in site-specific evaluations of impacts from low concentrations of DO; and provide some insight, based on previous experience, into the probable relative value of data sets in monitoring efforts.

For biological evaluations of likely low DO effects, three major questions need to be addressed. Does a DO problem exist? What is the severity (magnitude), duration and spatial extent of the DO depletion if it exists? Are there likely biological impacts? A further question derived from answers to the first three is, Are there manipulatable factors (engineering, operational, biological, or other) which can reduce identified impacts of low DO? The first two questions are addressed in reservoirs by monitoring of DO-temperature parameters through vertical and horizontal DO profile measurements defining the spatial and temporal character of DO problems within the reservoir. In the tailwater or regulated river, scrollcase or intake measurements in conjunction with a longitudinal and diurnal DO monitoring program along the affected regulated river reach under different operating conditions and at different seasons is a valid approach. For research purposes, decision making and determining reasonable mitigation strategies for reservoir-induced DO depletion problems in the river, predictive modeling of stream reaeration rates (Churchill et al., 1962, Negelescu and Rojanski, 1969), and of DO benefits accruing in the regulated river (Hauser et al., 1983) is an extremely useful approach. Hauser et al. (1983) discusses special discharge-operational considerations, instrumentation, sampling location, and frequency required to support a typical calibrated DO modeling effort.

Level of resolution for field monitoring-modeling efforts have a large effect in determining the significance of low DO concentrations, failure to meet regulatory DO criteria, or whether significant relationships between DO levels and biological parameters can be established by researchers. The extent, duration, and magnitude of occurrences of low

DO must first be modeled and documented. Where continuous monitoring is conducted, a single low DO measurement or criteria violation is thus of much less significance than where monitoring consists of weekly or monthly "grab" samples. Continuous monitoring may define the low DO event as small, whereas less intensive sampling cannot, and the event may be considerably worse or better than shown by the data.

Biological concerns to be considered and incorporated into site-specific field monitoring schemes of DO impacts where applicable, include: species and numbers of fish or other aquatic organisms and life stages present; the temporal and spatial co-occurrence of these organisms or life stages with regards to periods of low DO, or their susceptibility to impacts from seasonably low DO through other mechanisms; specific types and degree of biological impacts, as well as defined conditions under which they occur; and definition of the biological parameters or measures of concern to the agencies involved.

Except "in extremis," applicable water quality standards for reservoirs simply do not address nor particularly protect aquatic resources. For example, under low flow conditions occurring in 1986, most of the reservoir volume of Chickamauga Reservoir experienced DO levels well below 5 mg/l, but measurement of these extreme conditions at the 5-ft level was not assured in any sense. Additionally, the occurrence of DO concentrations below 5 mg/l at the 5-ft level accurately indicates neither the significance, nor the overall character of vertical DO concentrations in the reservoir when dealing with mixing events. Profile information may portray an entirely different picture of likely DO-related impacts in reservoirs.

The primary criteria of fishery effects is the degree of impairment to fishery production. Present DO criteria were set based primarily on growth impairment studies and, therefore, collection of appropriate data as measures of fish growth or health are of importance in future biologically based investigations. These include such measures as analyses of length-weight regressions, incremental growth over time, or "LeCren" condition factors (LeCren, 1951). The parameters affecting overall production, however, include not only growth, but reproduction and survival.

Biological Responses to Low Dissolved Oxygen

In many cases, differentiating sublethal DO-related effects from those produced by the many other co-occurring physical, chemical, and biological alterations caused by stratifying, hypolimnetic releases of impoundments is difficult in field evaluations. The following impacts, however, are known to occur as consequences of low concentrations of DO in reservoirs and downstream regulated rivers.

Benthos--Benthic organisms (those living on or among the bottom substrate) serve vital functions in the energetics of river systems, transforming nutrients and organic materials into biomass, and providing a food base for fishes and other vertebrate predators. The major effect of low DO on benthic communities is the reduction of species diversity (numerous studies reviewed in Ward, 1976; and Baxter, 1977). Regionally, measures of benthic communities in tributary tailwaters of the Tennessee River Valley have been correlated with minimum DO levels (McDonough et al., 1990) through the range of 0-7 mg/l DO. Crustaceans, freshwater snails, mussels, and aquatic insect larvae show avoidance of low

DO or behavioral responses such as suspension of feeding, inactivity, or drifting from affected areas (Hart and Fuller, 1974; Davis, 1975). Benthic organisms which die or drift from areas to avoid low DO are often replaced by other invertebrate species which can tolerate low DO conditions. Community composition is drastically altered in regulated rivers subjected to low concentrations of DO, but total standing crop (the biomass or total number of organisms present at a specific time) may not change or, actually may increase due to a lack of competition between species. Therefore, benthic communities in DO-altered tailwaters often consist of large numbers of the few species able to live under low DO conditions. Unfortunately, these few tolerant organisms are also most often of poor quality as a food base for fishes or other higher vertebrates.

Freshwater mussels, an important commercial resource in much of the Mississippi River drainage for the cultured pearl-producing industry of the U.S. and Japan, have been severely reduced by low DO levels within reservoirs and regulated river reaches. Exploitable mussel resources have completely disappeared in many permanent pool areas of tributary and mainstream reservoirs of the U.S. This reduction has been the result of multiple stresses including tremendous habitat losses (largely due to impoundment), habitat alterations from sedimentation and pollution, and commercial overharvest, but mussel distributions indicate that anoxic conditions in the hypolimnia of reservoirs have played a significant role in regional declines.

Fisheries--Documented detrimental impacts of low DO on fish or fisheries include (table F-1): decreased survival (i.e. "fish kills" and increased mortality of embryos, larvae, juveniles, and adults);

depression of growth rates with consequent impairment of production; decreased reproduction; impaired swimming performance; avoidance behavior of both young and adults leading to denial of access to spawning sites or downstream nursery areas by intervening areas of low DO; forcing of adult and juvenile fish into less than optimal habitat conditions; abnormal behavior probably resulting in an increase of fish being preyed upon; decreased fish species diversity; greater synergistic, toxicity-related mortalities from environmental contaminants under low DO conditions; and increased incidence of disease. The impacts of low DO levels on mortality, growth, and fecundity of fishes are similar to those observed for toxic pollutants, i.e., they have a range of impairment effects (toxicities), acute and chronic mechanisms, and affect specific organs, etc.

When not present in excess of need or below lethal concentrations essential for maintaining aquatic life, DO acts as a limiting factor, much as food availability does, setting intermediate sublethal limits to growth of fish. Impairments to fishery production (growth, reproduction, and survival) probably result from less-than-ambient DO concentrations in many reservoirs and river reaches across the U.S. However, neither validated models nor direct production-effects estimates have as yet been developed relating DO levels and fish production under field conditions. Development of national (EPA 1976; EPA 1986) and regional (International Joint Commission, 1976; Minnesota Pollution Control Agency, 1980) DO criteria have been based upon laboratory studies and represent the best available estimates of DO concentrations necessary to protect aquatic life or to estimate likely production effects for constant DO level exposures. Some evidence, discussed later in this section, suggests

that even these estimates seriously undervalue the severity of DO-related growth impairment at temperatures higher than reported in the literature. Sensitivities of fish to low concentrations of DO vary dramatically between the coldwater salmonids (trout, salmon, char, and whitefish) and warmwater or coolwater nonsalmonids, by species within these gross characterizations, and by life stage.

In terms of fish production, any reduction in DO levels below saturation has some measurable deleterious effect on fish growth or production. As a group, the coldwater salmonids appear to be the most sensitive fishes to low concentrations of DO. Salmonids, exhibit slight growth reductions at decreased DO levels above 6 mg/l (<10 percent impairment); "moderate" reductions (20 percent impairment) between 4 and 6 mg/l; and "severe" reductions (40 percent impairment at DO concentrations below 4 mg/l. These values are necessarily subjective, but are based upon examination of growth and survival data, generalizations of response curve shape, and assumed applicability of laboratory data to field conditions. With the presently known exception of the smallmouth bass, nonsalmonids appear considerably less sensitive to acute effects of low DO than coldwater salmonids.

Early life stages of salmonids do not appear any more susceptible to impacts from low DO than adults, both being more sensitive than warmwater and coolwater nonsalmonids. However, embryonic and early life stages of salmonids developing within the interstices of bottom substrate require about 3 mg/l higher DO concentrations in overpassing waters (as high as 11 mg/l) in order to ensure adequate intergravel DO concentrations for normal development. Early life stages of nonsalmonids species, however, are typically more sensitive to exposure

to low DO than juveniles or adults. Significant damage and mortalities have been reported by several authors for young nonsalmonids in the 3-6 mg/l DO range. Observed effects of low DO on nonsalmonids have included delayed development, reduced larval survival, and reduced growth of larvae and juveniles. As would be expected for any group comprised of several hundred species of fishes, survival data for warm and coolwater fishes does show a wide spectrum of relative tolerance to low concentrations of DO (figure F-2). Some species, such as the largemouth bass, white sucker, black crappie, and white bass, are relatively tolerant of low DO concentrations, whereas others such as the channel catfish, walleye, northern pike, and smallmouth bass are much less tolerant of low DO levels. Sensitivities to low DO concentrations of several important fishes in the Tennessee River System are unknown. Investigation of DO requirements (constant and fluctuating) of the sauger, juvenile temperate bass and buffalo fish would aid in future site-specific evaluations.

Most knowledge of DO-related impairment to fisheries has been gleaned under conditions of constant DO concentrations. However, DO concentrations below hydropower facilities used for "peaking" purposes typically vary drastically with flow over a 24-hr period. The degree of impairment to survival and growth of fishes subjected to diurnal fluctuations in DO, such as occur below these facilities, appears more controlled by the minimum DO concentration to which fish are exposed, rather than daily mean concentrations. Investigations (Fisher, 1963; Stewart et al., 1967; Whitworth, 1968; and TVA, 1987) have demonstrated that growth of fish under virtually any fluctuating DO pattern is less

than if fish were held at the daily mean DO concentration for the entire period.

Initial research into relative effects of various periods and diurnal variation in timing of exposure to low DO concentrations have tentatively indicated that some diurnal fluctuation regimes are less detrimental to fish than others. It is reasonable to expect further research along this avenue would yield site-specific alternatives for operational schemes at hydroelectric facilities that would mitigate aquatic biological impacts, while minimizing energy or operational costs and losses to power producers.

Biological Effects of Low DO as the Basis for Criteria

Of the many degrading alterations to water quality that affect fisheries, reduction of DO concentrations is one of the most common and important. When it is not present in excess of need or below lethal concentrations essential for maintaining aquatic life, DO acts as a limiting factor, much as food availability does, setting intermediate sublethal limits to growth of fish. The effects of reduced DO on aquatic life, particularly that of lethality, have been investigated as thoroughly as those of any water quality alteration resulting from pollution or reservoir operation. Generalities drawn from numerous studies are highlighted in the following section on biological responses, with more detailed information presented in individual species accounts.

Sensitivities of the salmonids (trout, chars, salmon, and whitefishes) to low DO have been investigated more thoroughly than for any other aquatic organisms. Their great economic value, ready availability of various life stages from hatchery stocks, and relative ease of

maintenance under laboratory conditions have strongly biased DO research towards this family of coldwater fishes. For this reason much of the information presented is based on salmonid data, but the generalities are germane to any discussion of likely effects of low DO on even warm or coolwater fisheries. Most of the available information for fishes on lethality, growth, feeding, physiology, early development of life stages, and swimming speed performance, has also been gained under laboratory-controlled conditions. Two major limitations of this information are first, that by design, laboratory studies typically attempt to preclude synergistic environmental or species interactions; and second, the tremendous variability of methodologies used. Though these studies represent the best available information, most reports do not meet the rigorous, standardized procedures now typically used by EPA for establishment of chronic toxicity or sublethal effects, by not including either a full life cycle or the sensitive larval stage, or the length of tests is too short-term for adequate appraisal of long-term survival and growth.

Physiology--The physiological responses of salmonids to varying degrees of hypoxia have been investigated in a great number of studies (reviewed in Douderoff and Shumway, 1970) measuring metabolic and cardiovascular responses to rapid, short-term exposures of fish to low DO concentrations. The main use of these studies for criteria development and application has been indirect (EPA, 1986), i.e., allowing understanding of how low DO levels physiologically act to affect fish production. The incipient oxygen response thresholds for selected North American fish species (Davis, 1975) are presented in table F-3. These thresholds

provide an indication of initial biological responses to low DO concentrations. Though intermediate assumptions are manifold, good correlations have been observed between physiological relationships such as blood dissociation curves for rainbow trout (Cameron, 1971) and reduction in growth of trout (Brett and Blackburn, 1981, Warren et al., 1973), the more important readily measured, "end product" of physiological processes used in evaluating relative impairment of production.

For nonsalmonids, the bulk of physiological research has been on relating resting oxygen consumption rates and low DO levels in order to define "critical" oxygen concentrations. This is the point where a reduction in resting metabolic rate is observable, resulting in greatly reduced energy available for growth and activity, a decrease in oxygen to the tissues and a partial shift to anaerobic energy processes. In general, critical oxygen concentrations for a variety of nonsalmonid fishes falls between 2 and 4 mg/l with higher temperatures yielding higher critical oxygen concentrations.

Direct Acute Lethality--Regarding lethal concentrations of low DO, North American salmonid data summarized by Douderoff and Shumway (1970) indicated mortality or loss of equilibrium usually occurred between 1 and 3 mg/l in tests of variable length for species of the genera Coregonus, Oncorhynchus, Salmo, Salvelinus, and Stenodus (table F-4). For exposure times less than 3.5 days, DO concentrations of 3 mg/l or higher should produce no direct mortality of salmonids (EPA, 1986). The differences between DO levels causing complete mortality and those allowing complete survival of brook trout was only about 0.5 mg/l for exposures of less than one week (Shepard, 1955; EPA, 1986), indicating a well-defined

threshold for lethal effects. Recent chronic tests using early life history stages of salmonids (Siefert et al., 1974; Siefert and Spoor, 1973; Brooke and Colby, 1980) generally confirm these lethal levels.

With the exception of some larval life stages, nonsalmonids seem to be less sensitive to lethal effects from low DO than salmonids. Data is limited to only a very few nonsalmonid species (figure F-2). In most cases, exposure to 3 mg/l DO in acute laboratory tests (24-96 hr in length) result in no mortality. Several species of nonsalmonids seem to be able to survive acute exposures to DO levels below 1 mg/l for several days (Moss and Scott, 1961; Downing and Merkens, 1957), but from such short-term tests virtually nothing is known about latent effects on longer-term survival. Additionally there is no data regarding the effects of repeated short-term exposures.

Growth--For six salmonid species in the genera Oncorhynchus, Salmo and Salvelinus, EPA (1986) and JRB Associates (1984) summarized data from 24 tests of DO effects on growth (table F-5). Median growth rate reductions from these tests were 7, 14, and 25 percent for fish held at 6, 5, and 4 mg/l, respectively. Reductions in growth seen above 6 mg/l (table F-5) were rarely statistically significant; those between 4 and 6 mg/l were typically slight or moderate, even at exposures of longer duration; but those below 4 mg/l were severe.

Growth of salmonids is most sensitive to effects of low DO at higher temperatures when their metabolic requirements are highest. Increasing temperatures and decreasing DO concentrations are conditions commonly occurring both within reservoirs and their regulated rivers as summer stratification of reservoirs strengthens. Warren et al. (1973) conducted tests on the influence of DO and temperature on growth rates

of coho and chinook salmon (tables F-6 and F-7). Major findings of this excellent study were that: the largest reductions of growth rate were at high temperatures (e.g., 17.8-21.7°C for chinook); the thresholds where effects occurred, rose to higher DO levels with increased temperature; and that extrapolation of probable DO reduction effects from tests conducted at lower temperatures would drastically underestimate effects of low DO at higher temperatures. Extrapolation of data summarized in tables F-6 and F-7 to higher temperatures would thus probably significantly underestimate effects of low DO on these other salmonid species. However, in the absence of more site-specific data (EPA, 1986) and information on such factors as current velocity, activity level, and food availability presented in some of the following individual species accounts, these data sets represent the best estimators of the effects of low DO on growth of salmonids.

Reproduction--Dissolved oxygen concentrations do appear to have an effect on reproductive status and success of fishes, but no information is presently available of the effects of low DO on fecundity, fertility, or reproduction of salmonids and very little for nonsalmonids. A complete life cycle exposure to low DO concentrations has been performed only for the fathead minnow (Brungs, 1971). No spawning occurred at 1 mg/l, fecundity was reduced at 2 mg/l, larval growth was less at DO concentrations below controls, and larval survival was related to DO concentration (6 percent at 3 mg/l; 25 percent at 4 mg/l; 66 percent at 5 mg/l and 50 percent in controls). In large channel tests (TVA, 1987; Yeager, 1990) occurrence of mature spawning bluegill appeared severely impacted at DO concentrations below 6.4 mg/l. This finding

is in apparent contradiction of Siefert and Herman (1977) who reported normal centrarchid spawning at DO concentrations as low as 2 mg/l.

Behavior and Swimming Performance--Fishes can detect and attempt to actively avoid low concentrations of DO. Salmonids (chinook and coho salmon) can detect and actively avoid low DO (Whitmore et al., 1960), selecting against concentrations of 3.0 mg/l or lower. Centrarchids (largemouth bass and bluegill) show definite avoidance of DO concentrations of 1.5 mg/l (Whitmore et al., 1960). Behavior of normally quiescent yolk-sac larvae of largemouth bass is elevated at 4-5 mg/l to unusually high activity (Spoor, 1977), which could result in much greater predation of larvae. Age appears to be a factor in the ability to detect differences in DO level. Young brown trout and Atlantic salmon 6-26 weeks of age avoided concentrations of up to 3-4 mg/l (Bishai, 1962), but those younger apparently could not detect differences. Swimming performance of largemouth bass (Katz et al., 1959; and Dahlberg et al., 1968), as for salmonids, is reduced and most sensitive to low DO when temperatures are lower.

Within reservoirs experiencing hypolimnetic DO depletion, the distribution of striped bass, largemouth bass, and walleye suggests they are sometimes detecting and actively avoiding areas of low DO. Chittenden (1971a, 1971b) found striped bass distribution to be bounded by the 3 mg/l isopleth and Coutant (1985) found them to avoid reservoir concentrations of low DO in the 0.5-2.5 mg/l range. In one study largemouth bass concentrations were found to be most strongly influenced by DO level and were greatest in areas with DO concentrations greater than 2 mg/l (Rinne et al., 1981). Scherer (1971) documented the greater occurrence of adult walleye in reservoir areas with DO concentrations

greater than 3-5 mg/l. Dendy (1945) documented the movement of walleye out of areas experiencing DO levels of 0.0-1.5 mg/l into upper reservoir strata. Walleye, losing their negatively phototactic behavior (light avoiding) if DO concentrations fall to 2-4 mg/l, may then move into shallow, more oxygenated waters (Scherer, 1971). As hypolimnetic oxygen-depletion spreads and summer epilimnetic temperatures rise above thermal tolerances for that species, fish moving to shallower waters to avoid DO-depleted areas may experience a thermal-oxygen "squeeze," resulting in metabolic stress, disruption of feeding or increased mortality rates. Creel characteristics of a fishery may also be affected by changes in fish behavior. Weithman and Haas (1984) reported decreasing harvest rates for the rainbow trout fishery with decreasing DO concentrations in Lake Taneycomo of Missouri. Consistent with the findings of Warren et al. (1973) relating growth impairment to reduced food intake under low DO conditions, they postulated that feeding behavior was impaired.

Early Life Stages--Many salmonid species have early life history stages which develop buried in gravel substrates. Dissolved oxygen levels in intergravel areas are dependent on DO diffusion, rates of water percolation, or convection, and the respiration of all gravel-dwelling organisms (EPA, 1986). The interrelationship of flow and DO level available to developing embryonic and larval salmonids is important. Dissolved oxygen requirements of early life stages of salmonids do not differ significantly from those of adults, but they may be subjected to much lower DO levels intergravely than that measured in overpassing waters. Intergravel DO concentrations may be depleted even when DO concentrations in overpassing waters may be at acceptable levels.

With adequate flow (>100 cm/sec), Brannon (1965) and Chapman and Shumway (1978) reported decreases of less than 10 percent by continuous exposure of trout and salmon to DO concentrations as low as 3 mg/l. However, available studies based on field observations (Koski, 1965; Hollander, 1981) indicate that developing salmonids buried in natural redds are exposed to DO levels approximately 3 mg/l lower than that of overpassing waters. This 3 mg/l differential was assumed in development of national DO criteria for salmonid species. Exposure of salmonid embryos and larvae to low concentrations of DO result in delays in embryonic development and hatching which could have significant effects on survival or growth of alevins or larvae (Carlson and Siefert, 1974; Siefert and Spoor, 1974), even at concentrations as high as 6 mg/l for some species (Coble, 1961; Siefert et al., 1974); and increased mortality of embryos (Siefert et al., 1974). Effects of low DO are greatest during late embryonic development when critical DO levels are highest (Alderice et al., 1958).

For nonsalmonids, larval and juvenile stages are most often more sensitive to low DO than other life stages. Several investigations have indicated reduced survival or significant damage to young of nonsalmonids in the range of 3-6 mg/l DO (EPA, 1986). Lethality data (figure F-2) on nonsalmonids show that some species are more tolerant (largemouth bass, black crappie, white bass, and white sucker) than other nontolerant ones (channel catfish, walleye, northern pike, smallmouth bass). The latter three fishes are often considered coolwater species, or are grouped with salmonids as sensitive coldwater species. More detailed discussions for young nonsalmonid fishes are included in the individual species accounts.

Fishery Diversity--Though only semiquantitative and not defining the actual long-term exposure levels experienced by fish communities, three pertinent field studies relating DO concentrations and diversity of fish assemblages have been conducted. Reporting numerous DO concentrations and fish collections from 982 stations in streams and rivers from June to September 1930-35, Ellis (1937) concluded that 5 mg/l was the lowest concentration at which a good mixed assemblage of warmwater fish species could be maintained in inland freshwaters. A two-year survey of the Ohio River (Brinley, 1944) indicated that fish were more abundant at DO concentration of 3-5 mg/l than at lower concentrations, but still showed a greater incidence of parasitization, sickness, and deformity than fishes in areas with greater than 5 mg/l DO. Working in the Wisconsin River, Coble (1982) reported that sport fish made up a significantly greater proportion of fish populations in areas with mean summer DO concentrations greater than 5 mg/l. All three studies indicate that composition, abundance and condition of these nonsalmonid fish assemblages did not noticeably improve with increases in DO above 5 mg/l.

Fluctuating Concentrations of Dissolved Oxygen--Fish and most other aquatic organisms in rivers and reservoirs are exposed to natural seasonally and diurnally fluctuating concentrations of DO. These conditions are quite different from exposure to constant DO concentrations, such as are typically maintained in laboratory studies. Additionally, biota of reservoirs, tailwaters, and rivers regulated by hydroelectric dams or experiencing physicochemical changes due to operational changes of power production facilities, are exposed to sometimes even more drastic unnatural "swings" or fluctuations in DO concentration on an

hourly, daily, or weekly basis. For daily or longer-term exposures to cyclic DO levels, minimum concentrations appear more important than mean values in determining the magnitude of effects on fish from exposure to these cyclic fluctuations. However, available data in this area is extremely limited. Studies by Fisher (1963) and Whitworth (1968) on effects from daily DO cycling indicate that growth of fish on unrestricted diets was much less than would have been estimated from daily mean DO concentrations. Growth of fish was only slightly better than that attainable by constant exposure to daily minimum DO values.

Atypically, most information presently available on effects of fluctuating DO concentrations has come from nonsalmonid, noncoldwater species. As found for constant DO concentrations, the growth responses of the varied groups of warmwater and coolwater fishes to fluctuating DO levels differed among species. Largemouth bass (Stewart et al., 1967) showed reduced growth from that which would be expected by exposure to constant mean concentrations with any fluctuation from a minimum of 2 mg/l to a maximum between 4 and 17 mg/l. Channel catfish growth was significantly impaired at fluctuations from about 3.1 mg/l down to 1.0 mg/l, but not at higher concentrations (Carlson et al., 1980). As found in constant DO studies, lesser sensitivity to DO fluctuations was observed for the yellow perch (Carlson et al., 1980), i.e., growth impairment was not observed for fluctuations from about 3.8-1.4 mg/l, even though food intake was reduced. Spawning of mature black crappie was unsuccessful at DO fluctuations between 1.8 and 4.1 mg/l, but successful at fluctuating higher mean DO levels where the degree of fluctuation around the mean DO concentration was similar (Carlson and Herman, 1978).

Rainbow trout held in large "mesocosm" channels with daily DO fluctuations changing from an average daily minimum of 3.5 mg/l (going to as low as 2.0 mg/l) to a mean daily average 4.7 mg/l (daily maximum averaged 6.0 mg/l) showed significantly impaired growth (TVA, 1987). Similar fluctuations around higher mean daily averages (6.3, 7.9, and 12.3 mg/l) had no significant impact on growth of rainbow trout. Experiments (TVA, 1987) using rainbow trout held in aquaria, with DO concentrations held at constant levels or varied in different manners simulating typical releases from hydroelectric facilities, demonstrated that: growth of rainbow trout was impaired at all levels below saturation; data indicate discharge regimes could probably be modified to reduce growth impairment to fishes; growth rates for daily periods of 7-9 hr of DO reduced to 4 mg/l (five days per week) and 2-4 hr of reduction to 3 mg/l (two days per week) resulted in growth rates equivalent to a continuous 5 mg/l treatment. Conceivably turbine releases with only 4 mg/l in conjunction with higher DO levels during periods of nonrelease may thus be biologically equivalent to exposure to a constant 5 mg/l. Additional research on effects of temperature and exposure times to mean and minimum DO concentrations, could lead to development of a practical growth rate model for rainbow trout.

Observations of fish during exposure to the lower DO concentrations of cyclic exposures include (Bouck and Ball, 1965; Stewart et al., 1967; Bouck, 1972; TVA unpublished experimental results): loss of natural color; increased ventilation rates; cessation of feeding; vomiting of food eaten as much as 12 hr earlier; and production of significant stress patterns in electrophoretic analyses of serum protein fractions for some species, but not all.

Species Accounts--Species occurring in Chickamauga Reservoir

discussed herein are those for which adequate data was available for generalizations; those considered likely to be impacted by low DO because of their behavior, distribution, spawning behavior, or economic value; or were mentioned as species of concern by particular State resource agency representatives as of concern. This section constitutes a thorough summary of currently available information on documented effects of low DO for these species. For additional coverage of several other species and groups including salmonids see Yeager (1990 M.S.).

Cyprinids Fathead Minnows (Pimephales), Carp (Cyprinus Carpio) and Goldfish (Carassius Auratus)

The three cyprinid species covered here are those for which most DO information is available. Most life stages of these species are tolerant of low DO levels and are undoubtedly unrepresentative of typical DO requirements for a large percentage of the species in the family Cyprinidae. This family includes a large number of species which dwell in riffles or runs, habitats typically high in DO concentrations.

Adult and juvenile carp are very tolerant of low DO, a condition of many of the warm, fertile waters where carp are often found (Sigler, 1955, 1958; and McCrimmon, 1968). Hover (1976) reported carp feeding in an oxygen-depleted hypolimnion at DO concentrations less than 2 mg/l. Adult carp gulp air when the DO is 0.5 mg/l or less (Yashouv, 1956).

Lethal concentrations (50 percent mortality) of constant 1 day exposure DO for carp are 0.4-0.8 mg/l at 10° and 20°C, respectively; and for 7-day exposures, 0.4, 1.2, and 2.8 mg/l at 10°, 16°, and 20°C, respectively (Downing and Merckens, 1957). Lower lethal oxygen levels reported for fry held in the laboratory are less than 1.6 mg/l (between

0.2 and 1.6 mg/l) at 21-22°C (Douderoff and Shumway, 1970; Askerov, 1975). At temperatures less than 20°C, the lower lethal oxygen levels for carp juveniles is less than 1 mg/l (Privolnev, 1954; Downing and Merkens, 1957). However, growth rate of juveniles begins to decrease at approximately 2.1 mg/l at 20-23°C (Chiba, 1965).

For the goldfish and fathead minnow, declining DO values less than 2 mg/l caused mortality (Fry et al., 1947 and Black et al., 1954, respectively). Carp eggs are, however, not tolerant of low oxygen levels, but minimal (4 percent) survival has been reported (Kaur and Toor, 1978) for short exposures to DO concentrations as low as 1.2 mg/l at 25°C. Hatching success increases with increasing DO. Kaur and Toor (1978) also reported 40 percent hatching success at 3 mg/l; 65 percent at 6 mg/l; and 92 percent at 9 mg/l DO, and stated that DO levels below 6 mg/l appeared inadequate for proper survival of carp embryos to hatching.

Critical concentrations (see largemouth bass section for definition) identified for the carp were 3.4 and 2.9 mg/l DO at 10° and 20°C, respectively (Beamish, 1964). Respiration becomes elevated (Itazawa, 1971; Davis, 1975) at or below 3-5 mg/l (13° and 23°C, respectively). For the goldfish, critical concentrations were 1.8 and 3.5 mg/l DO at 10° and 20°C, respectively. Barr et al. (1957) found that acclimation of goldfish to low DO concentrations affected their oxygen consumption and standard metabolism. As possibly occurs with many fish, acclimation rate and timing may thus affect the physiological needs of fish for maintenance of normal activities such as feeding. This factor could have large ramifications for impairment of production for species of fish either intermittently or dielly exposed to widely fluctuating DO levels in tailwaters. In general, critical concentrations for cyprinids fall

between 2 and 4 mg/l with higher temperatures correlated with higher critical DO levels. However, EPA (1986) critically evaluated the data of Beamish (1964) and suggested that, as indicated by increased ventilation rather than decrease in oxygen consumption, the first signs of hypoxic stress were at even higher DO levels (4.2 and 5.8 mg/l DO at 10° and 20°C, respectively) than previously reported for the carp.

Chronic effects of continuous low DO at several concentrations on the life cycle of the fathead minnow were thoroughly investigated by Brungs (1971). Spawning did not occur at 1 mg/l; number of eggs produced per female was reduced at 2 mg/l, but not at higher concentrations; and where spawning occurred, the percentage hatch of eggs (81-89 percent) was not affected when the larvae were exposed to the same concentration as their parents. With decreasing DO, incubation period increased from the normal 5 days to 8 days. Mean larval survival was 6 percent at 3 mg/l, 25 percent at 4 mg/l, 66 percent at 5 mg/l, and 50 percent in controls. Survival of larvae was thus directly proportional to DO concentration. Mean growth of surviving larvae at 5 mg/l was about 20 percent less than that of controls, but whether or not density-dependence was a factor is not known. Though commonly used in toxicity testing, the effects of fluctuating DO concentrations on this species are not known.

Channel Catfish (*Ictalurus Punctatus*)--Warmwater

Channel catfish are a ubiquitous species occurring in reservoirs, and rivers, as well as warm, cool, and even cold tailwaters throughout the U.S. Within lakes the distribution of channel catfish may be markedly affected by DO concentrations related to stratification. Within a small lake in Kansas (Mosher, 1983) where DO was nil at the 4 m depth,

channel catfish were confined (89 percent) to the upper 3 m of the water column. When stratification was prevented and the DO concentration was greater than 4 mg/l throughout the water column, 64 percent of the fish were located below the 3 m isopleth. Dissolved oxygen levels of 5 mg/l appear marginally adequate for growth and survival of channel catfish (MacMahon and Terrell, 1982), but DO concentrations greater than 7 mg/l are optimal. Below 5 mg/l feeding is reduced (Randolph and Clemens, 1976).

Exposure to low DO significantly reduces growth of fingerling channel catfish. After a six week exposure and maximal feeding, channel catfish reared at 60 percent (5 mg/l) saturation level DO, showed 22 percent less weight gain than those reared at 100 percent (8 mg/l) saturation (Andrews et al., 1973). On lower rations for 14 weeks channel catfish growth was reduced only at the 36 percent (3 mg/l) saturation level. At this DO concentration fish were noticeably lethargic and fed poorly. In long-term (up to 177 days) studies exposing catfish to different DO levels, Raible (1975) found a gradual reduction in growth at each decreasing concentration below 6 mg/l. For each mg/l increase in DO between 3 and 6 mg/l, he calculated a 10-13 percent increase in growth. When compared with control fish over a 10-week test period (Carlson et al., 1980), weight gain of catfish was reduced by 14, 39, and 54 percent at DO concentrations of 5.0, 3.4, and 2.1, respectively. Growth rates were reduced 5, 18, and 23 percent, respectively. If of long enough duration, moderate reductions in growth rate may thus have correspondingly larger effects on weight gain. The embryonic and larval stages of the channel catfish, along with the walleye, northern pike, and smallmouth bass, are more sensitive to low DO concentrations than

those of most other cool and warmwater fishes. Reduced DO concentrations lighten pigmentation, extend incubation periods, delay feeding and reduce early growth of channel catfish (Carlson et al., 1974). During 2- or 3-week exposures at 25°C, survival of embryos and larvae of channel catfish was slightly reduced at 5 mg/l and significantly reduced at 4.2 mg/l. At a slightly higher temperature (28°C) survival was reduced at 3.8, 4.6, and 5.4 mg/l. Total mortality occurred at 2.3 mg/l.

Striped Bass (*Morone Saxatilis*)--Warmwater

Both field observations and experimental results indicate that in both fresh water and estuaries, striped bass become physiologically stressed as DO concentrations decrease to about 3 mg/l. Concentrations of 2 mg/l DO are uninhabitable for striped bass. Chittenden (1971a, 1971b), working in Delaware Bay, found that the distribution of striped bass was bounded by the 3 mg/l isopleth. Cheek et al. (1985) observed progressive limitation of striped bass in a reservoir to areas where temperatures were less than 24°C and DO was greater than 4 mg/l. Talbot (1966) suggested 4 mg/l DO was too low for successful reproduction of striped bass. But striped bass appear to have the ability to somewhat tolerate DO conditions (Mansueti, 1961, Neumann et al., 1981) marginal for many other species of fish.

The performance of striped bass under conditions of low DO concentrations has been defined experimentally in several investigations. Krouse (1968) concluded that striped bass could survive DO concentrations of 3 mg/l in the 13-25°C range of temperatures, but not at 1 mg/l. Turner and Farley (1971) observed a reduction in survival of both eggs and larvae after eggs were exposed to 4 or 5 mg/l DO concentrations when

compared to those hatched at saturation levels of DO. As time of exposure to low DO increased from 6-30 hr mortality of eggs and larvae increased. Dorfman and Westman (1970) observed 80 percent survival of striped bass juveniles transferred from ambient DOs to 2 (20°C) or 3 mg/l (25.6°C). Juvenile striped bass acclimated to 18°C (Meldrim et al., 1974), avoided DO concentrations of 3.8-4.0 mg/l in experimental gradients. Appetite is affected adversely at low DO levels (Hoff et al., 1966). As DO levels were lowered, Chittenden (1971b) documented "restlessness" at 3 mg/l (16-19°C), with inactivity, loss of equilibrium, and death occurring at lower concentrations. Ventilation rate was maximum at 2-3 mg/l but declined at lower DO concentrations.

Striped bass are most often thought of as reservoir or anadromous estuarine fishes, but they will often leave warm deoxygenated reservoirs and, seeking both acceptable thermal and oxygen refugia, move into cooler, more oxygenated waters of mainstream reservoir tailwaters or spring-fed waters. Within some reservoirs, as summer epilimnetic temperatures rise above thermal tolerances and hypolimnetic oxygen depletion expands, a temperature-oxygen "squeeze" causes mortalities in some populations of larger adult striped bass (Coutant, 1985). In one instructive field study (Coutant, 1980), radio and thermister-tagged adults made repeated attempts to find habitat with acceptable temperature and oxygen levels by rapidly moving between shallow depths with suitable DO but too high temperatures (>25°C), to cooler (23-24°C) but oxygen-deficient depths. Fish consistently turned back toward the surface when encountering DO levels in the 0.5-2.5 mg/l range.

Sunfish (Lepomis spp.)--Warmwater

Other than for the adult bluegill, very little is known about the DO requirements for other species and life stages of warmwater sunfishes. Bluegills can tolerate DO levels below 1 mg/l for short durations (Baker, 1941; Cooper and Washburn, 1946; Moss and Scott, 1961; Petrosky and Magnuson, 1973), but adults showed considerable avoidance of 1.5-3 mg/l DO (Whitmore et al., 1960) in "channeled avoidance tanks." No avoidance of 4.5 mg/l was observed. The first external signs of stress occur as DO levels approach 5 mg/l; at 3 mg/l, bluegills intermittently swim to the surface; and at 1 mg/l, feeding ceases (Petit, 1973). Critical levels (see largemouth bass section for definition) of DO for bluegill are 0.75-1.5 mg/l at 25°C and 2.0 mg/l at 35°C (Moss and Scott, 1961). No adverse effects on growth, survival or distribution pattern have been documented when DO levels have exceeded 5.0 mg/l (Stewart et al., 1967; Petit, 1973).

Early life stages of bluegill are more hardy than smallmouth bass with respect to toleration of low DO. In in situ tests (Peterka and Kent, 1976), a 4-hr exposure to 0.5 mg/l caused no mortality of embryonic stages, but was lethal to sac-larvae. Sac-larvae, did survive similar exposure to 1.8 mg/l DO. However, the larval stage, probably the most DO sensitive life stage, was not tested. Adult warmouth sunfish are extremely tolerant of low DO conditions of short duration, being among the last species to die when subjected to low DO (Larimore 1957). Warmouth survived concentrations under laboratory conditions of 0.3-1.0 mg/l (Larimore, 1957) (Gould and Irwin, 1965), and in a lake where access to the surface was possible, down to 0.7-1.3 mg/l DO (Baker, 1941). However, based on oxygen consumption rate experiments

(Larimore, 1957), the critical DO level for long-term survival is 3.6 mg/l. Dissolved oxygen requirements for other life stages are unknown.

Periodic low DO may exacerbate the toxic effects of other substances (Pickering, 1968) on sunfish such as the bluegill, but little is known about such synergistic effects. Cairns and Scherer (1958) observed decreased tolerance to toxic substances in fish exposed to DO declining from saturation for 3 hr, held at 2 mg/l for 2 hr, and then raised to saturation in 3 hr.

Smallmouth Bass (*Micropterus Dolomieu*)--Coolwater

Smallmouth bass are at least as sensitive as northern pike to low DO concentrations. During in situ experiments (Peterka and Kent, 1976), hatching success of smallmouth embryos was 0 at 0.5 mg/l, only 69 percent at 1.8 mg/l and 87-91 percent at 3.5-7.9 mg/l and in controls. At a concentration of 2.2 mg/l, survival of sac-larvae in 6-hr in situ tests conducted at natural spawning sites was only 53 percent at two days. Survival was 73-83 percent in controls and at 4.2-9.0 mg/l. However, the life stage probably most sensitive to low DO, the larval, was not tested. Siefert et al. (1974) found that no egg hatching occurred at a constant 1.2 mg/l (20°C) DO, and that though hatching occurred at 2.5 mg/l (20°C), sac-larvae died by the fifth day of exposure. Dissolved oxygen concentrations reduced to 50 percent saturation (4.4 mg/l) were not adequate for proper survival of smallmouth young at their optimal temperature (Siefert et al., 1974). Survival at 4.4 mg/l (20°C) was reduced nearly 20 percent when compared to controls; completion of hatch was accelerated; and average growth in length was reduced. Survival at

a higher temperature (28°C) was reduced an additional 20 percent when compared to 20°C. Fry feeding ceased at DO levels less than 1 mg/l (Bulkley, 1975).

Largemouth Bass (Micropterus Salmonids)--Warmwater

The DO concentration at which a reduction in the resting metabolic rate of an organism first occurs is termed the critical oxygen concentration. This point is believed to represent a marked reduction in energy use for growth and activity, a decrease in the supply of oxygen to tissues, and a partial shift to anaerobic energy production. For the largemouth bass, critical oxygen concentrations were (Cech et al., 1979) 2.8 mg/l at 30°C; <2.6 mg/l at 25°C; and <2.3 mg/l at 20°C. Bouck and Ball (1965) also identified sublethal but stressing effects on largemouth bass from a diurnally fluctuating low DO pulse by exposing them to 3 mg/l low DO for 8 hr per day for 9 days. This exposure led to effects such as: dramatically increased blood clotting rate, modified serum proteins, interference with digestive processes and vomiting of undigested food, lethargy, loss of natural color, and increased ventilation rates. The DO level at which largemouth bass are not adversely affected is "well above" 3 mg/l (Bouck and Ball, 1965).

Total mortality has been reported for the largemouth bass under constant or declining DO levels from <1-3.1 mg/l (Moore, 1942; Hart, 1945). During experiments of constant exposure to low DO (Carlson and Siefert, 1974), survival of largemouth bass was reduced at 35 and 20 percent saturation, but not significantly at 50 and 75 percent saturation. Dudley (1969) also found that the survival of largemouth bass embryos decreased markedly at 2.0, 2.1, and 2.8 mg/l at 15°, 20°, and 25°.

and 25°C (about 20-35 percent saturation), respectively. Beginning the second day after fertilization and continuing until the sixth day of life (Speer, 1977), embryos and larvae of the largemouth bass become increasingly sensitive to oxygen deficiency, whether constant or varying. Thereafter, they became more resistant, possibly due to the beginning of opercular movement on that day. For all days preceding and following the sixth (the most sensitive day) survival consistently increased as: exposure period to low DO became shorter (24 vs 6 vs 3 hr); oxygen concentration was higher (1-2.5 mg/l); and temperature was lower (25°C vs 20°C). All largemouth larvae died after only a 3-hr exposure to a DO concentration of 2.5 mg/l at 25°C (Speer, 1977). Latent damage to the larvae's ability to open the mouth and feed after earlier exposure to low DO, was documented at all DO levels below 2.5 mg/l at 20°C. Even at 3 mg/l (20°C) and 4-5 mg/l (25°C) normally quiescent sac-larvae became very active, swimming vertically several centimeters. This behavior could result in drastically increased losses due to predation and displacement from nests. As for many species of nonsalmonids, acute laboratory tests (24-96 hr duration) typically just do not accurately reflect the latent mortality that probably occurs.

Growth rates of the largemouth bass are dependent upon DO concentration at temperatures between 1° and 29°C. Between 20° and 29°C, growth impairment, and decreased food consumption has been demonstrated for all DO concentrations below saturation (Warren et al., 1973). At 15°C dependence of growth rate on DO levels was apparent only at about 3.5 mg/l and below. Thus, there appears to be a critical temperature between 15° and 20°C, above which growth rates of largemouth bass are depressed by even moderate reductions in DO level below saturation.

The growth and food consumption rates of juvenile largemouth bass subjected to widely fluctuating DO concentrations (Warren et al., 1973) were markedly less than their estimated growth at constant concentrations equal to the means (arithmetic and geometric) of the fluctuating concentrations. Mean lower limit was about 2 mg/l and the mean upper limits in this study were about 6, 8, or 17 mg/l, depending upon treatment. The fish were exposed daily to high and low concentrations, usually for equal periods following periods of gradual transition. Low concentrations occurred at night and early in the morning. The growth of fish subjected to these diurnally fluctuating conditions often proved equivalent to that which would have occurred at constant levels only a little above the lower limit of the wide fluctuations. Exposure to cycling oxygen levels with daily minimums of about 2 mg/l and daily maximums of 4-17 mg/l reduced growth of juveniles held at 26°C (Stewart et al., 1967). Under any fluctuating regime the growth occurring was almost always less than that expected should the fish have been held at a constant concentration equal to the mean concentration.

Carlson and Siefert (1974) also reported decreases in growth of larvae with any reduction of DO below saturation. Concentrations from 1.7-6.3 mg/l reduced growth of early stages 10-20 percent. Even at concentrations as high as 4.5 mg/l hatching was premature and feeding was delayed, both factors which could lead to increased mortality of the young. Growth of juvenile largemouth is reduced at 5.9 mg/l DO and below (Stewart et al., 1967). Concentrations of 5.1 and 5.4 mg/l DO produced reductions in growth rate of 20 and 14 percent respectively, whereas 5.8 and 5.9 mg/l had no effect on growth. A limited study conducted in artificial ponds (Brake, 1972) indicated that a 2.5 mg/l

reduction in DO concentration below saturation at 26°C resulted in a 17 percent reduction in the mean growth rate of juvenile bass. Though the data are limited, good agreement between this "mesocosm" study and a laboratory study (Trent, 1971) on the degree of correlation between growth rate reduction and reduced DO levels, was observed. Overall the growth rate response to low DO for largemouth bass appears to be intermediate between the more sensitive salmonids and northern pike and the less sensitive yellow perch (EPA, 1986).

Juvenile largemouth show distinct avoidance of 1.5 mg/l and some avoidance of DO levels at or below 4.6 mg/l (Whitmore et al., 1960, Warren et al., 1973). Final maximum sustained swimming speeds are reduced (Dahlberg et al., 1968; Warren et al., 1973) below 5-6 mg/l (60-72 percent saturation) DO. Swimming ability by the largemouth bass in reduced oxygen may also be affected by temperature and season. Katz et al. (1959) reported that 6-cm largemouth bass could resist water current of 25 cm/sec at 25°C in September at oxygen levels as low as 2.0 mg/l. However, at 15-17°C in December they were unable to do so even at 5.0 mg/l. As for salmonids swimming performance of largemouth bass appears to be more affected by low DO at lower temperatures.

The distribution of largemouth bass within some reservoirs appears to be seasonally limited by DO levels. Within two southwestern reservoirs (Rinne et al., 1981) the factor most strongly associated with the distribution of largemouth bass and their prey was their limitation to areas with DO levels greater than 2 mg/l, rather than euphotic zone or temperature.

Crappie (Pomoxis spp.)--Warmwater

Both the white (Pomoxis annularis) and the black (P. nigromaculatus) crappie are discussed here. Lethal DO limits and conditions for the crappie have not been well defined. Acute mortality for the white crappie at 0.4 mg/l was reported as 100 percent (Baker, 1941), if fish were denied access to the surface and 50 percent if allowed access to the surface. Fish held in the laboratory with daily fluctuations in DO conditions of 1.8-4.1 mg/l exhibited aberrant behavior of breaking the water surface with their mouths, increased gill ventilation, erratic swimming behavior, and loss of color. These changes were observed cyclically and coincided with the lowest portion of the diel fluctuations in DO concentration. However, mortalities did not occur. In acute field tests of 24 or 48 hr duration (Moore, 1942), for the black crappie 100 percent mortalities have been reported at 1.4 mg/l DO in winter at 4°C, and 4.3 mg/l DO in summer at 26°C. Fish were held in cages submerged in a lake at relatively constant DO levels. Sigler and Miller (1963) reported that DO levels below 1.4 mg/l also often cause mortality in black crappie populations.

White crappie were found in reservoirs at DO concentrations as low as 3.3 mg/l (Grinstead, 1969), but were rarely found at 2.0 mg/l (Gebhart and Summerfelt, 1974). Whether these DOs constitute suboptimal DO conditions for growth, long-term survival, or production impairment of crappie in the field is not known.

Exposed in two sets of laboratory tests to constant DO concentrations of 2.5, 3.5, 4.0, 5.0, 5.5, 6.5, and 7.0 mg/l and ambient DO (Siefert and Herman, 1977; Carlson and Herman, 1978), mature black crappie spawned at all concentrations. No discernable effects of

reduced oxygen at the levels tested were observed on spawning success, numbers of embryos produced, viability, hatching success, or larval survival through the swim-up stage. However, timing of spawning appeared affected by DO concentration. Fish held at 2.5 mg/l exhibited territorial behavior, and started and finished spawning sooner at lower temperatures than fish held at higher DO levels. Fish held at saturation were among the last to spawn and this occurred at the highest spawning temperatures. Inducement of early spawning could affect the survival of offspring in the natural environment, but the production impairment or ecological significance of early spawning is at present unknown.

Fish exposed to mean diel DO fluctuations from 0.8-1.9 mg/l above and below concentrations of 2.5, 4.0, 5.5, and 7.0 mg/l successfully spawned at all concentrations except the lowest fluctuating treatment of 1.8-4.1 mg/l, where no spawning occurred (Carlson and Herman, 1978). These studies indicated that concentrations of 2.5 mg/l DO or above are adequate for overwintering and spawning of black crappie; and that diel fluctuations down to 1.8 mg/l caused hypoxic stress which inhibited reproduction.

Yellow Perch (*Perca Flavescens*)--Coolwater

Young yellow perch appear to be more tolerant of lower DO concentrations and more adaptable to moderate and gradual diurnal DO fluctuations at low DO concentrations than many other fishes. Survival of juvenile yellow perch in 67-day laboratory tests was not affected by either constant (treatment means from 2.0-8.5 mg/l) or diurnally fluctuating (3.8-1.4 mg/l fluctuations) DO levels between means of 1.4-8.5 mg/l (Carlson et al., 1980). In the constant DO tests,

consumption of food was somewhat reduced at 3.5 mg/l, and significantly so at 2.0 mg/l and below. Significantly reduced growth occurred only with fish reared near 2.0 mg/l. Reductions in weight gain were 2, 4, and 30 percent at 4.9, 3.5, and 2.1 mg/l, respectively. Carlson et al. (1980) concluded that mean diurnal fluctuations of 3.8-1.4 mg/l DO also did not affect growth, even though the percentage weight gains from initial weights were significantly lower for fluctuating DOs when compared to constant DO levels with similar means (79-93 percent vs 155-216 percent weight gain, respectively). Instead they attributed the differences to possible other factors such as food quality, greater disturbance by experimenters of fish in fluctuating DO tests, genetic differences, differences in initial starting weights, or environmental history.

Short-term (less than 5 days duration) laboratory and field studies on the winter DO requirements of yellow perch have determined that levels from 0.2-1.5 mg/l DO are lethal to adults (Moore, 1942; Cooper and Washburn, 1946; Magnuson and Karlen, 1970). However, 3.5 mg/l DO was lethal (Moore, 1942) at a summer temperature of 26°C.

Walleye and Sauger (Stizostedion spp.)--Coolwater

Although most investigations have related the spatial distribution of walleye in terms of food availability and depth of light penetration, the distribution-limiting effects within reservoirs of low DO on walleye and their congener, the sauger, has long been recognized (Dendy, 1945). Adult walleye can tolerate a DO concentration of 2 mg/l for short periods of time (Scherer, 1971), but the greatest abundance of walleye in reservoirs occurs where DO levels are greater than 3-5 mg/l. Walleye lose

their negatively phototactic (light avoiding) behavior at 2-4 mg/l DO and concentrations below 1 mg/l are lethal to adults (Scherer, 1971).

Adult walleye in reservoirs appear to undergo a thermal-DO "squeeze" somewhat similar to that experienced by the striped bass. In a reservoir in Tennessee, Dendy (1945) documented the movement of walleye out of areas where DO levels had dropped to 0.0-1.5 mg/l, into the upper portion of the reservoir where DO concentrations were at least 3 mg/l. As the seasonal depletion of DO advanced, both walleye and sauger were forced into much warmer water temperatures (70-80°F, and 60-70°F) than those customarily occupied by adult walleye and lethal for early life history stages (Siefert and Spoor, 1973). Dissolved oxygen levels above 3 mg/l did not appear to affect walleye distribution within reservoirs. In comparison, sauger appeared slightly more tolerant of low DO, the majority remaining in areas with 1.6-3.0 mg/l, but were forced to either move downstream or up above the low DO water when levels fell to 0.0-1.5 mg/l. Avoidance of these low DOs indicates stressful conditions. Scott (1976) and Ager (1976) also documented the summer confinement of walleye in Center Hill Reservoir of Tennessee to shallower areas of higher DO just above the thermocline, where although temperatures were less than optimal, the coolest water with sufficient DO was found.

Dissolved oxygen levels of greater than or equal to 5 mg/l are considered necessary for high survival and growth of embryos (Oseid and Smith, 1971). As indicated by a lack of carotenoid pigments, a poorly developed temporary embryonic respiratory system, and characteristics of adult spawning sites, embryos and larvae of the walleye

require well-oxygenated water for survival and development (Balon et al., 1977; McElman and Balon, 1979). Siefert and Spoor (1973) conducted continuous-level laboratory tests on walleye eggs and larvae of 12.5, 20, 25, 35, 50, and 100 percent DO saturation at 17°C (1.2, 1.9, 2.4, 3.4, 4.8, and 9.6 mg/l DO, respectively); and 25, 50, and 100 percent saturation at 20°C (2.2, 4.5, and 8.9 mg/l DO, respectively). Survival at 50 percent saturation (4.8 mg/l at 17°C) was comparable to that in 100 percent saturation controls. Survival was drastically reduced at 35 percent saturation (3.4 mg/l at 17°C) and all larvae at lower concentrations died before initiation of feeding. At 12.5 percent saturation (1.2 mg/l at 17°C), all eggs died before hatching. At 35 percent saturation and above, most mortality occurred to larvae; whereas at saturations below 35 percent, most mortality was that of eggs. At 20-25 percent saturation, larvae were noticeably weak swimmers.

Dissolved oxygen concentrations of 3.4 mg/l or lower result in delayed hatching, significant reductions in size at hatching and poor swimming ability (Van Horn and Balch, 1956; Colby and Smith, 1967; Oseid and Smith, 1971; and Siefert and Spoor, 1974). Optimal DO conditions for fry are concentrations above 5 mg/l (Siefert and Spoor, 1974). Moyle and Clothier (1959) also observed poor survival of stocked fry below 5 mg/l DO.

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Table F-1. Impacts of biological importance resulting from DO depletion in reservoirs. Not all impacts may occur within any one reservoir or downstream regulated river reach, and all are dependent upon the species of fish present.

Within both the reservoir and downstream regulated river

Impaired growth, and increased direct lethality, reducing survival of early life stages (embryos, larvae, alevins) not mobile enough, not able to sense low DO concentrations, or requiring higher inter-gravel concentrations of DO.

Disruption of upstream spawning migrations by acting as a barrier to fishes not able or willing to pass through areas of low DO to reach spawning grounds.

Blockage of downstream passage of young of anadromous fishes.

Behavioral changes induced by low DO stress, which may make young or adult fishes more susceptible to predation.

Loss of acceptable habitat meeting DO requirements of fish, resulting in emigration of fishes from the entire area to avoid low concentrations of DO.

Reduction (by direct mortality or by inducing drift) of diverse food supply by eliminating or decreasing numbers of "preferred" bottom-dwelling organisms such as burrowing mayflies in reservoirs or stoneflies in rivers.

Toxicity (lethal and sublethal) to fishes or benthos from hydrogen sulfide or re-solubilized manganese and iron forming in the anoxic hypolimnion of the reservoir and subsequent release to the regulated river.

Within the reservoir

Forcing of adult or juvenile fishes to move into shallower, more well-oxygenated, but possibly thermally stressful areas of the reservoir (thermal/DO "squeeze" Figure F-1). This movement may result in reduced survival (fish kills) and/or growth due to physiological stress, predation, disease, or by concentrating fish, making them more susceptible to harvest by anglers.

Reduction of spatial habitat for spawning by deepwater spawners.

Reduction or loss of deepwater nursery areas for fish species requiring such habitat

Within the downstream regulated river

Loss of riffle or shallow riverine spawning and nursery habitat to riverine species sensitive to low DO concentrations.

Fish kills resulting from sudden changes in DO levels in conjunction with other rapidly changing water quality factors resulting from reservoir operations.

Table F-2. Water quality criteria for ambient dissolved oxygen concentration.

	Coldwater Criteria		Warmwater Criteria	
	Early Life Stages ^{1,2}	Other Life Stages	Early Life Stages ²	Other Life Stages
30 Day Mean	NA ³	6.5	NA	5.5
7 Day Mean	9.5 (6.5)	NA	6.0	NA
7 Day Mean Minimum	NA	5.0	NA	4.0
1 Day Minimum ^{4,5}	8.0 (5.0)	4.0	5.0	3.0

¹ These are water column concentrations recommended to achieve the required intergravel dissolved oxygen concentrations shown in parentheses. The 3 mg/l differential is discussed in the criteria document. For species that have early life stages exposed directly to the water column, the figures in parentheses apply.

² Includes all embryonic and larval stages and all juvenile forms to 30-days following hatching.

³ NA (not applicable).

⁴ For highly manipulatable discharges, further restrictions apply (see page 37)

⁵ All minima should be considered as instantaneous concentrations to be achieved at all times.

Source: USEPA (1986)

Table F-3.

THE INCIPIENT OXYGEN RESPONSE THRESHOLDS FOR VARIOUS NON-SALMONID FISH. RESPONSE LEVELS REPORTED ARE INCIPIENT OXYGEN LEVELS WHERE EFFECTS FIRST BECOME APPARENT THUS PROVIDING A "BIOLOGICAL INDICATION" OF THE ONSET OF HYPOXIS STRESS.

<u>Species</u>	<u>Size</u>	<u>Temp (c)</u>	<u>mg O₂/liter</u>	<u>Response to oxygen level</u>
Brown, bullhead <u>Ictalurus nebulosus</u>	43-127 g	9-10	6.95-6.80	onset of oxygen- dependent of oxygen uptake
carp, <u>Cyprinus carpio</u>	77-350g 30-600g	10 20	3.59 4.71	standard oxygen uptake elevated (depressed at lower levels)
" "	235-785g	13.3-25	5.39-4.34	blood ceased to be fully saturated with O ₂ below this level
Walleye, <u>Stizostedion vitreum</u>	2 yr-old	22	4-2.0 5.5-4.0	loss of negative phototaxis (light avoidance behav- ior) increased mobility, "darting behavior"
Largemouth bass, <u>Micropterus</u> <u>salmonides</u>	5-9 cm	-	4.5 1.5	some indication of avoidance behavior marked avoidance
Largemouth bass, <u>Micropterus</u> <u>salmoides</u>	juvenile	25	5-6	final (maximum sustained) swimming speed reduced below this level
Bluegill, <u>Lepomis</u> <u>macrochirus</u>	5-9 cm	-	3.0 1.5	some avoidance behavior strong avoidance
American shad, <u>Alosa sapidissima</u>	-	-	2.5-3.0	threshold for migration through polluted areas
Northern pike, <u>Esox lucius</u>	from fertilization to feeding larvae	15,19	3.35-3.09	necessary O ₂ level for proper hatching, survival and development

Table F-4,

SUMMARY OF LETHAL LEVELS OF DISSOLVED OXYGEN PUBLISHED AFTER THE YEAR 1937.

Species of fish Scientific and Common Names	Age or Size	Dissolved O ₂ ^a mg/l ^a	Deaths	Exposure ^b / C	Temp C	Reference	Remarks ^c
SALMONIDAE							
<i>Coregonus autumnalis</i> Whitefish, Baikal omul	larvae	1.3-1.5	First	Declining O ₂	-	Mescheriakova and Cherniaev (1963)	
<i>Coregonus nasus</i> Broad whitefish	1 day	1.9*	-	Declining O ₂	12	Chernikova (1964)	*Cessation of opercular movement
	120 days	1.9*	-	Declining O ₂	12	Chernikova (1964)	*Same as above
	209 days	1.1*	-	Declining O ₂	10	Chernikova (1964)	*Same as above
	Fingerling	2.1*	-	-	17	Privolnev (1963)	*Reported threshold concentration; methods unknown
<i>Oncorhynchus gorbuscha</i> Pink salmon	Fingerling	2.0*	-	-	17	Privolnev (1963)	*Same as above
<i>Oncorhynchus keta</i> Chum salmon	4-11 cm	1.1-1.7	0-83%	Constant O ₂ 24 hours	12-20	Davison et al. (1959)	
<i>Oncorhynchus kisutch</i> Coho salmon	4-11 cm	1.5	15%	Constant O ₂ 24 hours	22	Davison et al (1959)	
	4-11 cm	2.1	3%	Constant O ₂ 24 hours	24	Davison et al (1959)	
	Juvenile	1.7-2.0*	0-90%	Constant O ₂ 24 hours	20-22	McNeil (1956)	*CO ₂ concentrations 3 to 20 mg/l
<i>Oncorhynchus mykiss</i> CO ₂ Rainbow trout	3-4 g	1.1-1.3	71%	Constant O ₂ 18-25 hours	12-13	Townsend et al (1938)	*Loss of equilibrium
	Yearling	1.2-1.6	50%*	Constant O ₂ 24 hours	14	Townsend and Earnest (1940)	*Loss of equilibrium
	6 mo	1.3-1.6*	50%	Constant O ₂	13-20	Alabaster et al (1957)	*Range of estimated values; no added
	6 mo	2.6-2.7*	50%	Constant O ₂ 24 hours	13-20	Alabaster et al (1957)	*Range of estimated values; CO ₂ concentration 30 mg/l

Table F-4,

(CONTINUED)

Species of fish Scientific and Common Names	Age or Size	Dissolved O ₂ ^a mg/l ^a	Deaths	Exposure ^b / C	Temp C	Reference	Remarks ^c / C
<i>Salvelinus fontinalis</i>	180 days	1.8*	None	Constant O ₂ 2 days	16	Bishai (1960)	*Same as above
	17 g	(2.0*	100%	Declining O ₂	17-20	Black et al (1954)	*CO ₂ tensions 0-40 mm Hg
	Yearling	2.0-3.4	First*	Declining O ₂	12-21	Burdick et al. (1954)	*Loss of equilibrium
	Yearling	1.6-2.6	50%*	Declining O ₂	12-21	Burdick et al. (1954)	*Loss of equilibrium
	Yearling	1.2-1.7	Last*	Declining O ₂	12-21	Burdick et al. (1954)	*Loss of equilibrium
for	27 g	above 2.5	None	Constant O ₂ 24 hours	12-23	Graham (1949)	
	27 g	below 1.9	100%	Constant O ₂ 24 hours	12-23	Graham (1949)	
	Fingerling	1.0-1.8*	50%	Constant O ₂	9	Shepard (1955)	*Estimated incipient lethal levels
				3.5 days			varying acclimation O ₂ levels
				Declining O ₂	21-23	King (1943)	
<i>Salvelinus fontinalis</i> (Cont.)	4.5 g	2.3	50%	-	0	Privolnev (1954)	Methods unknown
Brook trout	-	4.0-4.5	first	-	2	Karzinkin (1942)	*Reported lethal threshold; methods unknown
<i>Stenodus leucichthys</i>	4.7 g	2.5-2.6*	-				
Inconnu							

a The symbol (preceding an O₂ concentration value in this column indicates that several or numerous lethal O₂ concentrations reported were all less than (often much less than) the value shown.

b "Declining O₂" signifies gradual reduction of O₂; unless otherwise noted under Remarks, O₂ was reduced by respiration of test fish.

c. For references see Doudoroff and Shumway (1970).

d The asterisk (*) is used to indicate to which item or items in the columns at the left the remark pertains or is most pertinent.

Table F-4,

(CONTINUED)

Species of fish Scientific and Common Names	Age or Size	Dissolved O ₂ ^a mg/l ^a /	Deaths	Exposure ^b /	Temp C	Reference	Remarks ^c /
<i>Salmo trutta</i> Brown trout	40 days	0.7*	none	Constant O ₂ 2 days	5	Bishai (1960)	*Same as above
	80 days	2.8*	None	Constant O ₂ 3 days	9	Bishai (1960)	*Same as above
	135 days	2.2*	None	Constant O ₂ 2 days	16	Bishai (1960)	*Same as above
	3-6 g	0.7-1.6*	-	-	-	Nikiforov (1953)	*Range of lethal levels for individual fish; methods unknown
	7 cm	2.2*	None	Constant O ₂ 5 days	8	Lindroth (1949)	*Not reported as a tolerance limit
	Fingerling	1.5*	-	-	15	Privolnev (1963)	*Reported threshold concentration; methods unknown
	Yearling	1.9*	-	-	16	Privolnev (1963)	*Same as above
	36 days	3.1-3.7	-	Declining O ₂	15	Privolnev (1947)	
	107 days	1.2-1.3	-	Declining O ₂	15	Privolnev (1947)	
	Yearling	1.6-2.8	First*	Declining O ₂	9-21	Burdick et al. (1954)	*Loss of equilibrium
	Yearling	1.5-2.5	50%*	Declining O ₂	9-21	Burdick et al. (1954)	*Loss of equilibrium
	Yearling	1.3-2.3	100%*	Declining O ₂	9-21	Burdick et al. (1954)	*Loss of equilibrium
	-	1.1-3.3*	First	-	0	Privolnev (1954)	*Methods unknown
	Newly-hatched 40 days	0.3-6.6*	None	Constant O ₂ 5 days	7	Bishai (1960)	*Lowest O ₂ level tolerated by all
	2.9 g 80 days	3.2 1.6*	50% None	Constant O ₂ 2 days Declining O ₂ Constant O ₂ 3 days	5 22-24 9	Bishai (1960) King (1943) Bishai (1960)	*Same as above *Same as above

Table F-4.

(CONTINUED)

Species of fish Scientific and Common Names	Age or Size	Dissolved O ₂ ^a mg/l ^a	Deaths	Exposure ^b / C	Temp C	Reference	Remarks ^c
<i>Oncorhynchus nerka</i> Sockeye salmon	Yearling	1.3-2.5	First*	Declining O ₂	11-22	Burdick et al (1954)	*Loss of equilibrium
	Yearling	1.1-1.8	50%*	Declining O ₂	11-22	Burdick et al (1954)	*Loss of equilibrium
	Yearling	0.8-1.4	100%*	Declining O ₂	11-22	Burdick et al (1954)	*Loss of equilibrium
	4.4 g	2.5	50%	Declining O ₂	22-24	King (1943)	
	10 cm	2.9	None	Constant O ₂ 3.5 days	10-20	Downing and Merckens (1957)	
	10 cm	2.4-3.1	50%	Constant O ₂ 7 days	16-20	Downing and Merckens (1957)	
	Juvenile	1.6-1.7*	50-70%	Constant O ₂ 24 hours	16-20	McNeil (1956)	*CO ₂ concentrations 3-8 mg/l
	Yearling	1.5-1.6	10%	Constant O ₂ 18-24 hours	11-13	Townsend et al (1938)	*Loss of equilibrium
	Yearling	1.4 or less	100%*	Constant O ₂ 18-24 hours	11-13	Townsend et al (1938)	*Loss of equilibrium
	2 yr	0.8-1.2 0.5-1.5*	First -	Declining O ₂	17 15	Privoinev (1954) Streltsova (1964)	Methods unknown *Fish acclimated to 3 and 19 mg/l
<i>Oncorhynchus tshawytscha</i> Chinook salmon	88-235 mg	1.1-1.6*	-	Declining O ₂	15	Streltsova (1964)	*Same as above
	Adult	2.3-2.7	Most*	Declining O ₂	21-23	Chapman (1940)	*Dead or lost equilibrium
	Adult	2.3-2.7	most	Declining O ₂	21	Chapman (1940)	*Dead or lost equilibrium
	Fingerling	1.7-1.8	50%	Constant O ₂ 24 hours	20	Katz et al (1959)	
<i>Salmo clarki</i> Cutthroat trout	11-17 cm	1.2-1.4	50%*	Constant O ₂ 18-24 hours	11	Townsend et al (1938)	*Loss of equilibrium
<i>Salmo salar</i> Atlantic salmon tolerated	Newly- Atlantic salmon by all	0.3*	None hatched	Constant O ₂	7	Bishai (1960) 5 days	*Lowest tested O ₂ level

Table F-5. Percent reduction in growth rate of salmonids at various dissolved oxygen concentrations expressed as the median value from n tests with each species (calculated from JRB Associates, 1984).

Dissolved Oxygen (mg/l)	Species (number of tests)					
	Chinook Salmon (6)	Coho Salmon (12)	Sockeye Salmon (1)	Rainbow Trout (2)	Brown Trout (1)	Lake Trout (2)
9	0	0	0	0	0	0
8	0	0	0	1	0	0
7	1	1	2	5	1	2
6	7	4	6	9	6	7
5	16	11	12	17	13	16
4	29	21	22	25	23	29
3	47	37	33	37	36	47
Median Temp. (°C)	15	18	15	12	12	12

Table F-6. Influence of temperature on growth rate of chinook salmon held at various dissolved oxygen concentrations (calculated from Warren et al., 1973; JRB Associates, 1984).

Dissolved Oxygen (mg/l)	Percent Reduction in Growth Rate at					
	8.4°C	13.0°C	13.2°C	17.8°C	18.6°C	21.7°C
9	0	0	0	0	0	0
8	0	0	0	0	2	0
7	0	0	4	0	8	2
6	0	0	8	5	19	14
5	0	0	16	16	34	34
4	7	4	25	33	53	65
3	26	22	36	57	77	100

Table F-7. Influence of temperature on growth rate of coho salmon held at various dissolved oxygen concentrations (calculated from Warren et al., 1973; JRB Associates, 1984).

Dissolved Oxygen (mg/l)	Percent Reduction in Growth Rate at					
	8.6°C	12.9°C	13.0°C	18.0°C	21.6°C	21.8°C
10	0	0	0	0	0	0
9	0	0	0	5	0	0
8	0	1	2	10	0	0
7	1	4	6	17	0	6
6	4	10	13	27	0	1
5	9	18	23	38	0	7
4	17	29	36	51	4	19
3	28	42	51	67	6	37

Source: USEPA (1986)

WELL-MIXED SPRING CONDITIONS

EARLY SUMMER HEATING AND DEOXYGENATION

LATE SUMMER HEATING AND DEOXYGENATION

Figure F-1. Adverse Conditions for Dissolved Oxygen and Temperature Developing in a Stratified Freshwater Reservoir during the Summer.

Figure F-2. Effects of continuous exposure to various mean dissolved oxygen concentrations on survival of embryonic and larval stages of eight species of nonsalmonid fish. Minima recorded in these tests averaged about 0.3 mg/l below the mean concentrations (from EPA, 1986).

END

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