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EXHIBITS TO THE AFFIDAVIT OF DUANE A. NEITZEL

DUANE A. NEITZEL

Staff Scientist,
Ecology Group,
Environmental Technology Division
Battelle's Pacific Northwest Division

EDUCATION

B.A., Zoology, University of Washington, 1968
M.S., Biology, Washington State University, 1982

EXPERIENCE

Mr. Neitzel is a Staff Scientist with the Ecology Group at the Battelle Pacific Northwest Division. He is the Deputy to the Manager of the Laboratory's Resource and Ecosystems Management Product Line for Natural Resource Management. He joined Battelle in 1972. His research efforts have focused on the assessment of impacts to aquatic ecosystems from the development and production of energy, and the management of hazardous wastes. Mr. Neitzel's research efforts include:

- Fisheries Biology
  - Studying the impacts of shear and turbulence on juvenile fish to develop biological specifications for hydropower turbine design
  - Studying prespawning mortality in Columbia River Basin adult salmonids
  - Studying entrainment and impingement impacts to fish, shellfish, and plankton communities
  - Studying thermal tolerances of Columbia River fishes
  - Nuclear Power Plant Fouling Studies
  - Hydrogeneration Studies

- Environmental Assessment
  - Assessing nuclear powered, fossil powered, and hydro generating electrical facilities, siting and operation
  - Evaluating threats to protected and endangered animals
  - Preparation of Biological Assessments for nuclear power plants and uranium mill tailings operations
  - Preparation of 316(a) demonstrations at Columbia River nuclear power plants
  - Providing technical (primarily aquatic) guidance for the preparation of NEPA documents for nuclear power plants, Hanford Site operations, fish hatcheries in Washington State, and fish restoration programs in California

- Snake River Salmon Recovery Plan
- Editing an annual Hanford Site Characterization NEPA document to provide economy to NEPA activities at Hanford
- Baseline studies of the Columbia River at Hanford

• Planning, assessments of, and auditing of salmon hatcheries in the Columbia River Basin

- Integrated Hatchery Operations
- Yakima Fisheries Project

• Climate Change Studies

• Preparing field guides for hazardous waste managers

Mr. Neitzel has reported his work in over 100 journal articles, symposium proceedings, and technical reports. Some of his major assignments are summarized below:

Fisheries Biology

Impacts of Shear and Turbulence - Mr. Neitzel recently completed a study of the effects of fluid strain that occurs in shear environments on juvenile fish. The thrust of this study was to provide biological specifications that can be used in designing hydroelectric turbines. This work has been presented at meetings of the American Fisheries Society and HydroVision. It has been published in the Transactions of the American Fisheries Society. The work provides a quantified exposure strain rate that describes potential injurious effects and mortality for steelhead, rainbow trout, Chinook salmon, and American shad.

Prespawning Mortality – Mr. Neitzel Managed a project for the Army Corps of Engineers to assess head injuries on returning adult salmon and steelhead that have been observed at Columbia Basin fish passage facilities. The assessment was accomplished during laboratory tests exposing juvenile salmonids to pressure regimes encountered during turbine passage and rearing the exposed fish for up to 2 years. Adult fish with headburns were collected at adult collection facilities throughout the Columbia Basin and fish were examined to identify the fungi, bacteria, and pathologies that result in mortality. The results identified a procedure for treating adults with headburns that could reduce or eliminate prespawning mortalities.

Entrainment and Impingement Studies - Mr. Neitzel managed an evaluation of fish screening facilities that are being constructed in the Yakima River basin, Washington and Lemhi River basin, Idaho. The facilities are being built in irrigation canals and are designed to divert fish in the irrigation canals back to the Yakima River. The evaluation is being conducted for the Bonneville Power Administration as part of their salmonid enhancement efforts in the Columbia River basin.

Mr. Neitzel participated in a 5-year study of entrainment and impingement at two water intakes on the Columbia River. Studies included estimates of impacts to phytoplankton, zooplankton, and fish. These studies were used to support the Washington Public Power Supply System's National Pollutant Discharge Elimination System permit application. The fish studies concluded with an assessment of engineering and operational changes that eliminated significant entrainment and impingement mortalities for fish populations. In 1981, Mr. Neitzel prepared a report for the U.S. Fish and Wildlife Service that outlines procedures for providing biological input to the design, location, and modification of water intake structures. This project concluded with a guidance manual for implementation of the procedures.

Mr. Neitzel has presented the results of this regionally, nationally, and internationally, including the American Fisheries Society, an international meeting of fisheries engineers in Japan, and to the U.S. Congressional Office of Technical Assessment.

Thermal Tolerance of Fish and National Pollutant Discharge Elimination Studies - Mr. Neitzel has prepared 316(a) demonstrations for the Washington Public Supply System's Hanford Generating Project and the U.S. Department of Energy's N Reactor. He has also helped prepare other documents in support of the NPDES permit applications. These documents include: 1) a draft response to 31 questions from the Washington State Department of Ecology concerning the HGP application, 2) a justification for a Representative Important Species List of fish for the Columbia River near HGP, 3) a low impact rationale for all biotic categories except fish, and 4) a justification for redefining the mixing zone for the N Reactor discharge.

From 1982 to 1988, Mr. Neitzel managed a project to characterize the thermal discharge from a nuclear reactor. The characterization study includes: 1) a hydrological and mathematical description of the plume for a range of reactor operating conditions and river flows; 2) laboratory studies to define the thermal tolerance of five fish populations near the thermal discharge; 3) characterization of fish distribution near the discharge; and 4) and an assessment of the potential impacts to Columbia River biota. In addition to managing the project, Mr. Neitzel is responsible for the conduct of the laboratory studies.

Nuclear Power Plant Fouling Studies - Mr. Neitzel managed a team of Battelle biologists and engineers to assess fouling of nuclear power plant, service-water systems. The team prepared a "Technical Findings" document and a "Value/Impact Analysis" for improving the reliability of service-water systems at nuclear power plants. The project team first studied the correlation between biological characteristics of bivalves that promote biofouling and the engineering characteristics of service-water systems that enhance biofouling potential. Additionally, the team has studied surveillance and control techniques that are being used to prevent bivalve fouling and the interaction between potential power plant incidents and bivalve fouling. The team also studied inorganic fouling of service-water systems at nuclear power plants. The study includes an investigation of fouling and clogging by mud, silt, and corrosion products, a determination of what system components are most likely to be fouled, and an analysis of this information to improve the reliability of open cycle water systems at power plants.

Hydroelectric Generation Studies - Mr. Neitzel was responsible for planning and implementing water-level fluctuation studies, a part of the U.S. Department of Energy's Hydroelectric Program. The studies included: 1) monitoring of water-level fluctuations, temperatures, and fish populations in Columbia River sloughs, and 2) laboratory tests to determine the tolerance of intergravel developmental phases of Chinook salmon and rainbow trout to dewatering. He developed a laboratory system to mimic water-level fluctuations in salmon redds that might occur from hydroelectric utilization of water resources.

In 1983, Mr. Neitzel used this system to simulate Chinook salmon egg and embryo dewatering on Vernita Bar, Washington. This study was used to negotiate water releases at Priest Rapids Dam as required by Washington State Department of Fisheries and the Federal Energy Regulatory Commission. The studies also included a test of possible mitigation techniques for dewatered chinook salmon redds. Mr. Neitzel also participated in the reservoir impact study for the Bonneville Power Administration. This study included an assessment of impacts in six Pacific Northwest storage reservoirs from water-level fluctuations.

Environmental Assessments

Environmental Impact Statements – Mr. Neitzel has prepared EISs related to nuclear power operations and relicensing, fish hatcheries, and fish restoration projects. Recent project include the Oconee, Arkansas Nuclear One (Units 1 and 2), North Anna Power Station, Peach Bottom Atomic Plant and St. Lucie relicensing, the Trinity River Division, California, and the Central Valley Project Improvement Act. He prepared the fisheries assessment for the Early Site Permit at the North Anna Power Station in Mineral, Virginia. He was on the team that prepared the Solid Waste Management EIS for the Hanford Site. He was the document manager for the New Safe Containment EA for the Chernobyl, Ukraine. He helped prepare the EIS for the Moab Mill Tailings site in Utah for the Department of Energy. He also edits an annual Hanford Site NEPA Characterization document that to reduce the costs of NEPA document development for the U.S. Department of Energy at Hanford.

Threatened and Endangered Animals / Biological Assessments– Mr. Neitzel has prepared Biological Assessments for many NEPA documents. He recently completed documents for the Moab Mill Tailing site in Utah, power plants in Florida, Virginia, and Arkansas. Mr. Neitzel managed an effort to assess the status of the giant Columbia River spire snail *Fisherola nuttalli* and the great Columbia River limpet *Fluminicola columbiana*. Both species were candidates for protection under the federal Endangered Species Act. Data collected during this study will provide the U.S. Fish and Wildlife

Service with the data needed determine the level of protection required for these animals in the Columbia River basin. The study included a survey of sensitive aquatic habitat at the Hanford Site. During 1992, an undescribed species of *Cryptomatix* n. sp was found. This finding is used by the U.S. Department of Energy to manage the changing mission for the Hanford Site.

Preparation of 316(a) demonstrations at Columbia River nuclear power plants – see section above.

Providing technical (primarily aquatic) guidance for the preparation of NEPA documents – Recent documents:

- Generic Environmental Impact Statement for License Renewal of Nuclear Plants (Oconee Power Station, South Carolina)
- Generic Environmental Impact Statement for License Renewal of Nuclear Plants (Arkansas Nuclear One, Unit 1, Arkansas)
- Generic Environmental Impact Statement for License Renewal of Nuclear Plants (Edwin I. Hatch Nuclear Plant, Units 1 & 2, Georgia)
- Generic Environmental Impact Statement for License Renewal of Nuclear Plants (North Anna Power Station Units 1 and 2, Virginia)
- Generic Environmental Impact Statement for License Renewal of Nuclear Plants (Peach Bottom Atomic Power Stations Units 2 and 3, Pennsylvania)
- Generic Environmental Impact Statement for License Renewal of Nuclear Plants (St. Lucie, Units 1 & 2, Florida)
- Generic Environmental Impact Statement for License Renewal of Nuclear Plants (R.E. Ginna Nuclear Power Plant, New York)
- Generic Environmental Impact Statement for License Renewal of Nuclear Plants (Arkansas Nuclear One, Unit 2, Arkansas)
- Generic Environmental Impact Statement on Decommissioning of Nuclear Facilities
- Early Site Permit Environmental Impact Statement for License Renewal of Nuclear Plants (North Anna Power Station, Mineral, Virginia)
- Final Hanford Site Solid (Radioactive and Hazardous) Waste Program Environmental Impact Statement Richland, Washington
- Remediation of the Moab Uranium Mill Tailings, Grand and San Juan Counties, Utah, Draft Environmental Impact Statement
- Environmental Impact Assessment New Safe Confinement Conceptual Design Chernobyl Nuclear Power Plant – Unit 4
- Environmental Impact Statement/Environmental Impact Report (DEIS/EIR) for the Trinity River Mainstem Fishery Restoration.

Columbia River Ecological Studies - From 1973 through 1978 and again in 1981, Mr. Neitzel worked on preoperational studies for the siting of nuclear power plants on the Columbia River at Hanford. He has studied the plankton, benthos, and fish communities of the Columbia River. The studies include assessments of fish and plankton entrainment and impingement, fish stranding during low river flows related to plant construction, and turbidity sedimentation impacts. His main responsibilities were the supervision and coordination of the field and laboratory work. He was also responsible for, or assisted in, all phases of study design, sampling, subsequent laboratory analysis, and report writing.

In 1980, Mr. Neitzel participated in an assessment of aquatic and riparian resources of the Hanford Reach of the Columbia River relative to the siting of the Ben Franklin Lock and Dam Alternative. Mr. Neitzel contributed to the total report, with emphasis on the effects to white sturgeon and steelhead populations.

Planning Assessment and Auditing of Salmon Hatcheries

Integrated Hatchery Operations – Mr. Neitzel worked with a team of fisheries scientists and engineers to evaluate the operations salmon and steelhead hatcheries in the Columbia River Basin. The evaluation looked at hatchery operations, ecological interactions, and hatchery performance. He has developed a database of hatchery releases and recovery data for performance evaluations.

Yakima Fisheries Project - Mr. Neitzel managed Battelle's participation in the Yakima Fisheries Project. The projects include plans to build hatchery and rearing facilities for enhancing the salmon and steelhead populations of the Yakima Basin. Mr. Neitzel is personally involved in the long-range planning documentation which includes preparation of the project status report, project schedules, risk analysis, experimental designs, monitoring plans, an nd project reviews. These documents are used by the Bonneville Power Administration, the Yakama Indian Nation, and the State of Washington to direct this project. Battelle's participation also includes certification of monitoring facilities for juvenile and adult salmonids, statistical analysis of post release survival data, and the hypothesis analysis of the project experiments. Since 1991, Mr. Neitzel has prepared the project's planning documents for BPA, YIN, and Washington State.

Snake River Salmon Recovery Plan - Mr. Neitzel managed a project with the U.S. Army Corps of Engineers to provide technical assistance in support of the Corps' efforts to improve survival for Columbia River system salmon populations. To date, tasks have included monitoring the impacts of reservoir drawdown to salmon redd, riparian vegetation, wildlife habitat, and benthos. He is working on a biological plan to describe the potential impacts and management implications of drawing down the lower Snake River reservoirs. The plan describes effected populations, drawdown strategies, and risk management. The plan will be used by the Corps, the Bonneville Power Administration, and the U.S. Bureau of Reclamation.

Hanford Site Characterization NEPA Document – Mr. Neitzel edits this document to describe the U.S. Department of Energy's (DOE) Hanford Site environment. It is updated each year and is intended to provide a consistent description of the Hanford Site environment for the many environmental documents being prepared by DOE contractors concerning the National Environmental Policy Act (NEPA). The 2004 report was the sixteenth revision of the original document published in 1988 and is (until replaced by the seventeenth revision) the only version that is relevant for use in the preparation of Hanford NEPA, State Environmental Policy Act (SEPA), and Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) documents.

Climate Change Studies

Climate Change - Mr. Neitzel worked with an interdisciplinary group of scientists at Battelle to evaluate the potential effects of climate change on aquatic populations. The group uses archaeological data from the mid-Holocene period to analyze changes in the freshwater aquatic environs of the Pacific Northwest, United States. This assessment is used to adjust the parameters in fish-production models that are used to predict salmonid population changes in Pacific Northwest streams. The data are being used to assess the potential economic impacts related to changes in fish populations. The results of this work have been applied to chaos based models to estimate ocean survival of Pacific salmon.

Field Guides for Hazardous Waste Sites

Hazardous-Waste Site Studies - Mr. Neitzel worked with a team of scientists and engineers at Battelle for 4 years preparing guidance documents for the management of hazardous-waste sites and spills. The guidance documents are designed to aid scientific support personnel during the planning and implementation of a remedial action. Guidance documents produced or in progress include: 1) methods for implementing biological and environmental methods of cleaning waste sites; 2) methods for minimization of adverse environmental effects of cleanup-alternatives; 3) methods for risk-based selection of remedial actions for waste sites; 4) procedures for implementation of a remedial investigation study; 5) methods for biological and environmental sampling at hazardous-waste sites; and 6) methods for determining "clean" at a waste site.

Mr. Neitzel managed and facilitated three workshops to determine the technical information needs of state and the U.S. Environmental Protection Agency (EPA) regional hazardous-waste site managers. The workshops were conducted for the Hazardous Materials Assessment Team of the U.S. EPA's Corvallis Environmental Research Laboratory. The workshop results have been used as planning input for program development.

Selected Publications

Book

Becker, C. D., and D. A. Neitzel (eds). 1992. Water Quality in North American River Systems. Battelle Press, Columbus, Ohio.

Journal Articles

Neitzel DA, DD Dauble, GF Cada, MC Richmond, GR Guensch, RP Mueller, CS Abernethy, and BG Amidan. 2004. "Survival Estimates for Juvenile Fish Subjected to a Laboratory-Generated Shear Environment ." Transactions of the American Fisheries Society 133:447-454.

McMichael GA, JA Vucelick, CS Abernethy, and DA Neitzel. 2004. "Comparing Fish Screen Performance to Physical Design Criteria." Fisheries 29(7):10-16.

Johnson GE, BD Ebberts, DD Dauble, AE Giorgi, PG Heisey, RP Mueller, and DA Neitzel. 2003. "Effects of Jet Entry at High Flow Outfalls on Juvenile Pacific Salmon." North American Journal of Fisheries Management 23(2):441-449.

Scott, M.J., D.A. Neitzel, W.V. Mavros, and M.S. Madden. 1994. " A Preliminary Model of Salmon Ocean Survival Under Climate Change." Canadian Journal of Fisheries and Aquatic Science. Richland, Washington.

Chatters, J. C. , V. L. Butler, M. J. Scott, D. M. Anderson, and D. A. Neitzel. 1995. "A Paleoscience Approach to Estimating the Effects of Climatic Warming on Salmonid Fisheries of the Columbia River Basin." In R.J. Beamish [ed] Climate change and northern fish populations. Can. Spec. Publ. Fish. Aquat. Sci. 121.

Anderson, D. M., M. J. Scott, D. A. Neitzel, and J. C. Chatters. 1993. "The Costs of Climate Change: Economic Value of Yakima River Chinook Salmon." Contemporary Policy Issues. 11(4):82-94.

Chatters, J. C., D. A. Neitzel, M. J. Scott, S. A. Shankle. 1991. "Potential Impacts of Global Climate Change on Pacific Northwest Spring Chinook Salmon: An Exploratory Case Study." The Northwest Environmental Journal 7:71-92.

Neitzel, D. A., M. J. Scott, S. A. Shankle, and J. C. Chatters. 1991. "The Effects of Climate Change on Stream Environments: The Salmonid Resource of the Columbia River Basin." The Northwest Environmental Journal 7:271-294.

Neitzel, D. A., and T. J. Frest. 1990. "Survey of Columbia River Basin Streams for Columbia Pebblesnail and Shortface Lanx." Fisheries 15(2):2-3.

Neitzel, D. A., K. I. Johnson, and P. M. Daling. 1989. "Improving the Reliability of Service Water Systems at Nuclear Power Plants." Nuclear Plant Journal 7(3):44-57.

Becker, C. D., D. A. Neitzel, and D. W. Carlile. 1986. "Survival Data for Dewatered Rainbow Trout (Salmo gairdneri Rich.) Eggs and Alevins." Journal of Applied Ichthology 3(1986):102-110.

Becker, C. D., and D. A. Neitzel. 1985. "Assessment of Intergravel Conditions Influencing Egg and Alevin Survival During Salmonid Redd Dewatering." Environmental Biology of Fishes 12:33-46.

Becker, C. D., D. A. Neitzel, J. E. Rogers, and D. J. Silvera. 1985. "Evaluating Hazardous Materials for Biological Treatment." Nuclear and Chemical Waste Management 5:183-192.

Gray, R. H., T. L. Page, D. A. Neitzel, and D. D. Dauble. 1985. "Assessing Population Effects from Entrainment of Fish at a Large Volume Water Intake." Environmental Science and Health 21(2).

Neitzel, D. A., and C. D. Becker. 1985. "Tolerance of Eggs, Embryos, and Alevins of Chinook Salmon to Temperature Changes and Reduced Humidity in Dewatered Redds." Transactions of the American Fisheries Society 114:267-273.

Becker, C. D., D. A. Neitzel, and C. S. Abernethy. 1983. "Effects of Dewatering on Chinook Salmon Redds: Tolerance of Four Development Phases to One-Time Dewatering." North American Journal of Fisheries Management 3:373-382.

Neitzel, D. A., T. L. Page, R. H. Gray, and D. D. Dauble. 1983. "Once-Through Cooling on the Columbia River--the Best Available Technology?" Environmental Impact Assessment Review 3(1):43-58.

Becker, D. C., D. A. Neitzel, and D. H. Fickeisen. 1982. "Effects of Dewatering on Chinook Salmon Redds: Tolerance of Four Developmental Phases to Daily Dewaterings." Trans. Am. Fish. Soc. 111:624-637.

Neitzel, D. A., T. L. Page, and R. W. Hanf. 1982. "Columbia River Zooplankton." Northwest Science 57(2): 112-118.

Neitzel, D. A., T. L. Page, and R. W. Hanf. 1982. "Mid-Columbia River Microflora." Journal of Freshwater Ecology 1(5):495-505.

Gray, R. H., D. A. Neitzel, and T. L. Page. 1979. "Water Intake Structures: Engineering Solutions to Biological Problems." The Northern Engineer 10(1)26-33.

Technical Publications

Neitzel, D. A., C. S. Abernethy, and E. W. Lusty. 1990. A Fisheries Evaluation of the Wapato, Sunnyside, and Toppenish Creek Canal Fish Screening Facilities, Spring 1988. Prepared for the Bonneville Power Administration by the Pacific Northwest Laboratory, Richland, Washington.

Neitzel, D. A., C. S. Abernethy, and E. W. Lusty. 1990. A Fisheries Evaluation of the Westside Ditch and Wapato Canal Fish Screening Facilities, Spring 1989. Prepared for the Bonneville Power Administration by the Pacific Northwest Laboratory, Richland, Washington.

Neitzel, D. A., C. S. Abernethy, and G. A. Martenson. 1990. A Fisheries Evaluation of the Westside Ditch and Town Canal Fish Screening Facilities, Spring 1990. Prepared for the Bonneville Power Administration by the Pacific Northwest Laboratory, Richland, Washington.

Abernethy, C. S., D. A. Neitzel, and E. W. Lusty. 1989. Velocity Measurements at Six Fish Screening Facilities in the Yakima River Basin. Prepared for the Bonneville Power Administration by the Pacific Northwest Laboratory, Richland, Washington.

Neitzel, D. A., and T. J. Frest. 1989. Survey of Columbia River Basin Streams for Giant Columbia River Spire Snails Fluminicola columbiana and Great Columbia River Limpets Fisherola nuttalli. PNL-7103, prepared for the U.S. Department of Energy, Richland, Washington by Pacific Northwest Laboratory, Richland, Washington.

Neitzel, D. A., C. S. Abernethy, E. W. Lusty, and S. J. Wampler. 1988. A Fisheries Evaluation of the Richland and Wapato Canal Fish Screening Facility, Spring 1987. Prepared for the Bonneville Power Administration by the Pacific Northwest Laboratory, Richland, Washington.

Neitzel, D. A., and K. I. Johnson. 1988 Technical Findings Document for Generic Issue 51: Improving the Reliability of Open-Cycle Water Systems. NUREG/CR-5210, PNL 6623, prepared for the U. S. Nuclear Regulatory Commission, by the Pacific Northwest Laboratory, Richland, Washington.

Dauble, D. D., R. M. Ecker, L. W. Vail, and D. A. Neitzel. 1987. Downstream Extent of the N Reactor Plume. PNL-6310, prepared for the U. S. Department of Energy, Richland, Washington by Pacific Northwest Laboratory, Richland, Washington.

Dauble, D. D., L. W. Vail, and D. A. Neitzel. 1987. Evaluation of the Potential for Fish Passage Through the N Reactor and the Hanford Generating Project Discharges. PNL-6309, prepared for the U. S. Department of Energy, Richland, Washington by Pacific Northwest Laboratory, Richland, Washington.

Johnson, K. I., and D. A. Neitzel. 1987. Improving the Reliability of Open-Cycle Water Systems Volume 2: Application of Biofouling Surveillance and Control Techniques to Sediment and Corrosion Fouling at Nuclear Power Plants. NUREG/CR-4626, U.S. Nuclear Regulatory Commission, Washington, D.C.

Neitzel, D. A., C. S. Abernethy, and E. W. Lusty. 1986. A Fisheries Evaluation of the Richland and Toppenish/Satus Canal Fish Screening Facility, Spring 1986. Prepared for the Bonneville Power Administration by the Pacific Northwest Laboratory, Richland, Washington.

Neitzel, D. A., K. I. Johnson, and P. M. Daling. 1986. Improving the Reliability of Open-Cycle Water Systems Volume 1: An Evaluation of Biofouling Surveillance and Control Techniques for Use at Nuclear Power Plants. NUREG/CR-4626, U.S. Nuclear Regulatory Commission, Washington, D.C.

Neitzel, D. A., C. S. Abernethy, E. W. Lusty, and L. A. Prohammer. 1985. A Fisheries Evaluation of the Sunnyside Canal Fish Screening Facility, Spring 1985. Prepared for the Bonneville Power Administration by the Pacific Northwest Laboratory, Richland, Washington.

Neitzel, D. A., C. D. Becker, C. S. Abernethy, D. W. Carlile, and E. W. Lusty. 1984. Laboratory Simulations of Chinook Salmon Redd Dewatering: An Assessment of Potential Impacts at Vernita Bar. Prepared for the Public Utility District of Grant County by Battelle, Pacific Northwest Laboratories, Richland, Washington.

Neitzel, D. A., K. I. Johnson, T. L. Page, J. S. Young, and P. M. Daling. 1984. Bivalve Fouling of Nuclear Power Plant Service-Water Systems. Volume 1: Correlation of Bivalve Biological Characteristics and Raw Water Systems Designs. NUREG/CR-4070, U.S. Nuclear Regulatory Commission, Washington, D.C.

Neitzel, D. A., T. M. Poston, C. S. Abernethy, M. T. McLane, T. L. Page, and D. W. Carlile. 1984. Laboratory Simulation of four Species of Fish through the N Reactor Thermal Plume in Spring During Single-Purpose Mode of Operation. WHC-EP-0177, prepared for the U.S. Department of Energy, Richland, Washington by Pacific Northwest Laboratory, Richland, Washington.

Neitzel, D. A., T. M. Poston, C. S. Abernethy, T. L. Page, and D. W. Carlile. 1984. Laboratory Simulation of Late-Summer Juvenile Chinook Salmon Passage through N Reactor Thermal Plume During Single-Purpose Mode of Operation. WHC-EP-0176, prepared for the U.S. Department of Energy, Richland, Washington by Pacific Northwest Laboratory, Richland, Washington.

3.4 Cooling System

The plant cooling system for new units and the anticipated modes of operation of the cooling system are described in Section 3.4.1. The design data of the cooling system components; specifically, the intake, the discharge, and the heat dissipation system, and their performance characteristics for the anticipated operational modes are presented in Section 3.4.2. The parameters provided are used to evaluate the physical, chemical, and biological impacts to the environment that would result from the operation of the cooling system.

3.4.1 Description and Operational Modes

The selection of the type of cooling system for new units requires consideration of the total amount of waste heat that would be generated as a byproduct of the proposed electricity generation, as well as the impacts of the waste heat to the environment. The amount of waste heat rejected from the steam-electric system varies, depending on the reactor type, because the core thermal output and the gross electrical output are different among the reactor types being evaluated. Unless site-specific data are available to generate a more realistic and appropriate estimate of the design parameters, bounding values from the PPE (described in Section 3.1.3) were used to provide the basis for evaluation and selection of the types of cooling system best suited for the ESP site. Dominion would apply for the required environmental permits to support the construction of the new cooling system(s), including permits for the discharge and intake structures under the EPA CWA 316(a) and 316(b) regulations after a decision is made to proceed with development of the new units.

3.4.1.1 Normal Plant Cooling

According to the PPE, each new unit would require a primary cooling system to dissipate up to 9.7×10^9 BTU/hr of waste heat rejected from the main condenser and the auxiliary heat exchangers during normal plant operation at full station load. A once-through cooling system that uses the North Anna Reservoir as the cooling water supply and the WHTF as the primary heat sink would be used for the normal plant cooling of the new Unit 3, and a closed-cycle dry cooling system would be used for new Unit 4. The Unit 4 system would use dry cooling towers for heat dissipation in which the exhaust from the plant's steam turbines would be directed to a surface condenser where the heat of vaporization would be rejected to a closed loop of cooling water. The heated cooling water would be circulated to the finned tubes of the dry cooling towers where heat content of the cooling water would be transferred to the ambient air. To increase heat rejection to the atmosphere, electric motor driven fans would be used to force airflow across the finned tubes. After passing through the cooling towers, the cooled water would be recirculated back to the surface condenser to complete the closed-cycle cooling water loop. Except for the initial filling of the cooling water loop, Unit 4 would have no make-up water need since dry tower systems typically have no evaporative water losses and would have no continuous blowdown discharge to the WHTF. In the event that the cooling water loop would used an open pump sump configuration with a free surface,

2.4 Hydrology

2.4.1 Hydrologic Description

This section identifies the interface of the new units with the hydrosphere, the hydrological causal mechanisms that may require special plant design bases or operating limitations with regard to floods and water supply requirements, and the surface water and groundwater uses that may be affected by operation of new units at the ESP site.

2.4.1.1 Site and Facilities

The water source for the new units on the ESP site is an impoundment of the North Anna River, referred to as Lake Anna. This impoundment was created by a dam constructed across the North Anna River as part of the overall development of the NAPS site. The North Anna Reservoir currently serves as the principal water source for the two existing units, which use once-through cooling systems to dissipate heat from the turbine condensers.

The ESP site is situated approximately 5 miles upstream from the main dam and adjacent to the existing units. The grade of the proposed site would have the same minimum elevation as the existing units, which is 271 ft msl (Reference 1). There are no natural drainage features that require changes to accommodate new units at the ESP site. Figure 1.2-4 shows the external structures and components, to the extent known, of the new units that might be constructed at the ESP site.

The new units would also use the North Anna Reservoir as the source of cooling water. New Unit 3 would use a once-through cooling system that would withdraw water at rate of about 2540 cubic feet per second (cfs) from the North Anna Reservoir, circulate it through the condensers, and return the water to the reservoir via the WHTF. New Unit 4 would use a closed-cycle cooling system with dry cooling towers in which the exhaust from the plant's steam turbines would be directed to a surface condenser where the heat of vaporization would be rejected to a closed loop of cooling water. The heated cooling water would be circulated to the finned tubes of the dry cooling towers where heat content of the cooling water would be transferred to the ambient air. To increase heat rejection to the atmosphere, electric motor driven fans would be used to force airflow across the finned tubes. After passing through the cooling towers, the cooled water would be recirculated back to the surface condenser to complete the closed-cycle cooling water loop. Except for the initial filling of the cooling water loop, Unit 4 would have no make-up water need since dry tower systems typically have no evaporative water losses and would have no continuous blowdown discharge to the WHTF. In the event that the cooling water loop used an open pump sump configuration with a free surface, a small amount of evaporation losses, estimated to be about 1 gpm (0.002 cfs), will occur. Any make-up water necessary to replenish the small evaporative losses for Unit 4 and other service water needs for the new units would be obtained from the North Anna Reservoir.

REPRODUCTION OF RESIDENT STRIPED BASS IN SANTEE-COOPER RESERVOIR, SOUTH CAROLINA

GEORGE D. SCRUGGS, JR.

South Carolina Wildlife Resources Department
Moncks Corner, South Carolina [1]

ABSTRACT

An unprecedented sport fishery for striped bass, *Roccus saxatilis* (Walbaum), has developed in the Santee-Cooper Reservoir within the past 10 years. From a creel census from September 1, 1954, to August 31, 1955, the annual harvest was conservatively estimated to exceed 64,000 striped bass; this species accounted for 6.7 percent of the total harvest (by number) of all game fish caught.

Exchanges between the reservoir population and those making seasonal runs in lower Cooper River is restricted to the navigation lock at Pinopolis Dam. Two methods were used during 1954 and 1955 to determine the extent of movement. Year-round fishing with a large trammel net indicated very limited use of the lock by striped bass. In 1954, a total of 606 striped bass were captured, tagged, and released in the Tailrace Canal below Pinopolis Dam. Out of 37 recaptures 33 were caught downstream, revealing a seasonal migratory trend, and only 4 had moved through the lock into the reservoir.

To determine sexual maturity of striped bass in the reservoir, 165 male and 243 female fish were examined between February 16, and June 1, 1955. Most of the males were ripe by the end of March. Changes in the ratio of gonad to body weight, were used to classify the stage of maturity of the females. A small percentage of the females were mature at 20 inches, total length. More than 88 percent of all females over 24 inches long had maturing, mature, or spent ovaries.

The principal spawning grounds in the reservoir were located in 1954 by the collection of eggs in large plankton nets. In 1955 a more intensive study revealed that the spawning period started during the first week of April and reached a peak between April 21 and May 5. The minimum temperature for spawning was 58° F.

Most of the striped bass in Santee-Cooper Reservoir are land-locked and apparently are able to complete a full life cycle in freshwater.

INTRODUCTION

Completed in 1942, the Santee-Cooper Hydroelectric and Navigation Project, diverted and impounded the Santee River. It now supports one of the most important sport fisheries for striped bass in the eastern United States. This situation is unique in that fishing is maintained on a year-round basis in a fresh-water reservoir from a stock largely perpetuated by the spawning of resident fish.

The reservoir system consists of two large, shallow lakes connected by a canal (Fig. 1). The combined area of the lakes is 160,500 acres when filled to the top elevation of 76 feet. The shore is flat; the shoreline totals 415

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miles. The main flow is derived from the Congaree and Wateree Rivers which drain from the Piedmont of South Carolina and North Carolina. The maximum depth of Lake Marion, the upper lake, is 36 feet and that of Lake Maultrie, the lower lake, is 66 feet; the mean depth of the reservoir is approximately 15 feet. Wilson Dam on Lake Marion blocks the original Santee River and diverts the flow through a 7-mile-long Diversion Canal into Lake Moultrie. The hydroelectric plant is located at Pinopolis Dam on Lake Moultrie. Water is discharged through the turbines into the 4-mile Tailrace Canal which continues via the Cooper River for a distance of 50 miles to the Atlantic Ocean. The lock at Pinopolis Dam permits navigation between the reservoir system and Cooper River and at times provides a possible means for the migration of fish.

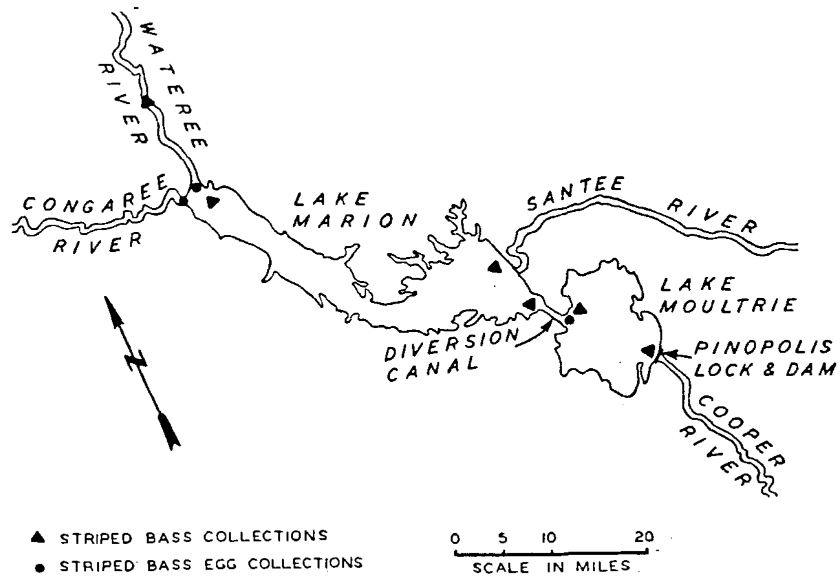

FIGURE 1.—Map of the Santee-Cooper Reservoir System including the location of striped bass and striped bass egg-collection stations.

Soon after the impoundment of the reservoir, seasonal concentrations of striped bass were observed in the Tailrace Canal below Pinopolis Dam. Catches were also reported by anglers from scattered localities in the reservoir. In the past 10 years the striped bass population has increased greatly in the reservoir.

The reservoir stock probably descended from the Santee River population which was trapped upstream at the time Wilson Dam was completed. Also, some recruitment has occurred by migration upstream through the lock from Cooper River.

The problem of determining whether the reservoir population is resident or migratory, concerns the operation of the lock at Pinopolis Dam which is the only means of passage to the reservoir available to migrating fish. Free movement of fish does not occur since the lock operations are irregular, depending on boat traffic. During the 5 years prior to July 31, 1954, the lock was operated by the South Carolina Public Service Authority, at the request of the South Carolina Wildlife Resources Department, to provide an opportunity for the seasonal migration of fish. From July 31, 1954, to September 1, 1955, the lock has been closed except for the infrequent passage of boats, and consequently the opportunity for fish migration has been greatly restricted.

On February 1, 1954, the South Carolina Wildlife Resources Department, supported partly by Federal Aid funds, inaugurated an investigation of the fish populations in the Santee-Cooper Reservoir; an important segment of the study concerned the life history of the striped bass.

Preliminary work by Scruggs and Fuller (1954), indicated that the migration of striped bass through the lock at Pinopolis Dam was not extensive and gave conclusive evidence that spawning occurred in the streams tributary to the reservoir. Scruggs (1955),[2] summarized the results of a full year's tagging designed to determine the migratory behavior of the Cooper River population and the degree of recruitment to the reservoir from this source. Raney and Woolcott (1955), reported in a racial study of southeastern striped bass that a significant difference occurred in the lateral-line scale count of those from the Reservoir as compared with samples from Cooper River, and concluded that two populations probably were present.

The present paper is concerned principally with the ability of striped bass to complete a full life cycle in the Reservoir. Also considered are the extent of migration through the Pinopolis Lock and the year-round availability and harvest by the sport fishery in the Reservoir. The status of sexual maturity of the Reservoir population was determined by an examination of the gonads of an adequate sample of adult fish. Actual spawning in the Reservoir was determined by the collection of fertilized eggs in large plankton nets.

Status of the Sport Fishery for Striped Bass

A creel census of the sport fishery, operated from five landings on Lakes Marion and Moultrie from September 1954 through August 1955, provided information on distribution, availability, and dominant size groups, as well as fishing effort. Commercial fishing is prohibited by law.

The creel census showed that 17,974 fishermen caught 95,750 fish represented by seven species. The catch of striped bass numbered 6,451, or 6.7 percent of the total catch. The average weight of 734 striped bass obtained

[2] Scruggs, George D. 1955. A study of the migration of the Cooper River population of striped bass. A paper presented at the annual meeting of the South Carolina Academy of Science. 11 pp. [Mimeographed]

from random samples in the fishery was 7.5 pounds. The catch of striped bass was significant during each month of the year, and was highest from October through January. The average catch of successful striped bass fishermen (Table 1) during this sample period did not vary widely from month to month.

The creel census is estimated roughly to have accounted for 10 percent of the total fishing effort for striped bass. The total annual harvest of striped bass from Santee-Cooper Reservoir was estimated to exceed 64,000 fish which weighed approximately 470,000 pounds.

TABLE 1.—*Results of a creel census on Lakes Marion and Moultrie from September 1, 1954, to August 31, 1955*

Successful striped bass fishermen		Striped bass catch		Successful striped bass fishermen		Striped bass catch	
Month	Number	Number caught	Catch per man	Month	Number	Number caught	Catch per man
September	106	118	1.1	March	326	372	1.1
October	366	793	2.4	April	395	542	1.4
November	667	1165	1.8	May	386	654	1.7
December	195	336	1.7	June	276	614	2.2
January	169	248	1.5	July	431	806	1.9
February	337	361	1.1	August	185	442	2.4

Migration Through the Lock at Pinopolis Dam

The lock at Pinopolis Dam has been used infrequently during the past several years as a navigation link between Cooper River and the Santee-Cooper Reservoir. The primary aim in opening the lock during the past 5 years has been to encourage interchange between the stocks of striped bass in Lake Moultrie and Cooper River, which was believed essential for the preservation of the striped bass fishery in the Reservoir.

The fish-way operations consisted of opening the lock 1 to 3 times per day to permit fish from the Tailrace Canal to be transferred to Lake Moultrie, or to pass from the lake to the canal. These operations were usually carried out from early January to the end of June each year. Beginning in 1954, two methods were employed to test the extent of the striped bass migration through the lock. In the first method a trammel net was fished periodically when the lock was operated. The second method consisted of tagging and releasing a large number of striped bass below Pinopolis Dam.

Trammel-net samples.—Starting on April 21, 1954, a large trammel net 65 feet long and 25 feet deep was suspended across the width of the concrete base of the upper lock gate to seal the entrance when the gate was opened into Lake Moultrie. The bottom and sides of the net were attached closely to the base and lock wall by metal snaps. The mesh size of the inner wall of the net was 2 inches, stretched measure.

The following procedure was carried out for each net sample taken:

(1) after the lower gate of the lock had been open for 1 hour the net was installed and the water level was raised to the level of Lake Moultrie; (2) the upper gate was then opened and the net was allowed to fish for 1 hour; (3) after the operation was completed the catch was sorted from both sides of the net to determine direction of movement.

In the period between April 21, 1954, and April 20, 1955, 29 sets of the net caught a total of 2,569 fish represented by 14 species. Only four small striped bass were captured. Herring (*Alosa mediocris* and *A. aestivalis*), channel catfish (*Ictaluras punctatus*), and billfish (*Tylosurus marinus*) were the only large species that showed a well-defined movement through the lock.

From April 21, to July 31, 1954, the lock was opened 179 times as follows: fish transfer, 140; boat passage, 29; and for trammel-net samples, 10. On July 31, 1954, lock operations for fish transfer were discontinued and until the end of the study period on April 20, 1955, trammel-net samples comprised 34 percent of all openings. In 1954 and 1955 the netting program started and ended on dates selected to include the height of the striped bass spawning season. Since the net caught very few striped bass over the period it would appear inconceivable that a large interchange occurred between the populations in Cooper River and the Reservoir.

Marking and recovery.—During the spring migration, March 25, to July 1, 1954, 545 striped bass were caught in dip and cast nets in the Tailrace Canal and tagged. An additional 61 were caught on hook and line and tagged between October 19 and December 16, 1954. The fish were marked with Peterson disk tags affixed by piercing the body with a nickel pin just below the first dorsal fin. All tagged fish were released in the Tailrace Canal below Pinopolis Dam. All tag recoveries were obtained by cooperation of sport fishermen. No reward was offered for tag returns but an effort was made to obtain them by placing announcements in newspapers and by posting printed notices at landings on the Reservoir and along Cooper River.

Of the 606 fish tagged and released, 37 (6 percent) were returned in the 18-months ending August 31, 1955. Thirty-three (89 percent) of the recaptures were returned from Cooper River and the Tailrace Canal; 4 tags (11 percent) were returned from Lake Moultrie. The latter fish moved upstream through the Pinopolis Lock. Figure 2 illustrates the distribution of tag recaptures by the month.

The movement of marked fish in Cooper River indicates that the population was located in the upper part of the river and Tailrace Canal during the spring, early summer, and late winter. The high percentage of returns from the upper 30 miles of the river (94.5 percent) suggests a population which has a predilection for fresh water and confirms the general observations of anglers and commercial fishermen that little or no coastal migration occurs in South Carolina. The most distant recoveries were of 2 fish taken 50 miles downstream at the mouth of Cooper River. The average time at liberty for the 33 tagged bass was 187 days. The longest time out was

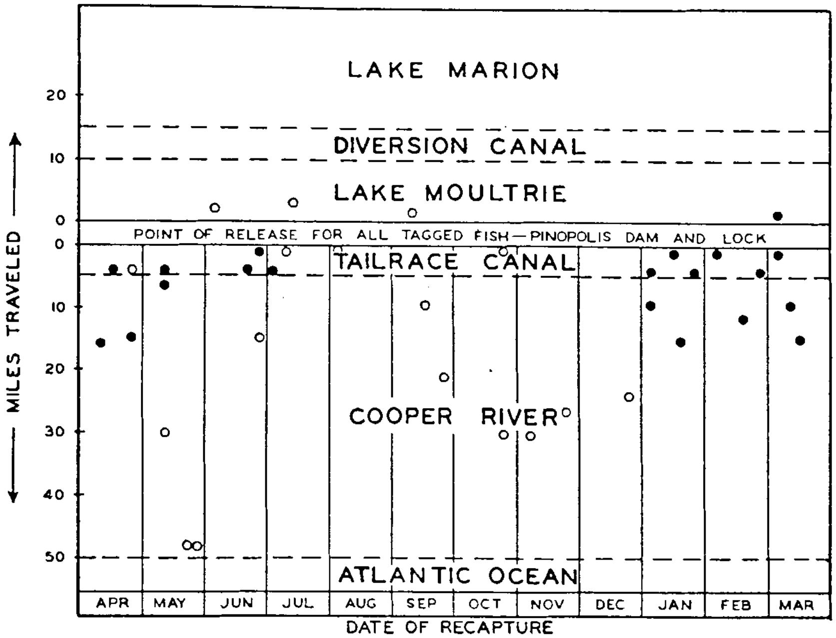

FIGURE 2.—Location and date of recapture of 37 striped bass in Cooper River and Lake Moultrie from April 1954 through August 1955. Open dots—recaptures in 1954; solid dots—recaptures in 1955.

430 days; this fish was captured near the original point of release in the Tailrace Canal. Nine other tags were out longer than 300 days.

Of the four tag returns from striped bass which moved through the lock into Lake Moultrie, three were caught within an average of 74 days. The other fish was free for 324 days. The movement of the four tagged bass in Lake Moultrie averaged a minimum of 1 mile. All were from groups tagged between April 13 and May 19, 1954; it seems possible that particular schools of fish passed through the lock between or soon after these dates. Two of the four caught were tagged on May 10, 1954. Of 197 tagged bass released after May 10, 1954 10 were later caught below Pinopolis Dam but none were taken in the Reservoir. The fishing pressure in all seasons was greater in the Reservoir than in Cooper River.

After routine operations for fish transfer were discontinued, the lock was opened only 55 times at irregular intervals between July 31, 1954, and July 31, 1955, to accommodate boat traffic. Since the average time required for each boat was 15 minutes, the lock was open to migrating fishes for only about 13 hours during the period from the end of the 1954 season to the end of the 1955 season. Evidence obtained from both the trammel-net samples and tag recaptures indicates that there is little striped bass migration through the lock.

Sexual Maturity

In view of the evidence indicating that the stock of striped bass in the Reservoir was not added to appreciably by recruitment from that in Cooper River, it was concluded that the Reservoir population was composed mostly of resident stock. The question then arose as to whether the resident fish were able to mature sexually and reproduce successfully without having spent at least part of their life cycle in saline water.

State of gonads.—Prior to and during the spawning season of 1955, adult striped bass were collected at various locations in Lake Marion and Lake Moultrie (Fig. 1). The specimens were obtained principally from the sport fishery but were supplemented by a sizeable gill-net catch. Between February 16 and June 1, 1955, 408 large bass were examined, of which 243 were female and 165 were male. They were inspected for gonad development, weighed, and classified in accordance with the following categories:

IMMATURE FEMALES: The ovaries were small with no sign of developing ova. The color in fresh fish varied from pale grey to a deep red. The main blood vessels of the ovaries were not dilated. The rattio of gonad weight to body weight ranged from 1:70 to 1:300. Not expected to spawn this season.

MATURING FEMALES: The ovaries were enlarged and contained developing ova. Color ranged from cream to a greenish-yellow. The blood vessels of the ovaries were dilated. The ratio of gonad weight to body weight averaged 1:40. Expected to spawn this season.

MATURE FEMALES: The ovaries were greatly enlarged, with developed ova. The color ranged from pale green to a darker shade of green as ripeness was approached. The blood vessels were extremely dilated. The ratio of gonad weight to body weight averaged around 1:10. These fish were almost ripe.

SPENT FEMALES: The ovaries were flabby. A few large ova were occasionally present. When the fish was stripped a bloody discharge was extruded. The color was a light shade of purple. Spawning had been completed by these fish.

MALES: The testes were classified as immature, maturing, or ripe. Immature testes were small and thread-like. Maturing testes were very large and white. Ripe tests were easily determined by the ready extrusion of milt when the fish were stripped.

The condition of the testes, determined by gross inspection, presented no difficulty in classification since practically all were either in the maturing or ripe stage at the time of examination. Soon after the study began in early spring it became apparent that the males were progressing from the maturing to the ripe stage as the season advanced. Gonads of approximately 98 percent of all males examined contained a bountiful supply of milt by the end of March. The smallest size at which the males matured was about 10 inches, total length.

Since practically all male fish were found to mature successfully, emphasis was placed on the study of sexual development of the females. As the spawning time approached the ovaries increased to a much larger size and consequently made up a higher percentage of the total fish weight. A similar change was previously noted by Vladykov and Wallace (1952) who gave comparative data on gross and gonad weight of striped bass in Chesapeake Bay. They examined a large sample of males but the number of females was rather small.

Among the 243 females examined, the total length ranged from 14 to 36.9 inches (Table 2). The relation between ovary development and length is clearly evident. As the season advanced the larger females were able to mature their ovaries. A small percentage of the females matured at about 20 inches but the majority did not mature until they reached 24 inches (Fig. 3). In order to show percentage maturity at different lengths all maturing, mature, and spent fish in each length group were considered as

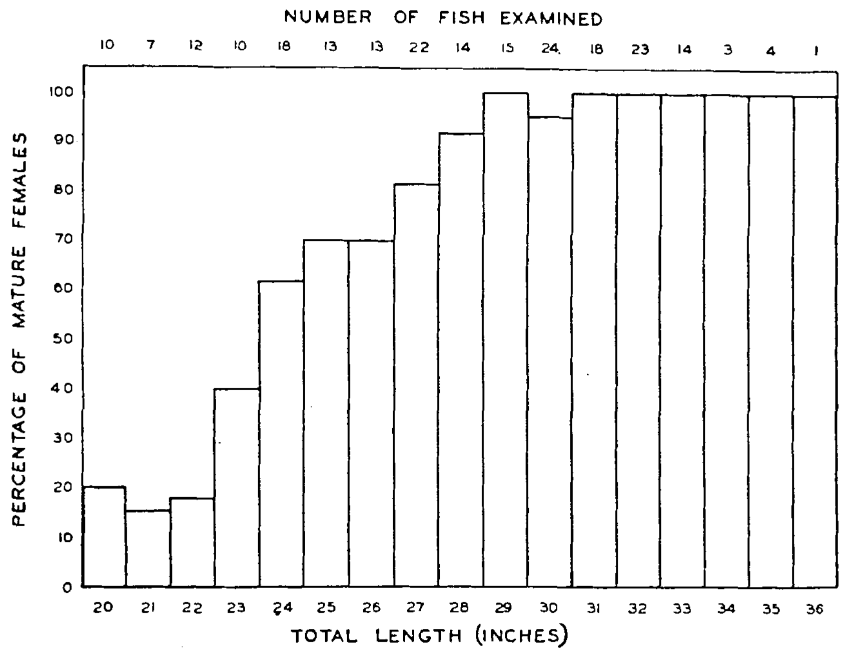

FIGURE 3.—Percentage of female striped bass able to mature sexually (includes all maturing, mature, and spent specimens) taken in Lakes Marion and Moultrie during February 16 to June 1, 1955.

a unit. A definite correlation is shown between the length of the fish and the percentage which were mature up to the 29-inch group. All fish less than 20 inches in total length were immature; from 20 to 24 inches, 23 percent were mature; from 24 to 29 inches, 75 percent were mature; and from 29 to 37 inches, over 99 percent were considered to be mature.

Spent striped bass of both sexes were consistently lighter in weight than fish of the same length (Table 3), particularly for the larger sizes. As expected, the weight loss for females was considerably greater than that for males.

TABLE 2.—*Number of immature, maturing, mature, and spent female striped bass taken from February 16 to June 1, 1955, in Lakes Marion and Moultrie*

[See text for descriptions of various states of organs]

Total length (inches)	All fish		Immature		Maturing		Mature		Spent	
	Number	Percentage of total	Number	Percentage	Number	Percentage	Number	Percentage	Number	Percentage
14-14.9	1	0.4	1	100.0	..	....	..	....	..	....
15-15.9	1	0.4	1	100.0	..	....	..	....	..	....
16-16.9	4	1.6	4	100.0	..	....	..	....	..	....
17-17.9	5	2.1	5	100.0	..	....	..	....	..	....
18-18.9	7	2.9	7	100.0	..	....	..	....	..	....
19-19.9	4	1.6	4	100.0	..	....	..	....	..	....
20-20.9	10	4.1	8	80.0	1	10.0	1	10.0	..	....
21-21.9	7	2.9	6	81.0	1	19.0	..	....	..	....
22-22.9	12	4.9	10	83.0	2	17.0	..	....	..	....
23-23.9	10	4.1	6	60.0	2	20.0	1	10.0	1	10.0
24-24.9	18	7.4	7	39.0	9	50.0	..	....	2	11.0
25-25.9	13	5.4	4	31.0	7	54.0	..	....	2	15.0
26-26.9	13	5.4	4	31.0	2	15.0	1	8.0	6	46.0
27-27.9	22	9.0	4	18.0	2	9.0	2	9.0	14	64.0
28-28.9	14	5.8	1	7.0	..	....	4	29.0	9	64.0
29-29.9	15	6.2	..	....	3	20.0	5	33.0	7	47.0
30-30.9	24	9.9	1	4.0	2	8.0	11	46.0	10	42.0
31-31.9	18	7.4	..	....	2	12.0	8	44.0	8	44.0
32-32.9	23	9.5	..	....	..	....	7	30.0	16	70.0
33-33.9	14	5.8	..	....	..	....	1	7.0	13	93.0
34-34.9	3	1.2	..	....	..	....	1	33.0	2	67.0
35-35.9	4	1.6	..	....	..	....	1	25.0	3	75.0
36-36.9	1	0.4	..	....	..	....	1	100.0	..	....
Totals	243	100.0	73	....	33	....	44	....	93	....

TABLE 3.—*Comparison of average weights of male and female striped bass from Lakes Marion and Moultrie from February 16 to June 1, 1955*

[Includes specimens taken before and after spawning]

Total length (inches)	Male				Female			
	Prespawning		Spent		Prespawning		Spent	
	Number	Pounds	Number	Pounds	Number	Pounds	Number	Pounds
10-10.9.....	3	0.5	..	....	2	0.5	..	....
14-14.9.....	..	....	..	....	1	1.8	..	....
15-15.9.....	3	1.8	..	....	1	2.0	..	....
16-16.9.....	2	2.5	1	2.2	4	2.5	..	....
17-17.9.....	6	2.7	..	....	5	2.6	..	....
18-18.9.....	5	3.2	..	....	7	3.1	..	....
19-19.9.....	26	3.6	..	....	4	3.2	..	....
20-20.9.....	33	4.1	..	....	10	3.9	..	....
21-21.9.....	25	4.8	1	4.2	7	4.8	..	....
22-22.9.....	10	5.4	2	4.4	12	5.5	..	....
23-23.9.....	5	5.9	..	....	12	6.0	1	5.3
24-24.9.....	6	7.0	4	5.9	17	6.8	2	5.8
25-25.9.....	6	7.2	6	6.1	18	7.0	2	6.0
26-26.9.....	1	7.5	4	6.8	11	7.7	6	6.2
27-27.9.....	3	8.9	8	8.0	13	8.6	14	7.6
28-28.9.....	2	9.9	2	8.4	3	10.5	9	8.8
29-29.9.....	2	10.5	3	9.8	12	11.5	8	10.0
30-30.9.....	..	....	1	11.9	10	13.5	10	11.1
31-31.9.....	..	....	..	....	12	14.5	8	12.0
32-32.9.....	..	....	..	....	6	16.0	16	13.6
33-33.9.....	..	....	..	....	4	17.0	13	14.9
34-34.9.....	..	....	..	....	1	19.0	2	16.5
35-35.9.....	..	....	..	....	1	22.0	3	18.0
36-36.9.....	..	....	..	....	1	24.5	..	....
Totals.....	138	....	32	....	174	....	94	....

A progressive change in the condition of the female gonads was observed as the spawning season advanced (Table 4). In the preparation of the table only fish between 24 and 36.9 inches long were considered since these fish constituted 75 percent of the total number examined and the majority of the fish that were able to mature fully. The total collection was composed of females covering a wide range in length; the predominance of certain sizes at various times may account for shifts in the percentages, especially for the immature fish. It is possible also that fish earlier classed as immature may have matured as the season advanced.

Sex Ratio.—The sex ratio varied during the collecting periods but the change reflects sampling bias rather than an actual shift of the ratio in nature. Of 162 fish examined prior to March 31, 74.8 percent were males and 25.2 percent were females. The collection of 139 fish made during April was composed of only 4.4 percent males and 95.6 percent females. During May a collection of 107 bass included 35.5 percent males and 64.5 percent females. Of the total 408 striped bass, 40 percent were males and 60 percent were females. The fluctuation in the sex ratio may be explained by the greater activities of males prior to the spawning season. After spawning began, the males were concentrated on the spawning grounds, whereas the females lingered below these areas and gradually moved up

TABLE 4.—*Percentage of immature, maturing, mature, and spent female striped bass from Lakes Marion and Moultrie, arranged by time periods in 1955*

[All specimens over 24 inches in total length]

Date of collection	Number examined	Percentage immature	Percentage maturing	Percentage mature	Percentage spent
February 16 — March 31...........	21	23.8	47.6	28.6	0.0
April 1 — April 15.................	35	17.2	22.8	48.6	11.0
April 16 — April 30...............	78	7.7	21.8	14.1	56.4
May 1 — May 31...................	48	4.2	2.1	2.1	91.6

as they matured. A majority of the bass were taken below the spawning grounds.

Growth and age at maturity.—Scale samples were collected from striped bass for age and growth determination in both 1954 and 1955. The scales were read and measured under magnification. Lengths were calculated by direct proportion.

The growth in length was greatest during the first 3 years of life (Table 5). The average growth increment was greater between the first and second years. The overlapping in the length ranges was considerable due to some extent perhaps, because of a rather long spawning season and a faster growing tendency of certain individuals.

The smallest mature male examined was 10.1 inches long and only 1 year old. The majority of the males did not mature until their second year. The largest male examined was 30 inches long and in its seventh year.

Approximately 23 percent of the females were mature by their fourth year. Maturity was 65 percent at 5 years, and 85 percent by the sixth year. Practically all females beyond the sixth year were mature. The largest female examined was 36 inches long and was in its tenth year.

The length distribution of 726 bass caught in the sport fishery (Fig. 4) implies a major support from age-groups III–IX. Although age-groups I and II are represented, the smaller number caught was probably due to selective fishing for the larger sizes.

TABLE 5—*Total length (inches) of the age groups at capture and calculated growth (from scale measurements) of striped bass in Santee-Cooper Reservoir*

[Fish collected in 1954 and 1955]

Age group	Number of fish	Length at capture		Year of life	Calculated length	Increment
		Average	Range			
I................	108	7.8	5.2–11.4	1	7.1	...
II................	92	15.1	12.4–17.8	2	14.9	7.8
III...............	70	20.3	16.3–22.5	3	19.5	4.6
IV...............	56	24.1	20.1–25.3	4	22.2	2.7
V................	30	26.0	23.3–27.1	5	25.1	2.9
VI...............	31	27.8	25.2–29.1	6	27.5	2.4
VII..............	15	30.5	28.7–31.5	7	30.1	2.6
VIII.............	9	32.8	31.6–33.5	8	32.3	2.2
IX...............	3	35.2	34.1–36.	9	34.6	2.3

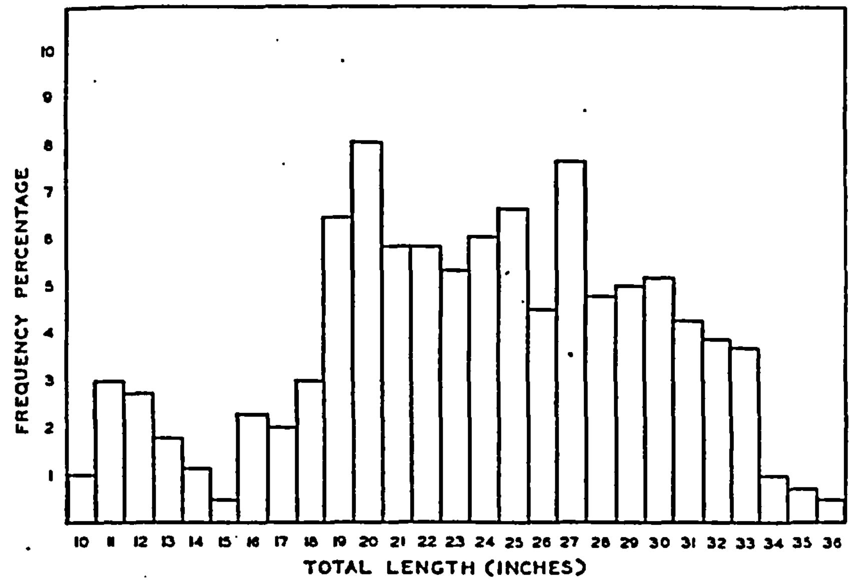

FIGURE 4.—Length distribution of 726 striped bass caught in the Santee-Cooper Reservoir from September 1, 1954 to August 1, 1955.

The strength of older age-groups indicates high availability of mature-size fish as brood stock.

SPAWNING

During the spring of 1954 a survey was made to locate the spawning grounds of the striped bass in the Santee-Cooper System. This work was intended mainly as exploratory to find direct evidence of spawning. Elsewhere, Tresselt (1952) made a thorough study of striped bass spawning grounds of some Virginia streams tributary to Chesapeake Bay through the collection of eggs in plankton nets. Calhoun and Woodhull (1948) summarized their studies in locating striped bass eggs and larvae in the Sacramento and San Joaquin Rivers, California.

The preliminary study in 1954 was successful in that eggs and larvae of the striped bass were taken in the Congaree and Wateree Rivers, tributary streams of the Reservoir, in the Diversion Canal, and also downstream in Cooper River. A plankton net, 1 meter in diameter, made of nylon netting was towed by boat to collect samples. The sampling was carried out more intensively in Cooper River where it was found that spawning occurred between April 22 and May 11 in the upper 12 miles of the river.

Further study was intended to delimit the spawning season of 1955 and to determine the relative intensity of spawning in various localities in the

Reservoir area. Only a few collections were made in Cooper River. Again 1-meter plankton nets were used but they were anchored in the current in the Congaree and Wateree Rivers, and in the Diversion Canal.The samples were taken periodically for the duration of the spawning season, by setting the net from 30 minutes to 1 hour at each station on selected dates. All samples were obtained from surface sets since collections in 1954 revealed more eggs at the surface than at the bottom. Samples were preserved in formalin.

Diversion Canal.—Samples were taken near the mouth of the canal between March 22 and June 1, 1955. The erratic flow during the spawning season ranged from 1 mile to about 4 miles per hour. The rate of flow was determined by the discharge of water from tributary rivers into Lake Marion and the amount drawn through and discharged by the hydroelectric plant at Pinopolis Dam. The maximum depth of the canal at the sampling station was 30 feet; the bottom is composed of marl. Eggs were first collected on April 6, when the water temperature was 58°F. (Table 6).

TABLE 6.—*Collection of striped bass eggs from the Diversion Canal in 1955*

Date	Current	Water temperature (F.°)	Number of samples	Sample period (minutes)	Number of eggs	Number per minute
March 22	Medium	57	1	45	0	0.00
March 23	Medium	57	1	30	0	0.00
April 6	Fast	58	1	60	5	0.08
April 21	Fast	71	1	60	3	0.05
April 27	Very Fast	71	1	60	55	0.92
May 3	Medium	70	1	60	0	0.00
May 11	Slow	74	1	60	41	0.68
May 18	Slow	72	1	60	0	0.00
May 25	Slow	74	1	60	0	0.00
June 1	Slow	76	1	30	0	0.00

Other egg collections were made on April 21, April 27, and on May 11. The spawning may have reached a peak on April 27. Spawning in the canal is believed to have been maintained by intermittent runs of fish from Lake Moultrie.

Congaree River.—Collections were made between March 25 and June 9, 1955 below the bridge on U. S. Highway 601, approximately 2 miles from the mouth of the river. The Congaree is very turbid from an abundance of red clay. The flow is maintained by the discharge from Saluda Dam on Lake Murray, 50 miles upstream and by the considerable flow from Broad River. The estimated volume of flow during the spawning season ranged from 2,200 to 39,100 cubic feet per second. Eggs were first collected on April 8, when the water temperature was 61°F. and other collections were made on April 21, May, 5, May 19, and June 2 (Table 7). Spawning apparently reached a peak on April 21.

The collection of eggs suggests that the Congaree was the most important spawning ground sampled. The length of the season and number of eggs collected were greater than from any other area. Since eggs were in various stages of development, spawning probably took place over a long stretch of the river.

Wateree River.—The Wateree River was sampled between March 25 and June 9 at a station 200 yards upstream from its confluence with the Congaree River. The Wateree is much clearer than the Congaree although the presence of considerable organic matter and debris made th sorting difficult in all samples. The flow is primarily dependent on the discharge

TABLE 7.—*Collection of striped bass eggs from the Congaree River in 1955*

Date	Current	Water temperature (F.°)	Number of samples	Sample period (minutes)	Number of eggs	Number per minute
March 25	Medium	59	1	60	0	0.00
April 8	Fast	61	1	60	65	1.08
April 21	Very Fast	70	1	30	2500	83.40
May 5	Slow	74	1	30	155	5.17
May 12	Slow	72	1	30	0	0.00
May 19	Fast	70	1	30	69	2.30
May 26	Very Fast	74	1	45	0	0.00
June 2	Fast	76	1	30	6	0.20
June 9	Fast	77	1	30	0	0.00

from Wateree Dam, located approximately 60 miles from the mouth; during the spawning season it ranged from 1,480 to 44,885 cubic feet per second. The first eggs were collected on April 8, when the water temperature was 59°F. and others were collected on April 21, May 5, and May 19 (Table 8). Spawning may have reached a peak on May 5.

Spawning in the Wateree and Congaree Rivers was maintained by runs from Lake Marion.

The combined collection of eggs from the three spawning areas in the Reservoir, indicate that the minimum duration of spawning extended from April 6 to June 2, 1955 for a total of 58 days—and that spawning reached a maximum intensity in the latter part of April.

Cooper River.—Collections of eggs in 1954 proved that spawning took place during April and May in the upper 12 miles of the river. Samples were taken in 1955 between March 12 and April 1, but collecting was discontinued after April 1, because of time limitations and shortage of personnel. The station was approximately 17 miles below the Pinopolis Dam. Eggs were first collected on March 16, when the water temperature reached 61° F. Eggs were also collected on March 17, 19, 21, and 26. Although no eggs were obtained on April 1, this failure does not prove that spawning was completed since the water temperature had been greatly lowered at this time by unseasonal cold.

The significance of the spawning ground below Pinopolis Dam lies in the fact that it is distantly separated from spawning areas in the Reservoir; it is not necessary for bass from Cooper River to pass through the lock to find a satisfactory spawning area. Spawning began several weeks earlier in Cooper River, possibly because of a higher water temperature and early sexual maturity of the fish.

Volume of spawning.—Difficulties inherent in the sampling technique prevented any attempt to obtain detailed quantitative estimates of the volume of eggs discharged into the Reservoir. Such factors as erratic current velocities, variation in vertical distribution of eggs, and the infrequent sampling made such estimates impractical. A very rough index is provided by the number of eggs collected per minute on certain dates.

TABLE 8.—*Collection of striped bass eggs from the Wateree River in 1955*

Date	Current	Water temperature (F.°)	Number of samples	Sample period (minutes)	Number of eggs	Number per minute
March 25	Fast	58	1	30	0	0.00
April 8	Very Fast	59	1	60	11	0.18
April 21	Very Fast	67	1	45	9	0.20
May 5	Very Fast	70	1	30	106	3.53
May 12	Fast	73	1	45	0	0.00
May 19	Fast	72	1	30	3	0.10
May 26	Very Fast	74	1	30	0	0.00
June 2	Very Fast	76	1	30	0	0.00
June 9	Fast	76	1	30	0	0.00

Between April 1 and April 15, the percentage of females in the Reservoir, that were mature or almost ripe reached a peak (Table 4). Spawning began on April 6 and reached a peak between April 21 and May 19. As the spawning continued the percentage of fish in the mature stage declined steadily; in sharp contrast, the number of spent fish rose continuously. By the end of May, when spawning was near completion, as judged from egg collections, the percentage of spent fish reached 91.6 percent of the total.

ABUNDANCE OF YOUNG

Efforts to collect young striped bass, made soon after the spawning seasons, were successful in both 1954 and 1955. A total of 281 young of the 1954 year class were collected by seines from widely scattered areas along the shore of both lakes between June 23, 1954, and April 29, 1955. On June 30, 1955, 55 young were collected from Lake Moultrie and on July 29, 1955, 35 were caught in Lake Marion.

The relative ease with which young striped bass could be caught after the spawning seasons of 1954 and 1955 reflects wide distribution and relatively high abundance.

The collections of young-of-year gives final evidence that the life cycle of striped bass is completed in Santee-Cooper Reservoir.

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LITERATURE CITED

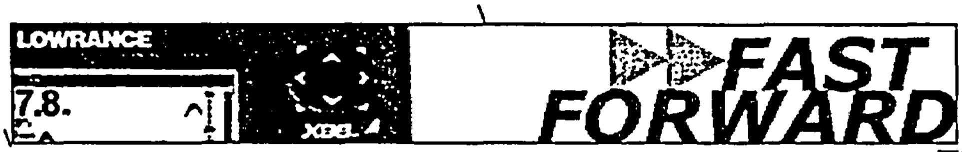
CALHOUN, A. J., and C. A. WOODHULL
1948. Progress report on studies of striped bass reproduction in relation to the Central Valley Project. Cal. Fish. Game, Vol. 34, pp. 171–188.

RANEY, E. C., and W. S. WOOLCOTT
1955. Races of the striped bass, *Roccus saxatilis* (Walbaum), in southeastern United States. Jour. Wildlife Man., Vol. 19, No. 4, pp. 444–450.

SCRUGGS, G. D., and J. C. FULLER
1955. Indications of a fresh-water population of striped bass *Roccus saxatilis* (Waubaum) in Santee-Cooper Reservoir. Proceedings of the Southeast. Assoc. of Game and Fish Comm., pp. 64–69.

TRESSELT, E. F.
1952. Spawning grounds of the striped bass, *Roccus saxatilis* (Walbaum), in Virginia. Bull. Bingham Oceanogr. Coll., Vol. 14, pp. 98–110.

VLADYKOV, V. D., and D. H. WALLACE
1952. Studies of the striped bass, *Roccus saxatilis* (Walbaum), with special reference to the Chesapeake Bay region during 1936–1938. Bull. Bingham Oceanogr. Coll., Vol. 14, pp. 132–177.



- The National Striped Bass Association (NSBA) & the Southeastern Striped Bass Foundation (SSBF)
- The Association Concept
- Association Objectives
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The National Striped Bass Association (NSBA)

Much like many other organizations and tournament trails, the NSBA started out as a dream. The dream of one man, Warren Turner. To most who know him, it is without question that Warren Turner has the ability to run a striped bass organization, knows his way around the winner's circle of a competitive striper tournament trail, knows how to put on a very well organized striper tournament, and has a strong desire to help protect, preserve, and promote the freshwater striped bass fishery. But for those who don't know him, let's take a look at his history in dealing with striped bass issues as a club member, as a club leader, and as a tournament fisherman. What has he done to, and for, the striped bass fishery that has given him such strong credibility in the eyes of, not just his club members, but also with the other striped bass fishermen that know him?

Turner is the former President of Striper Kings, Inc. of Greenville South Carolina, as well as being the founder and president of the non-profit Southeastern Striped Bass Association. During Warren's presidency with Striper Kings, active membership has reached new levels, including approximately 120 new members. As a Striper Kings member, he has served on their Tournament Committee (including 3 years as their Tournament Committee Chairman and 2 years as their Tournament Director), served on their Wildlife Conservation Committee, served as the Wildlife Projects Coordinator, served as their Newsletter Editor, and as their Vice President. Turner has personally participated in many activities that were designed to improve the South Carolina striped bass fishery including fund raising and hands-on project work at the South Carolina Jack D. Bayless Striped Bass Hatchery. He has also written articles and has given presentations across the southeastern United States on striped bass fishing techniques and bait catching methods including a special technique he developed on casting nets.

Turner has been fishing striped bass tournaments for over twelve years, and has won the coveted Striper Kings Points Championship angler-of-the-year, named after fallen member and friend Ricky Norris, an unprecedented four times (1995, 1997, 2000, 2001) in the past seven years. This is against a field of over 200-striper fishermen, including many veteran tournament anglers. In 1996 he finished 3rd in the points race and in 1998, he finished 2nd. Only in 1999, when his partner finished 2nd in the points race, and Warren finished 7th, has he not finished 3rd or higher since 1995. Additionally, Turner holds several of the clubs records, including the highest points earned in a tournament year, and he and his partners hold, not just the highest 4-fish weigh-in, but the top-2 highest 4-fish weigh-ins in club history. Those weigh-in records are 87.89 pounds (1998) and 82.99 pounds (1995) respectively. Additional, he and his partners have won the Striper Kings Championship Invitational Tournament twice (1995, 1996), and finished 2nd in 2001. To add to these credentials, in 1996, Turner and his partner set two Striper Kings Championship Invitational Tournament (CIT) records in one tournament, when they weighed in the largest striper (29.97-pounds) in Striper King CIT history and also had the largest 4-fish CIT weigh-in in Striper King history. Warren and his team have won the CIT Big Fish award in 1995, 1996, and 2001. Additionally, Warren's team has won first place in the following Open Striper Tournaments: Striper Kings Winter Classic Open Team Tournament (2000, 1999, Jan/1997, Feb/1997, 1996, 1995), the Striper Kings Summer Classic SCDNR Benefit Open Team Tournament (2000), and the Lake World Lake Murray Open Striper Tournament (2000), along with many other top 3 finishes, including 2nd Place in the 2001 2nd Annual Clark's Hill Striper Club GADNR Benefit Open Team Tournament. As I said, Warren knows his way around the winner's circle.

But, it was through his experiences as a regular member of Striper Kings, as well as the experience received while serving as their President that the idea of developing an alliance, between the existing Striper Clubs and the Striper Fishermen from around the area began to develop and grow. Thus, he started a non-profit organization called the Southeastern Striped Bass Association (SSBA for short), with the intention to help the area striped bass fishing clubs and fishermen promote and protect their local striped bass fishery. When asked about the SSBA, Warren said, "In a very short time we were able to see the benefits of an alliance. However, I did not have the resources to make any significant moves very fast. Then I met Bill Haire, host and producer of several television shows, including Kingmasters and South Carolina Outdoors. Bill and his staff at South Carolina Outdoors, Inc., had the contacts, marketing experience, and skills to promote this alliance idea into reality. Therefore, in September 2001, together we formed a new organization called the National Striped Bass Association." Turner then gave me his insight of the SSBA and the NSBA and where each has a defined role in the future. Let me tell you a little about that, and why he feels the NSBA will promote and protect our striper fisheries.

The Association Concept

First, you might be asking, why does the striper fishery need protecting, or you might even be saying- I did not even know I had a local striped bass fishery. Well, some striper clubs have already been working since the early 1990's to protect and promote their local striped bass fishery, and several have accomplished many things to improve the striper and hybrid fishery in their states. This has been accomplished by the hard works of many people working together, which were dedicated to the common cause of preserving and improving the local striper and hybrid fishery. Most of the improvements were obtained by working directly with the various Department of Natural Resources biologists and providing them with both equipment and labor to implement ideas that they needed to achieve rapid improvements. As a result, the striped and hybrid striped bass fishery has flourished in many areas, but not all areas. This is where the NSBA can come into play and help on a larger and more directed scale. Sometimes it takes a large-scale player to have an impact.

According to Warren, as he began to travel around and contact the other striper clubs in the southeastern area, he found many good groups of people and made many new friends. However, he immediately found himself confronted with two different battles facing striper fishermen in our area. First, the Tennessee striper fishermen, who were just recovering from the lawsuit, by largemouth fishermen to stop the stocking of stripers in Tennessee waters, were now confronted with a new dilemma on Lake Cherokee. After finding out the details causing the major striper kills each summer on that specific lake, Warren decided to support the Tennessee Striped Bass Association (TSBA) and their President, and sent email letters of support and encouragement to the Tennessee Wildlife Resources Agency (TWRA). Additionally, he wrote and posted facts to dispel rumors concerning stripers, on various Tennessee fishing boards. In the end, all the hard work of the TSBA and their president paid off and the Lake Cherokee striper fishery was protected for the future. Second, a South Carolina State legislative representative pushed a new law through that removed the minimum length for striped bass on Lake Murray during the summer. This legislative action was without support of the SCDNR biologists who managed the Lake Murray striped bass fishery. Warren joined forces with the Midlands Striper Club and wrote a letter to the South Carolina governor. The Midlands President and Warren co-signed the letter. The governor agreed with them and refused to sign the law into effect until the year 2000 affected period was over. Thus giving them the time to address this issue with the legislators from each of their areas. According to Warren, "we won a small battle by working together outside the confines of our separate individual Clubs. However, since that time we have been unsuccessful in getting the law changed to add back the minimum size limits". This confirmed even stronger to Warren that an alliance needed to be formed and formalized. But, how big should an alliance be?

Did you know that over 37 states in the United States stock freshwater lakes and rivers with either striped and/or hybrid striped bass annually? Thus, if the need exists to protect and preserve this fishery, it must exist virtually all across the country. Therefore, we need to have a National Striped Bass Association and fellowship. However, like he said, Warren alone did not have the resources to address these issues. Bill Haire and his partners had a wealth of knowledge and contacts in the marine fishing and saltwater fishing tournament industry. This was done through their involvement with the Southern Kingfish Association (SKA) and the TV Show that South Carolina Outdoors Inc. produced for the SKA called Kingmaster's. South Carolina Outdoors had already established a very good reputation of being concerned with conservation issues. Add to that, their experience as a SKA tournament host, and anyone could see that South Carolina Outdoors had some very solid experience in running a fishing association and fishing tournament. Additionally, South Carolina Outdoors had a wealth of experience in developing corporate type sponsorships, and Bill Haire was know as a solid competitive Kingfish tournament angler. By combining the experiences of both groups, the National Striped Bass Association (NSBA) was conceived and developed with a wealth of experience that should compliment each other to build a truly beneficial association for striped bass fishermen. So, if you now believe that a potential threat to our striped bass fishery exists, and you believe that Warren and Bill can put together a solid association, you might be wondering how the NSBA would help the striped bass fishery. Let's look at the NSBA objectives to see what is expected.

Association Objectives

Conservation

The NSBA will serve as the glue that will hold the alliance together. It will provide funding opportunities for striped bass conservation and research. The Southeastern Striped Bass Association (SSBA) will continue to exist as a non-profit foundation under the National Striped Bass Association (NSBA) umbrella, and will target areas where fishermen and biologists can put resources together to protect striped bass fisheries in the southeastern states (NSBA Zone-1). We will change the name of the SSBA to the Southeastern Striped Bass Foundation (SSBF). It is intended that like other non-profit foundations, such as Quail Unlimited, Ducks Unlimited, etc., the SSBF will be used to protect and preserve the striped and hybrid striped bass fisheries. Additionally, it is expected that other striped bass non-profit foundations will be developed for other NSBA Zones as the NSBA tournament trail spreads throughout the country. Therefore, local fishermen and women would be working together to protect the fishery in their area, as opposed to working to protect a fishery across the continent that they may never visit.

A major function of the Association is to help promote and develop research studies to continue to improve the striper fishery. Warren and Bill believe that there is a possibility that a small, low water volume, live holding system could be developed for stripers that would allow those who want to "catch and release" stripers to do so even during tournaments, and possible even during the hot summer months. According to Warren, the basic idea here is to hold stripers and give them oxygen while their body allows the "lactic acid" buildup that occurs during the fight, to breakdown. In theory, the system could work. Warren and Bill hope the Association could make this a reality.

Fellowship

The NSBA is not intended to be a Striper Club, or to compete with local striper clubs for members. It purpose is to unite people with a common goal of assisting and improving the striped and hybrid striped bass fisheries from across the United States. In doing such, a major part of the Associations function will be assisting with getting new Striper Clubs started near lakes that have striped and hybrid striped bass stocked. Then the Association will help that Club to become independent and self-managed, and then to assume the responsibility to become the primary local voice to promote and protect their local striper fishery. The Association would continue to serve and advise the new Club, as well as existing clubs, as needed. As a matter of fact, the current plan is to offer many things to the Striper Clubs without asking for any fees from the Clubs. Striper Club membership in the Association would be offered free. The fees and monies of the Association will come from major corporate sponsors, and from those individuals who desire "Association" membership.

Protection

A major function of the Association would be a place to draw support and political power that comes with numbers. As Warren pointed out earlier, in Tennessee the battle was won. However, in South Carolina, we won the first battle but were stopped in our tracks in 2001. The war is still on and we must be unified. As long as there are people out there who, either due to stubbornness, or ignorance, promote the idea of catching striped bass and cutting their throats, or tossing them up on the bank to kill and waste them, we must work together to make sure the real story, of how stripers compliment the fishery, gets to the public.

Fishery Promotion & Expansion Through New Legislature

South Carolina and Georgia have worked together to make the Savannah River system striper and hybrid fishery something to be proud of. However, neither state has an area that can be called a trophy striper fishery that is designated specifically to produce that "Wall-hanger" fish that many sport fishermen seek. Additionally, the striped bass is considered by many to be a "meat fish" rather than a sport fish. The NSBA would like to see a trophy striper fishery set up. Here is what Warren recently propose to the SC and GA biologists.

Location: Lake Russell, Savannah River System

Since Lake Russell is not an official striper fishery with an annual stocking program from either SC or GA;

And, since the original plans for GA have not produced a significant middle GA area lake fishery for trout on Lake Russell;
And, since many states are successful at producing trout and striped bass lake fisheries simultaneously;
And, since the state of GA is continuously looking for a solid dependable source of striped bass brood fish;
And since Lake Russell is the source of many large striped bass caught each year;
And, since Lake Russell Dam already has oxygen lines installed above the Lake Russell dam which will help keep a population of large stripers healthy during the hot summer months on Lake Russell;
And, since SC and GA have developed an agreement by which GA will spawn stripers for the Savannah River system and SC will raise them to stocking age and stock them;
And, since any new fishery, and thus new fishing regulations will have little to no adverse impact on others using this lake (including largemouth fishermen, crapple fishermen, etc.);
And, since the current SC State record Striped Bass was caught from Lake Russell. And its age having been determined to be from the year class 1-year before the Russell Dam was closed off;

We would like Lake Russell to be officially recognized as a SC/GA Trophy Striper Fishery with special rules and regulations established to make it work.

Stock Lake Russell annually with a nominal stocking of 50,000-75,000 stripers and 0- hybrids, with the actual stocking numbers would be determined by the Lake Thurmond DNR biologists.
Establish a Lake Russell specific slot and creel limit regulation that includes only 2-fish per angler per day. All stripers measuring between 32 and 42 inches must be returned to the water.
Anglers may keep only one fish per day over 42-inches as part of their two fish creel limit. All other fish kept must measure less than 32-inches.
No striped or hybrid striped bass fishing in Lake Russell from June 15 until September 15 each year. And no striped bass or hybrid striped bass allowed being in possession during this time period.

These new proposed regulations would not adversely affect any current fishermen since the fishery will be virtually gone in a few more years without annual striper stockings. Additionally, with a small annual stocking, we feel that the fishery would not exceed the lakes potential. SCDNR and GADNR will be responsible for managing this new fishery.

Additionally, this system would follow a similar one that takes affect for the 2001-2002 season on Lake Cordell Hull in Tennessee. South Carolina is the state where the freshwater striped bass fishery was born. Our state and its fishermen deserve to have a trophy striped bass fishery.

This is an example of what a National Association can do for its anglers.

Competition Tournament Trail

According to one state's DNR records, in a recent survey of people buying fishing license, approximately 24% listed striped and hybrid striped bass as their primary fish to target, as opposed to 36% of the same state's fishermen listed largemouth bass as their primary target. Yet, unlike largemouth fishermen, there is no organized striped and hybrid striped bass tournament trails for freshwater striper fishermen. Largemouth, Walleye, and Crappie fishermen have a national association and national fishing circuits with major sponsors. The NSBA will be the "National" association of striped and hybrid striped bass fishermen from all across the United States. The current plans for the NSBA call for it to have its own magazine, its own web-site, and to feature a competitive tournament trail, a National Angler-of-the-Year, a National Youth-Angler-of-the-Year, a National Female-Angler-of-the-Year, and a televised National Striped Bass Invitational Championship Tournament. We have done this by including the various striper clubs from around the area. The NSBA has offered the various clubs the publicity and contacts that it can provide as a tournament sanction for their open tournaments. As a tournament sanction, the tournament remains the property of the club, or tournament host. The club, or host makes the tournament rules, determines the tournament fees and tournament payouts. If the tournament keeps any of the entry fees, those proceeds will belong to the club that serves as the tournament host. The NSBA will expect absolutely no cash from the clubs tournaments. The NSBA will promote the tournament in the NSBA magazine, over the TV, and in local newspapers. The NSBA will expect only to be authorized to have the floor for a few moments of the clubs "Captains meeting" and during the weigh-in and prize announcements. And the NSBA will expect to receive from the club a complete listing of the tournament results. Additionally, the NSBA will guarantee that the organization that hosts 2 tournaments on the same lake, will get a NSBA Division Title assigned to the lake, and a total of 5 slots for those tournaments to receive an invitation to participate in the National Striped Bass Invitational Championship Tournament. This should serve as a bonus system to encourage people to fish the club's tournaments. We feel this is a win-win situation that will benefit all. Warren will explain in a separate article how this tournament trail will be structured.

We believed that this tournament system will augment the clubs and will serve as the mortar that holds together a great, new, larger, soon to be known all around the country, association of striped bass fishermen called the NATIONAL STRIPED BASS ASSOCIATION. So what are you waiting for? Better get on board.

home ◈ *tournament trail* ◈ *forum* ◈ *member services* ◈ *articles*
photo gallery ◈ *about NSBA* ◈ *sponsors* ◈ *contact*

Threatened and Endangered Species System (TESS)

Listings by State and Territory as of 05/01/2005

Virginia

Notes:
- *Displays one record per species or population.*
- *The range of a listed population does not extend beyond the states in which that population is defined.*
- *This list includes non-nesting sea turtles and whales in State/Territory coastal waters.*
- *Includes species or populations under the sole jurisdiction of the National Marine Fisheries Service.*

Go to the Threatened and Endangered Wildlife and Plants Page
Go to the TESS Home Page

Back to Table of Contents

- *Click on the highlighted scientific names below to view a Species Profile for each listing.*

Virginia -- 71 listings

Animals -- 56

Status	Listing
E	Bat, gray (*Myotis grisescens*)
E	Bat, Indiana (*Myotis sodalis*)
E	Bat, Virginia big-eared (*Corynorhinus (=Plecotus) townsendii virginianus*)
XN	Bean, Cumberland (pearlymussel) AL; Free-Flowing Reach of the Tennessee River below the Wilson Dam, Colbert and Lauderdale Counties, AL (*Villosa trabalis*)
E	Bean, purple (*Villosa perpurpurea*)
E	Blossom, green (pearlymussel) (*Epioblasma torulosa gubernaculum*)
T	Chub, slender (*Erimystax cahni*)
T	Chub, spotfin Entire (*Cyprinella monacha*)
E	Combshell, Cumberlandian Entire Range; Except where listed as Experimental Populations (*Epioblasma brevidens*)
XN	Combshell, Cumberlandian AL; Free-Flowing Reach of the Tennessee River below the Wilson Dam, Colbert and Lauderdale Counties, AL (*Epioblasma brevidens*)
E	Darter, duskytail Entire (*Etheostoma percnurum*)
T	Eagle, bald (lower 48 States) (*Haliaeetus leucocephalus*)
E	Fanshell (*Cyprogenia stegaria*)
E	Isopod, Lee County cave (*Lirceus usdagalun*)
T	Isopod, Madison Cave (*Antrolana lira*)
E	Logperch, Roanoke (*Percina rex*)
XN	Madtom, yellowfin Holston River, VA, TN (*Noturus flavipinnis*)
T	Madtom, yellowfin (except where XN) (*Noturus flavipinnis*)
E	Monkeyface, Appalachian (pearlymussel) (*Quadrula sparsa*)
E	Monkeyface, Cumberland (pearlymussel) Entire Range; Except where listed as Experimental Populations (*Quadrula intermedia*)
XN	Monkeyface, Cumberland (pearlymussel) AL; Free-Flowing Reach of the Tennessee River below the Wilson Dam, Colbert and Lauderdale Counties, AL (*Quadrula intermedia*)
E	Mucket, pink (pearlymussel) (*Lampsilis abrupta*)
E	Mussel, oyster Entire Range; Except where listed as Experimental Populations (*Epioblasma capsaeformis*)
XN	Mussel, oyster AL; Free-Flowing Reach of the Tennessee River below the Wilson Dam, Colbert and Lauderdale Counties, AL (*Epioblasma capsaeformis*)
E	Pearlymussel, birdwing Entire Range; Except where listed as Experimental Populations (*Conradilla caelata*)
E	Pearlymussel, cracking Entire Range; Except where listed as Experimental Populations (*Hemistena lata*)
E	Pearlymussel, dromedary Entire Range; Except where listed as Experimental Populations (*Dromus dromas*)
E	Pearlymussel, littlewing (*Pegias fabula*)
E	Pigtoe, finerayed Entire Range; Except where listed as Experimental Populations (*Fusconaia cuneolus*)
XN	Pigtoe, finerayed AL; Free-Flowing Reach of the Tennessee River below the Wilson Dam, Colbert and Lauderdale Counties, AL (*Fusconaia cuneolus*)
E	Pigtoe, rough (*Pleurobema plenum*)
E	Pigtoe, shiny Entire Range; Except where listed as Experimental Populations (*Fusconaia cor*)
XN	Pigtoe, shiny AL; Free-Flowing Reach of the Tennessee River below the Wilson Dam, Colbert and Lauderdale Counties, AL (*Fusconaia cor*)
T	Plover, piping (except Great Lakes watershed) (*Charadrius melodus*)
E	Puma (=cougar), eastern (*Puma (=Felis) concolor couguar*)
E	Rabbitsfoot, rough (*Quadrula cylindrica strigillata*)

E Riffleshell, tan (*Epioblasma florentina walkeri (=E. walkeri)*)
E Salamander, Shenandoah (*Plethodon shenandoah*)
T Sea turtle, green (except where endangered) (*Chelonia mydas*)
E Sea turtle, hawksbill (*Eretmochelys imbricata*)
E Sea turtle, Kemp's ridley (*Lepidochelys kempii*)
E Sea turtle, leatherback (*Dermochelys coriacea*)
T Sea turtle, loggerhead (*Caretta caretta*)
E Snail, Virginia fringed mountain (*Polygyriscus virginianus*)
E Spinymussel, James (*Pleurobema collina*)
E Squirrel, Delmarva Peninsula fox (except Sussex Co., DE) (*Sciurus niger cinereus*)
E Squirrel, Virginia northern flying (*Glaucomys sabrinus fuscus*)
E Sturgeon, shortnose (*Acipenser brevirostrum*)
E Tern, roseate (northeast U.S. nesting pop.) (*Sterna dougallii dougallii*)
T Tiger beetle, northeastern beach (*Cicindela dorsalis dorsalis*)
T (S/A) Turtle, bog (=Muhlenberg) (southern) (*Clemmys muhlenbergii*)
E Wedgemussel, dwarf (*Alasmidonta heterodon*)
E Whale, finback (*Balaenoptera physalus*)
E Whale, humpback (*Megaptera novaeangliae*)
E Whale, right (*Balaena glacialis (incl. australis)*)
E Woodpecker, red-cockaded (*Picoides borealis*)

Plants -- 15

Status Listing

T Joint-vetch, sensitive (*Aeschynomene virginica*)
T Amaranth, seabeach (*Amaranthus pumilus*)
E Rock-cress, shale barren (*Arabis serotina*)
T Birch, Virginia round-leaf (*Betula uber*)
E Bittercress, small-anthered (*Cardamine micranthera*)
E Coneflower, smooth (*Echinacea laevigata*)
T Sneezeweed, Virginia (*Helenium virginicum*)
T Pink, swamp (*Helonias bullata*)
E Mallow, Peter's Mountain (*Iliamna corei*)
T Pogonia, small whorled (*Isotria medeoloides*)
T Orchid, eastern prairie fringed (*Platanthera leucophaea*)
E Harperella (*Ptilimnium nodosum*)
E Sumac, Michaux's (*Rhus michauxii*)
E Bulrush, Northeastern (*Scirpus ancistrochaetus*)
T Spiraea, Virginia (*Spiraea virginiana*)

United States Department of the Interior

FISH AND WILDLIFE SERVICE
Ecological Services
6669 Short Lane
Gloucester, VA 23061

Date: October 25, 2004

Project name: NRC's North Anna and Surry Power Stations

Project number: 9064 City/County, VA Surry, Louisa, Hanover, Caroline, Orange, + Spotsylvania

The U.S. Fish and Wildlife Service (Service) has reviewed your request for information on federally listed or proposed endangered or threatened species and designated critical habitat for the above referenced project. The following comments are provided under provisions of the Endangered Species Act (ESA) of 1973 (87 Stat. 884, as amended; 16 U.S.C. 1531 *et seq.*).

_____ We believe that the proposed action will not adversely affect federally listed species or federally designated critical habitat because no federally listed species are known to occur in the project area. Should project plans change or if additional information on listed and proposed species becomes available, this determination may be reconsidered.

_____ We recommend that you contact both of the following State agencies for site specific information on listed species in Virginia. Each agency maintains a different database and has differing expertise and/or regulatory responsibility:

Virginia Dept. of Game & Inland Fisheries
Environmental Services Section
P.O. Box 11104
Richmond, VA 23230
(804) 367-1000

Virginia Dept. of Conservation and Recreation
Division of Natural Heritage
217 Governor Street, 2nd Floor
Richmond, VA 23219
(804) 786-7951

If either agency indicates a federally listed species is present, please resubmit your project description with letters from both agencies attached.

__✓__ If appropriate habitat may be present, we recommend surveys within appropriate habitat by a qualified surveyor. Enclosed are county lists with fact sheets that contain information the species' habitat requirements and lists of qualified surveyors. If this project involves a Federal agency (Federal permit, funding, or land), we encourage the Federal agency to contact this office if appropriate habitat is present and if they determine their proposed action is likely to affect federally listed species or critical habitat.

_____ Enclosed is information about communication towers and measures to minimize and avoid impacts to migratory birds, including a list of types of work that do not require further coordination with the Service.

_____ Determinations of the presence of waters of the United States, including wetlands, and the need for permits are made by the U.S. Army Corps of Engineers. They may be contacted at: Regulatory Branch, U.S. Army Corps of Engineers, Norfolk District, 803 Front Street, Norfolk, Virginia 23510, telephone (757) 441-7652.

Our website http://virginiafieldoffice.fws.gov contains many resources that may assist with project reviews. Point of contact is Eric Davis at (804) 693-6694, ext. 104.

Sincerely,

J. Eric Davis Jr.

for Karen L. Mayne
Supervisor
Virginia Field Office

cc: CBFO (David Sutherland)

KEY

LE - federally listed endangered.

LT - federally listed threatened.

PE - federally proposed endangered.

PT - federally proposed threatened.

EX - believed to be extirpated in Virginia.

LE(S/A) - federally listed endangered due to similarity of appearance to a federally listed species.

LT(S/A) - federally listed threatened due to similarity of appearance to a federally listed species.

C - candidate species; the U.S. Fish and Wildlife Service has enough information to list the species as threatened or endangered, but this action is precluded by other listing activities.

SOC - species of concern; those species that have been identified as potentially imperiled or vulnerable throughout their range or a portion of their range. These species are not protected under the Endangered Species Act.

G - global rank; the species rarity throughout its total range.

G1 - extremely rare and critically imperiled with 5 or fewer occurrences or very few remaining individuals; or because of some factor(s) making it especially vulnerable to extinction.

G2 - very rare and imperiled with 6 to 20 occurrences or few remaining individuals; or because of some factor(s) making it vulnerable to extinction.

G3 - either very rare and local throughout its range or found locally (abundantly at some of its locations) in a restricted range; or vulnerable to extinction because of other factors. Usually fewer than 100 occurrences are documented.

G_T_ - signifies the rank of a subspecies or variety. For example, a G3T1 would apply to a subspecies of a species that is very rare and local throughout its range or found locally in a restricted range (G3) but the subspecies warrants a rank of T1, critically imperiled.

G_Q - The taxon has a questionable taxonomic assignment.

SURRY COUNTY, VIRGINIA
Federally Listed, Proposed, and Candidate Species

SCIENTIFIC NAME	COMMON NAME	STATUS
BIRDS		
Haliaeetus leucocephalus[1]	Bald eagle	LT
PLANTS		
Aeschynomene virginica	Sensitive joint-vetch	LT

Species of Concern (No official Federal status)

INVERTEBRATES		
Speyeria diana	Diana fritillary	G3
Stygobromus araeus	Tidewater interstitial amphipod	G2
VASCULAR PLANTS		
Carex decomposita	Epiphytic sdege	G3
Chamaecrista fasciculata var. macrosperma	Marsh senna	G5T2
Desmodium ochroleucum	Creamflower tick-trefoil	G2G3
Rudbeckia heliopsidis[2]	Sun-facing coneflower	G2
Trillium pusillum var. virginianum	Virginia least trillium	G3T2

[1]Nesting occurs in this county; concentrated shoreline use has been documented on the James River.
[2]Surveys needed within 5-miles of Prince George County species location.

March 22, 1999
Prepared by U.S. Fish and Wildlife Service, Virginia Field Office

LOUISA COUNTY, VIRGINIA
Federally Listed, Proposed, and Candidate Species

SCIENTIFIC NAME	COMMON NAME	STATUS
INVERTEBRATES		
Alasmidonta heterodon	Dwarf wedgemussel	LE

Species of Concern (No official Federal status)

SCIENTIFIC NAME	COMMON NAME	STATUS
INVERTEBRATES		
Elliptio lanceolata	Yellow lance	G3
Lasmigona subviridis	Green floater	G3

February 8, 2001
Prepared by U.S. Fish and Wildlife Service, Virginia Field Office

HANOVER COUNTY, VIRGINIA
Federally Listed, Proposed, and Candidate Species

SCIENTIFIC NAME	COMMON NAME	STATUS
BIRDS		
Haliaeetus leucocephalus	Bald eagle	LT
INVERTEBRATES		
Alasmidonta heterodon	Dwarf wedgemussel	LE
VASCULAR PLANTS		
Aeschynomene virginica[1]	Sensitive joint-vetch	LT
Helonias bullata[2]	Swamp pink	LT
Isotria medeoloides[2]	Small whorled pogonia	LT

Species of Concern (No official Federal status)

INVERTEBRATES		
Elliptio lanceolata	Yellow lance	G3
Lasmigona subviridis	Green floater	G3
Sigara depressa	Virginia Piedmont water boatmen	G1G3
VASCULAR PLANTS		
Chamaecrista fasciculata var. macrosperma[1]	Marsh senna	G5T2

[1]This species has been documented in an adjacent county and may occur in this county.
[2]This species has been documented in an adjacent county & may occur in this county east of I-95.

November 12, 2002
Prepared by U.S. Fish and Wildlife Service, Virginia Field Office

CAROLINE COUNTY, VIRGINIA
Federally Listed, Proposed, and Candidate Species

SCIENTIFIC NAME	COMMON NAME	STATUS
BIRDS		
Haliaeetus leucocephalus[1]	Bald eagle	LT
VASCULAR PLANTS		
Aeschynomene virginica[2]	Sensitive joint-vetch	LT
Helonias bullata	Swamp pink	LT
Isotria medeoloides	Small whorled pogonia	LT

Species of Concern (No official Federal status)

BIRDS		
Aimophila aestivalis	Bachman's sparrow	G3
INVERTEBRATES		
Sigara depressa	Virginia piedmont water boatman	G1G3
Stygobromus indentatus	Tidewater amphipod	G2G3
VASCULAR PLANTS		
Chamaecrista fasciculata var. macrosperma[2]	Marsh senna	G5T2
Desmodium ochroleucum	Creamflower tick-trefoil	G2G3
Eriocaulan parkeri	Parker's pipewort	G3
Juncus caesariensis	New Jersey rush	G2
Sabatia kennedyana	Plymouth gentian	G3

[1]Nesting occurs in this county; concentrated shoreline use has been documented on the Rappahannock River.
[2]This species has been documented in an adjacent county and may occur in this county.

May 29, 2001
Prepared by U.S. Fish and Wildlife Service, Virginia Field Office

ORANGE COUNTY, VIRGINIA
Federally Listed, Proposed, and Candidate Species

SCIENTIFIC NAME	COMMON NAME	STATUS
INVERTEBRATES		
Alasmidonta heterodon[1]	Dwarf wedgemussel	LE

Species of Concern (No official Federal status)

SCIENTIFIC NAME	COMMON NAME	STATUS
INVERTEBRATES		
Elliptio lanceolata	Yellow lance	G3
Lasmigona subviridis	Green Floater	G3
Speyeria idalia	Regal fritillary	G3

[1]This species has been documented in an adjacent county and may occur in this county.

September 19, 2002
Prepared by U.S. Fish and Wildlife Service, Virginia Field Office

SPOTSYLVANIA COUNTY, VIRGINIA
Federally Listed, Proposed, and Candidate Species

SCIENTIFIC NAME	COMMON NAME	STATUS
INVERTEBRATES		
Alasmidonta heterodon	Dwarf wedge mussel	LE
VASCULAR PLANTS		
Helonias bullata[1]	Swamp pink	LT
Isotria medeoloides	Small whorled pogonia	LT

Species of Concern (No official Federal status)

INVERTEBRATES		
Elliptio lanceolata	Yellow lance	G3
Lasmigona subviridis	Green floater	G3
Sigara depressa	Virginia Piedmont water boatmen	G1G3
Speyeria idalia	Regal fritillary	G3
NON-VASCULAR PLANTS		
Sphagnum carolinianum	Carolina peatmoss	G3

[1]This species has been documented in an adjacent county & may occur in this county east of I-95.

November 12, 2002
Prepared by U.S. Fish and Wildlife Service, Virginia Field Office

Bald Eagle

Haliaeetus leucocephalus

Description - The bald eagle occurs throughout the United States. It is a large bird-of-prey with dark brown plumage, a white head and tail, and a yellow bill, feet, and eyes. Juvenile eagles generally have a dark brown body, sometimes with white patches on the tail, belly, and underwings. The head and tail become completely white when full adult plumage is reached at four to five years of age.

Life History - The majority of Virginia's eagle population is found on the coastal plain. The bald eagle breeding season begins in mid-November when large nests are built (or the previous year's nest is repaired) usually in loblolly pine trees that are in close proximity to water. Eagles lay one to three eggs between mid-January and late March. In March, most eggs hatch and by June or July most young have fledged. However, the young will continue to use the nest for several weeks. In Virginia, during the summer and winter months, juvenile and nonbreeding adult eagles congregate along large rivers in areas with abundant food and little human disturbance. During the day, these eagles feed and perch along the river shoreline. In late afternoon, they move inland to roost either singly or communally. Roosts are typically located away from human disturbance and near water and a food source. Bald eagles feed primarily on fish, but will also eat carrion, waterfowl, small mammals, snakes, and turtles.

Conservation - The bald eagle was federally listed as an endangered species in the Chesapeake Bay Region on March 11, 1967. On July 12, 1995, the bald eagle was reclassified to threatened throughout the 48 lower states because the population had increased due to the banning persistent pesticides, habitat protection, and other recovery activities. On July 6, 1999, the bald eagle was proposed for removal from the list of endangered and threatened wildlife in the lower 48 states. This action was proposed because the available data indicated that this species has recovered. The recovery is due in part to habitat protection and management actions initiated under the Endangered Species Act. It is also due to reduction in levels of persistent pesticides occurring in the environment. If and when the eagle is no longer protected by the Endangered Species Act, it will still be protected by the Bald and Golden Eagle Protection Act, Migratory Bird Treaty Act, and state laws. Until the eagle is officially delisted, it will continue to receive protection pursuant to the Endangered Species Act. Bald eagles in the Chesapeake Bay are increasing. However, habitat destruction through urban and residential development and human disturbance in nesting, roosting, and foraging habitats continue to be a threat.

What You Can Do To Help - If you know of a bald eagle nest on or near property proposed for clearing, development, or logging please contact one of the following agencies for assistance:

Virginia Department of Game and Inland Fisheries
P.O. Box 11104
Richmond, Virginia 23230
(804) 367-1000

U. S. Fish and Wildlife Service
6669 Short Lane
Gloucester, Virginia 23061
(804) 693-6694

References

U.S. Fish and Wildlife Service. 1990. Chesapeake Bay Region bald eagle recovery plan: first revision. Newton Corner, Massachusetts.

U.S. Fish and Wildlife Service. 1999. Proposed rule to remove the bald eagle in the lower 48 states from the list of endangered and threatened wildlife. Federal Register 64(128): 36453-36464.

Watts, B.D., K.W. Cline, and M.A. Byrd. 1994. The bald eagle in Virginia: An information booklet for land planners. The Center for Conservation Biology, College of William and Mary, Williamsburg, Virginia.

U.S. Fish and Wildlife Service
Virginia Field Office
6669 Short Lane
Gloucester, Virginia 23061
(804) 693-6694
http://www.fws.gov
August 1999

Sensitive Joint-Vetch

Aeschynomene virginica

© M. Rollins

Description - The sensitive joint-vetch is an annual legume native to the eastern United States. Populations currently exist in Maryland, New Jersey, North Carolina, and Virginia. The historical range for the species extended to Delaware and Pennsylvania. In Virginia, populations are found along the Potomac, Mattaponi, Pamunkey, Rappahannock, Chickahominy, and James Rivers and their tributaries. This plant usually attains a height of three to six feet in a single growing season, but may grow as tall as eight feet. The flowers are yellow, streaked with red and the fruit is a pod, turning dark brown when ripe.

Life History - The joint-vetch occurs in fresh to slightly brackish tidal river systems, within the intertidal zone where populations are flooded twice daily. It typically occurs at the outer fringe of marshes or shores; its presence in marsh interiors may be a result of nutrient deficiencies, ice scouring, or muskrat herbivory. The sensitive joint-vetch is found in localities where plant diversity is high and annual species are prevalent. Bare to sparsely vegetated substrates appear to be a habitat feature of critical importance for establishment and growth of this species. Plants flower from July through September and into October in some years. Fruits are produced from July through late October, concurrent with flowering.

Conservation - The sensitive joint-vetch was federally listed as a threatened species on June 19, 1992. Threats to the species include sedimentation, competition from non-native plant species, dams, dredging, filling, recreational activities, shoreline stabilization, shoreline structures, road and bridge construction, commercial and residential development, water withdrawal projects, water quality degradation, agricultural practices, introduced pest species, mining, timber harvest, over-visitation, declines in muskrat populations, rise in sea level (this may also be a result of natural cycles), and collection. Natural threats are often identified with disturbances, such as wave and ice action associated with severe storm events, competition, herbivory, channel migration, sea level rise and natural sedimentation processes. Adequate habitat conservation for this species will only be achieved through on-site protection of marshes supporting plant populations when coupled with protection of the natural ecological processes responsible for creating and maintaining habitat for the sensitive joint-vetch.

What You Can Do To Help - Avoid the use of herbicides in or near waterways. If you are planning construction or stabilization activities along the shoreline in one of the counties indicated on the attached map, please contact the U.S. Fish and Wildlife Service.

References

Davison, S.E. and L.P. Bruderle. 1984. Element stewardship abstract for *Aeschynomene virginica* - sensitive joint vetch. The Nature Conservancy. Arlington, Virginia.

Hershner, C. and J.E. Perry. 1987. Population status of potentially threatened vascular plants from coastal plain tidal rivers in Virginia. College of William and Mary, Virginia Institute of Marine Science, Gloucester Point, Virginia.

Rouse, G.D. 1994. Sensitive joint-vetch life history and habitat study, 1993 Field Season, Mattaponi and Rappahannock River systems, Virginia. Schnabel Environmental Services. Richmond, Virginia.

U.S. Fish and Wildlife Service. 1995. Sensitive joint-vetch (*Aeschynomene virginica*) recovery plan. Hadley, Massachusetts.

U.S. Fish and Wildlife Service
Virginia Field Office
6669 Short Lane
Gloucester, Virginia 23061
(804) 693-6694
http://www.fws.gov
August 1999

Dwarf Wedge Mussel

Alasmidonta heterodon

B. Windsor

Description - The dwarf wedge mussel has a spotty distribution in Atlantic coast drainage rivers and their tributaries from Canada to North Carolina. It is a small mussel whose shell rarely exceeds 1.5 inches in length. The shell outline is ovate or trapezoidal. The female shell is shorter, trapezoidal, and inflated in the back whereas the male shell is elongate, compressed, and ovate. The outer shell layer is brown to yellowish-brown, with greenish rays in young or pale-colored specimens. This mussel is unique in that it has two lateral teeth on its right valve and only one tooth on its left valve (opposite of all other North American mussel species).

Life History - The dwarf wedge mussel lives in shallow to deep rivers and creeks of various sizes where the current is slow to moderate. This mussel lives on muddy sand, sandy, and gravel stream bottoms that are nearly silt free. Like other freshwater mussels, this species is a filter feeder. It feeds on plankton collected from water that is passed over its gills. Reproduction occurs sexually. Females carry eggs in their gills. During spawning, the male releases sperm into the water column and the sperm is taken into the female through the gills. The resulting larvae (known as glochidia) are released from the female into the water column and must attach to a fish host to survive. While attached to the fish host, development of the glochidia continues. Once metamorphosis is complete, the juvenile mussel drops off the fish host and continues to develop on the stream bottom. Fish hosts for this species include the mottled sculpin (*Cottus bairdi*), slimy sculpin (*Cottus cognatus*), tessellated darter (*Etheostoma olmstedi*), and johnny darter (*Etheostoma nigrum*).

Conservation - The dwarf wedge mussel was federally listed as an endangered species on March 14, 1990. The decline of this species is due to human degradation of habitat and water quality which have resulted in the continuing decline and subsequent loss of this species from previously occupied habitat. Threats to the species include agricultural, domestic, organic, and industrial pollution; impoundments that destroy habitat and cause silt deposits, low oxygen levels, and fluctuations in water levels and temperatures of the flooded area; and erosion and siltation from land clearing and construction of bridges or roads.

What You Can Do To Help - If you reside on property that borders a stream or other waterway, avoid using chemicals or fertilizers. To help control erosion and reduce runoff, maintain a buffer of natural vegetation along streambanks. Install fencing to prevent livestock from entering streams to reduce trampling of mussels, siltation, and input of waste products. Protecting water quality is the most effective way to conserve mussels.

To find out more about the dwarf wedge mussel contact:

Virginia Department of Game and Inland Fisheries
P.O. Box 11104
Richmond, Virginia 23230
(804) 367-1000

References

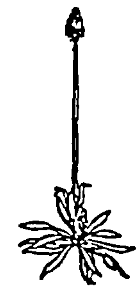
Michaelson, D.L. and R.J. Neves. 1995. Life history and habitat of the endangered dwarf wedgemussel *Alasmidonta heterodon* (Bivalvia:Unionidae). Journal of the North American Benthological Society 14(2):324-340.

U.S. Fish and Wildlife Service. 1993. Dwarf wedge mussel (*Alasmidonta heterodon*) recovery plan. Hadley, Massachusetts.

U.S. Fish and Wildlife Service
Virginia Field Office
6669 Short Lane
Gloucester, Virginia 23061
(804) 693-6694
http://www.fws.gov
August 1999

Swamp Pink

Helonias bullata



Description - The swamp pink is a perennial evergreen herb found in scattered populations from New Jersey south to Georgia. Historically, this plant was found from Staten Island, New York to the southern Appalachians. In Virginia, this lily has been documented in four counties. Its bright green, lance-shaped leaves form a basal rosette. A hollow flower stalk rises one to two feet from the center of the rosette and produces a pink or lavender flower head that consists of 30 to 50 small fragrant flowers. Few of the plants in a population produce flowers.

Life History - Swamp pink occurs in a variety of wetland habitats that include bogs, spring seeps, stream edges, wet meadows, and headwater wetlands. Sites are saturated year-round, but are rarely flooded and soils are generally neutral to acidic. Wetland habitat is easily altered through both direct and secondary disturbance. It is difficult for seedlings to get established and they are particularly vulnerable to human foot traffic. Flowering occurs from March to May. The basal leaves turn reddish-brown in the winter and lie flat on the ground or are slightly raised. These winter leaves are often hidden by fallen leaf litter. Reproduction is primarily asexual and seed dispersal is limited.

Conservation - The swamp pink was federally listed as a threatened species on September 9, 1988 due to population decline and threats to its wetland habitats. Historically, wetland drainage and/or filling associated with urban and agricultural development have been the primary threat to this species. However, with the enactment of the federal Clean Water Act and state wetland legislation, direct habitat loss has been slowed. Secondary effects from activities such as timber clearing, land development, siltation from run-off associated with adjacent development, and agriculture have become the major threat. These activities affect the hydrologic regime and increase the release of sediments and pollution. Plant collection and soil compaction from trampling are also threats to this species.

What You Can Do To Help - If you find a plant that appears to be the swamp pink, take note of the location and photograph the plant, if possible. Please do not remove the plant!

U.S. Fish and Wildlife Service
Virginia Field Office
6669 Short Lane
Gloucester, Virginia 23061
(804) 693-6694
http://www.fws.gov
August 1999

Contact one of the following agencies for assistance:

Virginia Department of Agriculture
and Consumer Services
Office of Plant Protection
P.O. Box 1163
Richmond, Virginia 23209
(804) 786-3515

Virginia Department of
Conservation and Recreation
Division of Natural Heritage
217 Governor Street, 3rd Floor
Richmond, Virginia 23219
(804) 786-7951

U.S. Fish and Wildlife Service
Virginia Field Office
6669 Short Lane
Gloucester, Virginia 23061
(804) 693-6694

References

Stevens, E.C. 1991. Swamp pink. Pages 88-89 in K. Terwilliger, ed. Virginia's Endangered Species, Proceedings of a Symposium. McDonald and Woodward Publishing Company, Blacksburg, Virginia.

U.S. Fish and Wildlife Service. 1991. Swamp pink *(Helonias bullata)* recovery plan. Newton Corner, Massachusetts.

Small Whorled Pogonia

Isotria medeoloides


© D.D. Tyler

Description - The small whorled pogonia is a herbaceous perennial orchid. It has a widely scattered distribution in the eastern United States along the Atlantic coast from Maine to Georgia with outlying occurrences in the midwest and Canada. This species has pale green, elliptical leaves, usually five or six, that grow in a single whorl at the top of a hairless, grayish-green stem. The one or two flowers per plant are yellowish-green, unscented, and form in the center of the whorl.

Life History - In Virginia, the small whorled pogonia is found in ordinary looking third-growth upland forests with an open understory and a closed canopy where the topography is typically moderately sloping or almost level. The plants are usually associated with decaying vegetative matter such as fallen trunks and limbs, leaf litter, bark, and tree roots. The pogonia is found in soils that are acidic sandy loams with low nutrient content. The flowers appear in late April to mid-May. The small whorled pogonia reproduces primarily through self-pollination and occasionally vegetatively. It is often confused with the Indian cucumber-root (*Medeola virginiana*) and the large whorled pogonia (*Isotria verticillata*). The Indian cucumber-root has deep green leaves with a stem that is thin, hairy, and wiry. The large whorled pogonia has a reddish-purple stem and dark green leaves; its flower is reddish-purple.

Conservation - The small whorled pogonia was federally listed as an endangered species on September 10, 1982. It was reclassified as threatened on November 7, 1994. This was possible because at the time of reclassification 61% of the viable populations had been protected. The small whorled pogonia and its habitat continue to be threatened, directly and indirectly, by residential and commercial development. The upland habitat where it is found is seldom protected by federal or state laws unless it occurs on federally-owned property. Without voluntary landowner protection many pogonia populations have been and will be destroyed. Other threats to this species are collection by plant enthusiasts and browsing by white-tailed deer and invertebrates.

What You Can Do To Help - If you find a plant that appears to be the small whorled pogonia, take note of the location and photograph the plant, if possible. Please do not remove the plant!

Contact one of the following agencies for assistance:

Virginia Department of Agriculture and Consumer Services
Office of Plant Protection
P.O. Box 1163
Richmond, Virginia 23209
(804) 786-3515

Virginia Department of Conservation and Recreation
Division of Natural Heritage
217 Governor Street, 3rd Floor
Richmond, Virginia 23219
(804) 786-7951

U.S. Fish and Wildlife Service
Virginia Field Office
6669 Short Lane
Gloucester, Virginia 23061
(804) 693-6694

References

U.S. Fish and Wildlife Service. 1992. Small whorled pogonia (*Isotria medeoloides*) recovery plan, first revision. Newton Corner, Massachusetts.

Ware, D.M.E. 1991. Small whorled pogonia. Pages 95-97 in K. Terwilliger, ed. Virginia's Endangered Species, Proceedings of a Symposium. McDonald and Woodward Publishing Company, Blacksburg, Virginia.

U.S. Fish and Wildlife Service
Virginia Field Office
6669 Short Lane
Gloucester, Virginia 23061
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August 1999

SENSITIVE JOINT-VETCH

(Aeschynomene virginica)

SURVEY CONTACTS IN VIRGINIA

This list contains individuals who we have already determined are qualified to conduct surveys for the species listed above. This list does not include all individuals qualified or authorized to survey for this species. If you select someone not on this pre-approved surveyor list, please provide the proposed surveyor's qualifications to this office 30 days prior to the start of the survey. Please send copies of all survey results to this office. If the survey determines that any rare species are present, please contact this office to allow us the opportunity to work with you to ensure that a project avoids or minimizes adverse effects to rare species and their habitats. Inclusion of names on this list does not constitute endorsement by the U.S. Fish and Wildlife Service or any other U.S. Government agency. Listed alphabetically. September 8, 2004

John Brooks, III
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Smithsonian Institution
Washington, DC 20013-7012
(202) 633-2563
strong.mark@nmnh@si.edu

ATLANTIC SLOPE FRESHWATER MUSSELS
SURVEY CONTACTS IN VIRGINIA

This list contains individuals who we have already determined are qualified to conduct surveys for the species listed above. This list does not include all individuals qualified or authorized to survey for this species. If you select someone not on this pre-approved surveyor list, please provide the proposed surveyor's qualifications to this office 30 days prior to the start of the survey. Please send copies of all survey results to this office. If the survey determines that any rare species are present, please contact this office to allow us the opportunity to work with you to ensure that a project avoids or minimizes adverse effects to rare species and their habitats. Inclusion of names on this list does not constitute endorsement by the U.S. Fish and Wildlife Service or any other U.S. Government agency. Listed alphabetically. September 9, 2004

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Lake Anna - The Beginning of a Treasure

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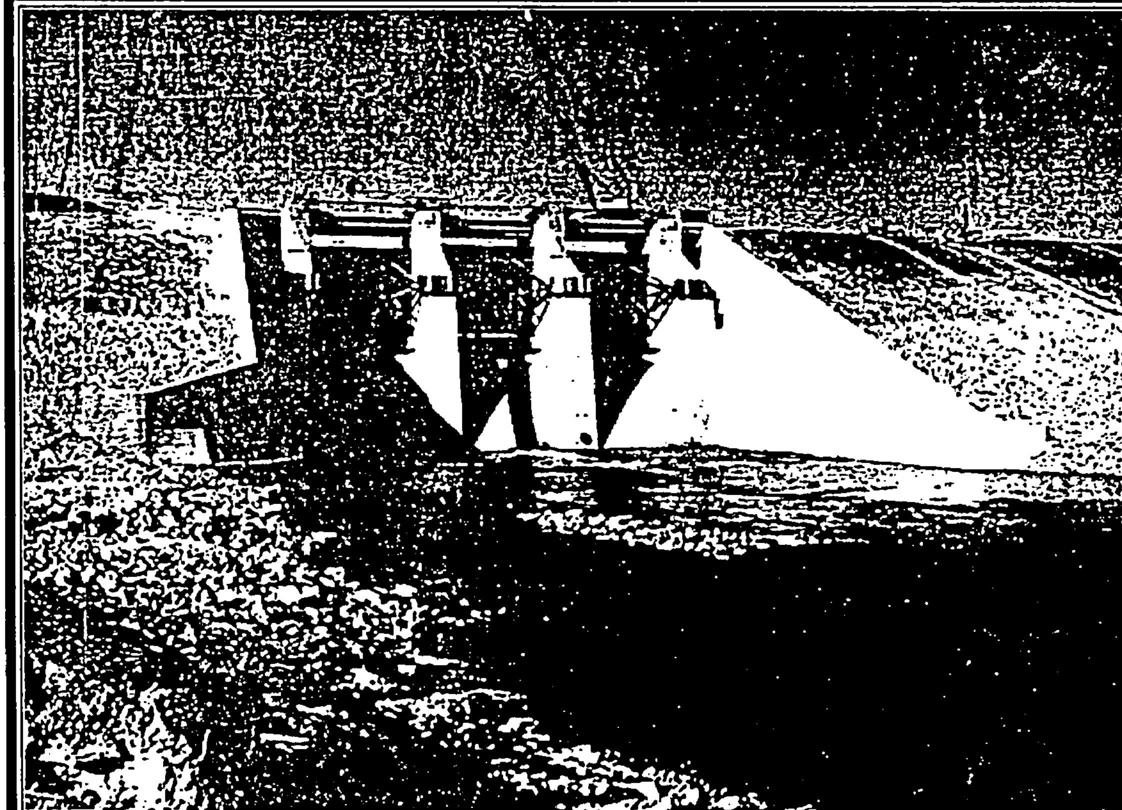
Reprinted By The Central Virginian Newspaper of a press release from the public relations department of Virginia Electric and Power Company, Richmond, VA, January 10, 1972



VEPCO closes dam to create Lake Anna

Virginia Electric and Power Company's 9,600-acre Lake Anna began filling Monday, January 10, 1972 at ceremonies closing the dam on the North Anna River in Louisa County. The lake will provide water for Vepco's $1 billion North Anna Power Station, the company's second nuclear station. Lake Anna, located 40 miles northwest of Richmond, is expected to offer a variety of recreational benefits. It is estimated that it will take two years to fill the lake.

A new lake named Lake Anna began filling today, when a mile-long dam across the North Anna River was plugged during ceremonies held by Virginia Electric and Power Company.

The signal for the dam to be closed - a blast from a boater's horn - was given by FitzGerald Bemiss, chairman of the Virginia Commission of Outdoor Recreation, who commented on the potential for recreation associated with the 9,600 acre lake.

Lake Anna is being formed as part of the development of Vepco's billion dollar North Anna Power Station, a four-unit nuclear generating plant under construction in Louisa County about five miles northwest of the dam. Cooling of power station circulating water will be supplemented by a series of three separate lagoons which cover 3,400 acreas and are connected by canals.

Until the horn sounded today, the North Anna river had been flowing through a 12-foot wide channel in the dam. On the signal from Bemiss, a crane lowered a 12-foot square steel plate into place, blocking the river flow except for minimum release which must be maintained at all times. Based on normal weather conditions, the lake will take an estimated two years to fill.

John M. McGurn, chairman of the board of Vepco, said Lake Anna was named after the Queen of England and Ireland who reigned in the early 18th Century, and for whom the North Anna River was named.

"Every phase of the design of both plant and lake has been studied and restudied in order to be as certain as is humanly possible that the facility will have the least possible adverse effect on the total environment," Mcgurn said.

The 200-mile shoreline around the lake is expected to result in new homes, new visitors and new businesses in the surrounding areas of Louisa, Spotsylvania and Orange counties, he said.

The mile-long dam contains more than a million cubic yards of earth; the concrete spillway section is about 90 feet tall. Under average conditions, the water will be 80 feet deep at the dam.

The first two units at the power station are scheduled for completion in 1974 and 1975, with the second two units due in 1977 and 1978. Total capability of the station will be nearly four million kilowatts.

Based on present cost estimates and tax levels, the total project on completion would contribute about $3 million a year in property and other taxes to the area.

T. Justin Moore Jr., president and chief financial officer of Vepco, introduced Bemiss and presented him with the boater's horn used to signal the closing of the dam.

The Rev. Garland H. Sparks, pastor of Louisa Baptist Church in Louisa, gave the invocation.

It was reported that McGurn told those assembled that they were "standing on the site of the largest construction project ever undertaken in Virginia." He foresaw the lake providing a great boost to the "enjoyment and the economy of this entire section of Virginia in terms of new homes, new visitors, new businesses and a new enjoyment of life for people in the surrounding area." He predicted the construction of 5,000 new homes and 400 businesses.

In his remarks, Bemiss stated that he believed "the lake will be a powerful magnet. It will attract quantities of people and developments of all sorts. The change brought to the area will be great."

Portions reprinted from a Vepco brochure, The North Anna Power Station, Lake Anna, Va.

The Lake

When Vepco's 17-mile long lake with more than 200 miles of shoreline is complete, experts believe the lake can be developed into a major recreational attraction.

The Virginia Division of Parks is considering plans for the development of a 2,000-plus-acre state park on the north shore of the lake in about 1976. Current plans call for both day-use and overnight facilities, including a beach for swimming, a boat launching area and a marina.

Vepco is cooperating with the Virginia Commission on Outdoor Recreation in the preparation of a detailed development plan for recreational use of the lake. Theodore J. Wirth and Associates, a nationally recognized recreational consultant, has been retained to study the region and recommend a plan for development.

A preliminary report by the firm indicates the potential use of the lake could be in excess of two million visitors annually by the year 2000. The area, according to Wirth, is capable of supporting not only a state park but two regional parks and a half-dozen public access areas. More than 1,500 boats could be accommodated on the main body of the lake, their firm said.

Some of the boats could be handled by the recommended public boat ramps on the lake, according to the report, and the remainder by private development of the lakeshore property.

Beaches capable of accommodating 4,000 swimmers are suggested, along with picnicking facilities for more than 5,000 and about 3,500 campsites.

The Fishing

The reservoir at North Anna has the potential to be one of the finest fishing spots on the East Coast.

A number of species are expected to carry-over from the existing river and stream system into the lake, including pumpkin-seed sunfish, spotted bass, gizzard shad and several types of catfish.

In addition the lake can be stocked with popular gamefish: Largemouth Bass, Muskellunge, Crappie, Bream, Brown Trout, White Bass, Coontail Perch, Coho Salmon and Striped Bass.

Sportsmen can anticipate reasonable catches within two years after the reservour has filled. As the fish become established and effective stocking management programs are worked out, the fishing should become excellent.

The North Anna Power Station

Fast facts from 1972

- **Location:** In Louisa, Orange and Spotsylvania Counties.
- **Size:** Approximately 18,000 acres.
- **Power Station Capability:** When completed, 3,760,000 kilowatts.
- **Total project cost:** Approximately $1 billion.

- **Operating schedule:** First two units in 1974 and 1975; second two units in 1977 and 1978.
- **Reservoir:** 9,600-acre Lake Anna, 17 miles long with more than 200 miles of shoreline. Maximum depth about 80 feet near dam. Filling time depends on weather, but lake should be full in 1974.
- **Cooling system:** Cooling of power station circulating water will be supplements by a series of three separate lagoons which cover 3,400 acres and are connected by canals.
- **Dam:** Approximately one mile long, earthfill with concrete spillway section, located about five miles southeast of power station.
- **Employment:** Construction force will average about 2,600 men. Aproximately 100- 125 Vepco personnel will operate plant.
- **Taxes:** $3 million annually when all four units are completed, based on present cost estimates, tax rate and assessment ration.
- **Water Flow:** Under State Corporation Commission license, minimum water flow in the river will be 40 cubic feet per second.
- **Environment:** Plant is being constructed and will be operated in accordance with rigid standards set up and enforced by State and Federal agencies.

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About Lake Anna

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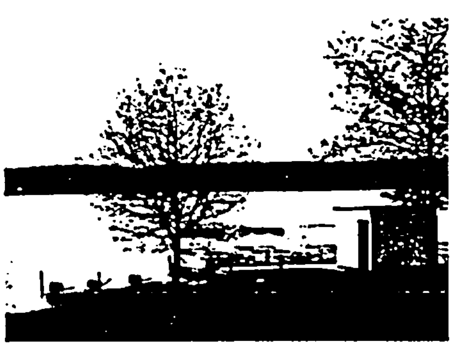
Lake Anna was formed in 1972 when the North Anna River was dammed to form a cooling resovoir for the North Anna Nuclear Power Reactor operated by Virginia Power. The lake is actually comprised of two separate sections: a 3,400 acre impoundment that provides the water for the power plant's cooling requirements (much as the water in a radiator is used to cool a car engine), and a 9,600 acre "main lake" impoundment that is used to disperse the warmer water that results from the reactor cooling process. The smaller impoundment, known as the "hot side" by the locals, is accessible only to property owners. The larger lake, on which High Point Marina and the Lighthouse Inn are located, is a public facility open to all.

After the lake was formed in 1972, the Virginia Department of Game and Inland Fisheries (VDGIF) stocked it with more than 350,000 baby bass. Several years later, this initial stocking was augmented with 80,000 Florida-strain bass. The ongoing lake management program provided by VDGIF and the abundant population of baitfish such as threadfin shad, gizzard shad, and blueback herring, has resulted in Lake Anna becoming the premier bass lake in all of Virginia. In fact, Anna consistently produces more citation bass (8 lb or 22 ") each year than any other body of water in the state. During 2001, 50 citation bass were recorded by Lake Anna anglers. Also in 2001, Anna ranked 3rd in the state for citation crappie with 18. Because of the influence of the warm water coming from the "hot side", particularily on the lower end of the lake, nearly half of these citation fish were caught in the months of December, January, February, and March - a time when most other lakes are in near hibernation. The months of April, May and June can provide non-stop, heart pounding action. As a result of its much deserved reputation, Anna has become a "must" stop for most serious fisherman throughout the region, and is a favorite on the local bass tournament schedules.



Lake Anna has also become one of the top landlocked Striped Bass lakes in the area. The stripers cannot naturally reproduce in the impoundment so VDGIF stocks approximately 200,000 fingerlings each year. This past year provided a bumper crop for striper fisherman. 4-fish limits were not uncommon, with quality fish in the 8-12 lb range a common occurence at our scales.

While largemouth bass and stripers are the two main

draws to Anna, it also has significant populations of many
other species. Anna is well-known in the area as a mecca for crappie fisherman, with many of them taking strategic positions at bridge pilings and brush piles. Other panfish such as bluegill are abundant and there are also good populations of yellow perch, white perch. Fisherman fishing for bass or stripers in the Contrary Creek area will occasionally be startled to have their offering engulfed by a hard-hitting chain pickerel. The name "Lake Anna" will bring a smile to many knowing catfish fanciers. One of the better kept secrets on the Lake is the good population of walleye. Anglers fishing deeper structure for striped bass are surprised when the fish pulling on their line turns out to be a walleye instead of the expected striper.

Lake Anna also provides hours of enjoyment for recreational boaters, skiers, and others during the summer months. It's 250 miles of shoreline provides scenic views of natural woods, beautiful lake homes, and an abundance of wildlife. Its many coves provide an opportunity for a "lake lunch" or a relaxing swim.

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Virginia Department of Game & Inland Fisheries

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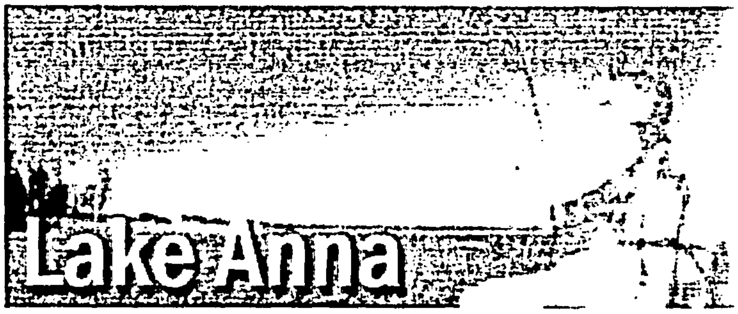

- 2003 Biologist/Fisheries Report

Lake Anna is a 9,600-acre impoundment located in Louisa, Orange, and Spotsylvania counties, owned by the Dominion Power Company. The impoundment was completed in 1972 and serves as cooling water for the North Anna Nuclear Power Station. Initial stockings began in 1972, with introductions of largemouth bass, bluegill, redear sunfish, and channel catfish. Subsequent stockings of channel catfish, largemouth bass (northern and southern strains), redear, striped bass, and walleye were made to improve and diversify the fishery. Blueback herring and threadfin shad were successfully introduced in the 1980's to provide additional forage for pelagic (open-water) predators.

Annual stockings of striped bass and walleye are generally made to maintain the fishery. Prior to 1985, a 12-inch size limit was in effect for largemouth bass. Since that time, a 12 - 15 inch protected slot has been in effect to restructure the largemouth bass population. The current regulation allows harvest of fish less than 12 inches and larger than 15 inches. Fish between 12 and 15 inches must be released. Striped bass are currently managed under a 20-inch minimum size limit.

Lake Anna is a reasonable drive from both Northern Virginia and the Richmond area. Outdoorsman can access Anna at nine private marinas, several campgrounds, and at Lake Anna State Park. Reservoir accessibility creates heavy use by both anglers and boaters, especially during summer months. A 2000 creel survey indicated that fishing pressure was around 24 hours/acre. The most popular species fished for included largemouth bass (69 %), striped bass (15 %), and crappie (12 %). Crappie (70%) were harvested at the highest rate, followed by striped bass (29 %) and largemouth bass (1 %). Surprisingly, almost 99 % of all largemouth bass caught were released!

Hydrilla vertricillata, an exotic aquatic weed, became established into Lake Anna during the late 1980's. Abundance increased from 96 acres in 1990 to 832 acres in 1994. Triploid (sterile) grass carp were stocked into Virginia Power's Waste Heat Treatment Facility in 1994 to control Hydrilla, and Hydrilla abundance is now quite low in both impoundment's.

North American Journal of Fisheries Management 2:66–73, 1982

#19

Seasonal Distribution of Striped Bass in Keystone Reservoir, Oklahoma

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ABSTRACT

Sixteen striped bass (*Morone saxatilis*) from Keystone Reservoir, Oklahoma, were successfully implanted with ultrasonic transmitters and located periodically during a 337-day monitoring period. A total of 220 sightings were plotted, 154 (70%) of which occurred during the summer months (June–August). Striped bass exhibited seasonal migratory and distributional patterns, showing areas of concentration in the headwaters of the reservoir during the spring and fall with summer concentrations in the main body of the reservoir.

Striped bass (*Morone saxatilis*) were introduced into Oklahoma waters in 1965 both as an additional sport fish and as a biological management tool to control over-abundant clupeid populations. Keystone Reservoir, a 10,643-hectare hydro-electric impoundment on the Arkansas River, was stocked from 1965 through 1969 with fingerling striped bass. Natural reproduction was identified in 1970 (Mensinger 1970) and has occurred for 12 consecutive years.

Seasonal distributions and movement patterns of anadromous striped bass stocks have received much attention. Chesapeake Bay stocks of striped bass have been studied by Mansueti (1961), Massmann and Pacheco (1961), Chapotan and Sykes (1961), Hollis (1967), and Moore and Burton (1975). Movements of striped bass found in Long Island Sound were studied by Clark (1968). Striped bass populations in the Sacramento-San Joaquin Estuary were investigated by Calhoun (1952), Chadwick (1967), and Orsi (1971). These authors found discernible migratory patterns for mature striped bass but little or no movement of immature fish.

Movement patterns of striped bass in freshwater have been studied by Scruggs (1955) in the Cooper River, South Carolina; Dudley et al. (1977) in the Savannah River, Georgia; Coutant and Carroll (1980) in quarry lakes in Tennessee; Waddle et al. (1980) and Schaich and Coutant (1980) in Cherokee Reservoir, Tennessee; and Summerfelt and Mosier (1976) in Keystone Reservoir, Oklahoma. Summerfelt and Mosier (1976) investigated pre-spawning movement in Keystone Reservoir and showed that striped bass preferred both the Cimarron and Arkansas River headwater areas plus Salt Creek Cove during the spring season.

Striped bass distributional studies throughout the year have not been conducted although striped bass have been widely introduced into reservoirs in southeastern states. The objective of this study was to examine the seasonal distribution of striped bass in Keystone Reservoir to help fill the knowledge gap that exists for striped bass distribution in reservoirs.

METHODS

Striped bass used for telemetry implants were captured by gill nets (0.08 m × 2.4 m × 91.4 m, bar mesh) during the fall of 1976 and spring of 1977. Ultrasonic transmitters were implanted in 16 striped bass: five from the Arkansas River, seven from the Cimarron River, and four from the Salt Creek areas of Keystone Reservoir during November 1976 and March 1977 (Table 1). These fish ranged from 597 to 780 mm in total length and weighed from 2.7 to 6.0 kg.

Transmitters (74 kHz) used in the study had varying identifiable pulse rates, were 16 × 65 mm, and weighed 20 g in air and 8 g in water. These transmitters were surgically implanted into the body cavity following the procedures of Summerfelt and Mosier (1976). Recovery from

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Table 1. Tagging and tracking information from striped bass bearing ultrasonic transmitters in Keystone Reservoir, 1976–1978.

Date tagged	Tag number	Total length (mm)	Weight (g)	Sex	Location of capture[a]	Date of last sighting	Total time tracked
24 November 1976	12	625	2,722	M	S	17 November 1977	260.4[b]
1 March 1977	20	697	4,423	F	S	13 October 1977	227.0
7 March 1977	11	780	5,959	F	S	10 December 1977	277.4
7 March 1977	10	700	4,086	F	S	25 May 1977	79.0
10 March 1977	22	634	3,600	M	C	31 March 1977	20.7
10 March 1977	14	661	3,405	M	C	18 August 1977	160.7
11 March 1977	18	681	3,405	F	C	13 March 1977	1.9
11 March 1977	21	617	2,898	M	C	31 January 1978	326.1
11 March 1977	16	634	3,008		C	29 August 1977	171.0
12 March 1977	17	597	3,178	M	C	31 March 1977	18.9
12 March 1977	15	644	3,348	M	C	1 September 1977	172.8
14 March 1977	25	730	4,682	F	A	7 June 1977	85.1
14 March 1977	9	644	3,292	M	A	16 November 1977	246.3
14 March 1977	29	710	4,881	F	A	17 August 1977	155.8
16 March 1977	19	708	4,082	F	A	21 November 1977	249.8
16 March 1977	13	722	4,082	M	A	30 November 1977	259.8

[a] S = Salt Creek Area; C = Cimarron River arm; A = Arkansas River arm.
[b] Tracking started 1 March 1977. Actual time at large was 357.4 days.

surgery took place in a 1–4 hour furacin bath (100 mg/liter) in a 1-m circular stock tank with a recirculating system.

Striped bass distributions were monitored approximately 15 days each month in Keystone Reservoir from 1 March 1977 to 31 January 1978. Locating was conducted throughout the reservoir. Starting locations generally were at the confluence of the Cimarron and Arkansas River arms of the reservoir, but as distributions became apparent, daily starting locations were determined from the last sightings of previous monitoring days. Locating continued either until all fish were located or until the entire reservoir was searched.

Results

Seasonal distributions of Keystone Reservoir striped bass were determined from a total of 220 sightings during the 337-day study period (Table 2). During the spring season (March–May), locating effort and sightings were limited because most tagged fish were ascending tributary streams to spawn. Distribution patterns (Fig. 1) were determined from a total of 35 sightings made during the spring. Re-locations of tagged striped bass during the spring were made primarily in March, within the 2-week period following implantation and release. In March, 14 of the 16 tagged fish were re-located, but in April and May only three and six tagged fish were located, respectively, during a total of 12 sightings. Spring distributions showed major concentrations of tagged fish in the upper portion of the Cimarron River arm of the reservoir, with additional sightings made on fish as they moved between the Cimarron tributary and the lower portion of the reservoir. Although striped bass were tagged and released in the upper Arkansas River arm of the reservoir, no tagged fish were re-located in that area or in the Arkansas tributary during the spring months. In March, two fish tagged in the upper Arkansas arm were located shortly after release in the concentrations of fish in the upper Cimarron arm. As spring progressed (April–May), one of these two tagged fish was located again in the Arkansas arm of the reservoir along with two fish tagged in the Cimarron arm and one from the Salt Creek area. Similar occurrences of fish moving from the Arkansas River arm to the Cimarron River arm and back were reported by Summerfelt and Mosier (1976).

Summer distributional patterns (June–August) were determined from 154 observations or 70% of the total sightings (Fig. 1). Following spawning runs into the tributary streams, primarily the Arkansas River (Mensinger 1970), tagged fish descended into the main body of the reservoir during the summer. There were three concen-

Table 2. Seasonal summaries of tagged striped bass sightings by major area of Keystone Reservoir.

Tag number	Location[a]																Total sightings
	Spring				Summer				Fall				Winter				
	A	C	S	Σ	A	C	S	Σ	A	C	S	Σ	A	C	S	Σ	
12					7	1	1	9	2			2					11
20		4		4	2	13	1	16			1	1					21
11	2			2	10	4	2	16		1		1		1		1	20
10		5		5		1[b]		1									6
22		2[b]		2													2
14		1		1	2	2		4									5
18		1[b]		1													1
21	2	1		3	8	2	4	14		9		9		8		8	34
16	1	3		4	17	1		18									22
17		2		2													2
15		3		3	14	2		16	1			1					20
25	1[b]			1													1
9		1		1	12			12									13
29		2		2	5	8		13									15
19					1	15	2	18		8		8					26
13	2	2		4	9	1	7	17									21
Totals				35				154				22				9	220

[a] A = Arkansas River arm; C = Cimarron River arm; S = Salt Creek area.
[b] = Confirmed death of tagged fish.

tration areas: (1) the Arkansas River arm around the U.S. 64 highway bridge; (2) the mouth of Salt Creek Cove in the Cimarron River arm; and (3) a submerged island in Salt Creek Cove.

Early in the summer, tagged fish were located in the Arkansas River arm of the reservoir. These fish gathered in the lower portion during June prior to their segregation in late summer into areas of concentration. Eleven of the 13 tagged fish at large during the summer months were located in the Arkansas arm during the early summer. By late summer (July–August) tagged fish had moved into areas of concentration in the lower end of the reservoir. These tagged fish segregated themselves into distinct summering groups, with individuals of those groups occasionally intermingling in another area of concentration. Fish tagged in the Cimarron River arm (Fig. 2) showed a preference for the lower Arkansas arm and the main body of the reservoir near the U.S. 64 bridge during the summer, with 78% of the sightings in this area. Only nine sightings were made in the Cimarron River arm (12%) or the Salt Creek Cove (11%) areas. Conversely, figh tagged in the Arkansas River arm (Fig. 3) used the Cimarron River arm and Salt Creek area extensively (61%). The Arkansas River arm near the U.S. 64 bridge also was frequented (39%), primarily by one individual (10 sightings), but not as much as other areas of concentration. Distribution patterns of fish tagged in Salt Creek Cove (Fig. 4) were extensive. They used the same summer areas as fish tagged in the Cimarron and Arkansas arms. Areas of preference were not as apparent as for fish tagged in other areas, with sightings distributed among the Arkansas arm, Cimarron arm and the Salt Creek area (43, 47, and 11% of the sightings, respectively). When concentrated, these tagged fish distributed themselves along inundated river and creek channels. These concentration areas are characterized by steep drop-offs, submerged islands, heavy rock riprap, submerged trees, and tree stump beds in the summer.

Fall distributions (Fig. 5) of tagged fish were scattered throughout the reservoir after the summer concentrations of fish broke up and moved toward the headwaters. During fall (September–November), only six of 12 tagged fish at large were located during 22 sightings. Tagged fish randomly distributed themselves about the reservoir during early fall. By late October–November, they apparently moved towards the confluence of each arm of the reservoir and concentrated there. Three tagged fish were located in the upper Cimarron River arm during 18 sightings, two fish were located in the upper Arkan-

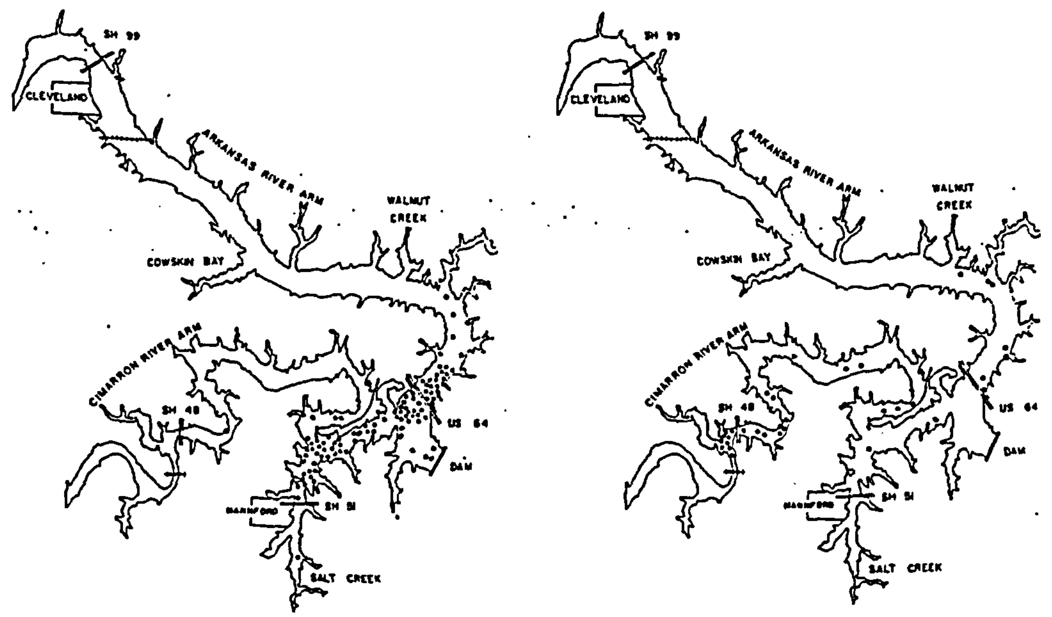

Figure 1. Spring (left) and summer (right) locations of tagged striped bass in Keystone Reservoir.

sas River arm (three sightings), and one tagged fish remained in Salt Creek Cove.

Information on the distribution of fish during the winter (December–February) was restricted to two of the 12 tagged fish at large that were located nine times (Fig. 5). Most sightings were in the headwater region of the Cimarron River arm of the reservoir, where one tagged fish remained for the winter. Standard search procedures for tagged fish were terminated in January 1978 due to heavy ice cover on the reservoir. Tracking of fish No. 21 continued through the ice until February on the upper Cimarron arm. Further work through the ice was precluded by winter drawdowns that produced unstable ice. In March 1978, when ice cover broke up on Keystone Reservoir, tagged fish No. 21 was relocated in the upper Cimarron River arm where apparently it had remained for the winter near its original release point of the previous year.

Discussion

Mature striped bass in Keystone Reservoir exhibit a yearly migratory pattern. Previous research had shown that mature striped bass concentrate at the confluence of the main tributaries of the reservoir in March (Summerfelt and Mosier 1976). These areas of concentration are known as staging areas and are defined as sites where congregations or temporary gatherings of pre-spawning fish occur prior to upstream movement. Tagging operations during the present study took place within or immediately downstream of these staging areas reported in Summerfelt and Mosier (1976). In March subsequent to tagging, striped bass were located in one of the two staging areas on Keystone Reservoir. Concentrations of fish in staging areas in the Arkansas River tributary, as reported by Summerfelt and Mosier (1976), were not located during the present study. Heavy siltation in this area of the Arkansas River prevented passage by boat from the reservoir into the river staging area. Background static caused by physical conditions of the river also interfered and made locating tagged fish nearly impossible in the river. Failure to locate tagged fish in the upper Arkansas River arm in the spring, and again during fall months, probably was caused by our inability to locate tags due to physical conditions in the area rather than a reflection of the usage of the area by striped bass. Only six tagged fish were located in the reservoir during April and May, indicating that most mature fish had already ascended the river systems on their spawning runs. Tagged fish began appearing in the main

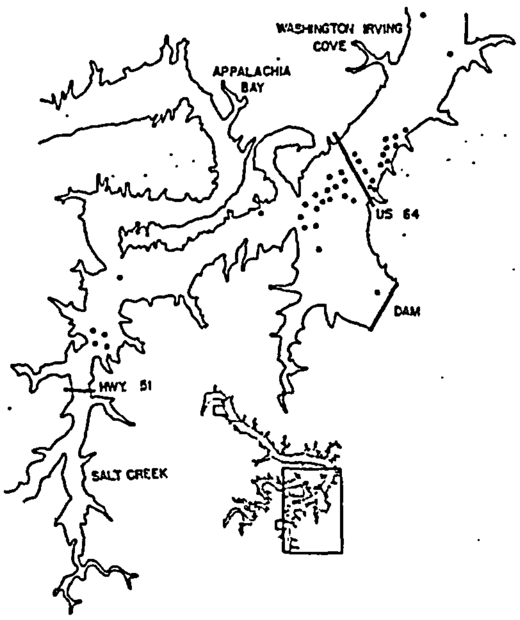

Figure 2. Summer locations (July–August) of striped bass tagged in the Cimarron River arm of Keystone Reservoir.

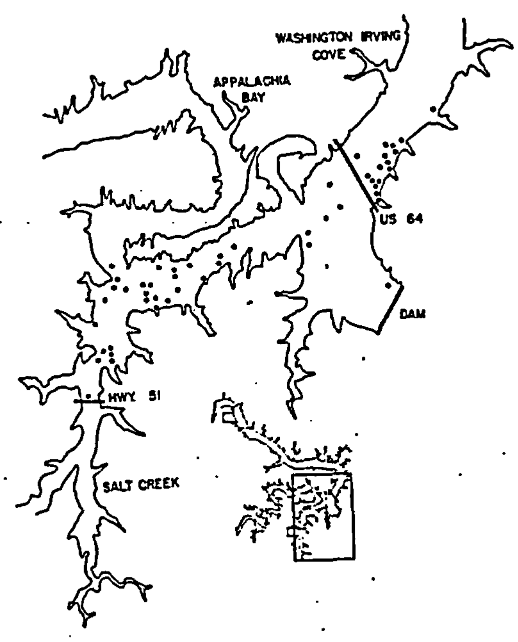

Figure 3. Summer locations (July–August) of striped bass tagged in the Arkansas River arm of Keystone Reservoir.

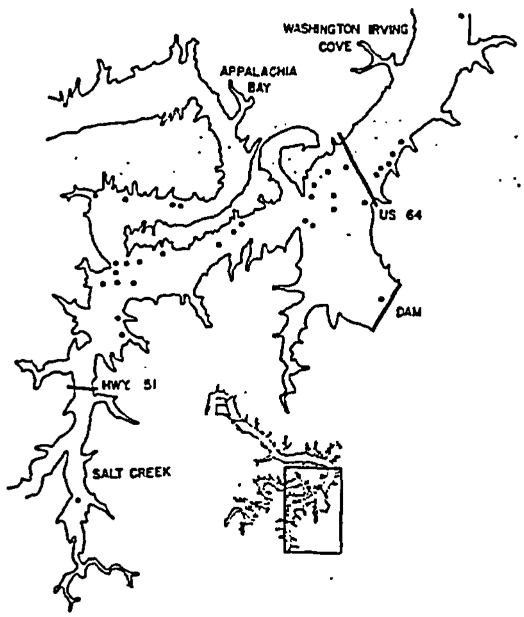

Figure 4. Summer locations (July–August) of striped bass tagged in the Salt Creek area of Keystone Reservoir.

body of the reservoir early in June and remained concentrated around the confluence of the Arkansas and Cimarron rivers; Salt Creek and the Cimarron River through July and August. During the fall, tagged striped bass migrated back to the staging areas in the upper end of the reservoir where they remained until the spawning run in the spring.

The migratory pattern of striped bass in Keystone Reservoir closely resembles that of anadromous striped bass stocks. In Calhoun's (1952) study of the migratory habits of striped bass in the Sacramento-San Joaquin Delta, fish moved downstream following the spring spawning run into the lower bays and ocean for the summer months. The fish then moved back upstream into the Delta in the fall, where they remained until the spring spawning run. Further studies by Chadwick (1967) and Orsi (1971) revealed a similar pattern, although more extensive summer migrations and a shift of the overwintering area downstream were noted. Massmann and Pacheco (1961), Chapotan and Sykes (1961), Nichols and Miller (1967), and Grant et al. (1969) observed similar seasonal migratory patterns for Chesapeake Bay stocks of striped bass. Clark (1968) also noted a similar migratory pattern for three

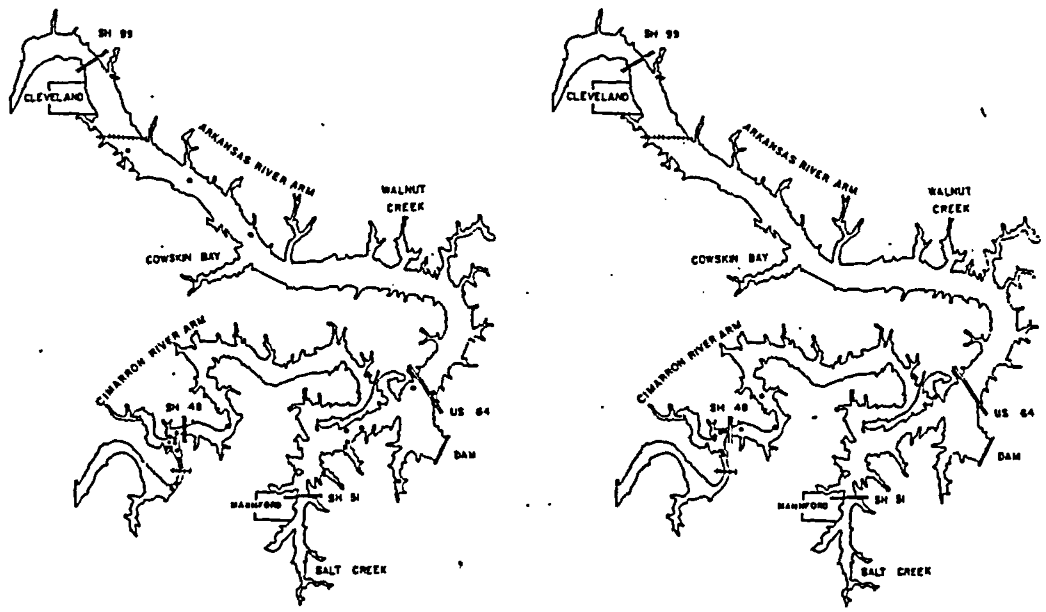

Figure 5. Fall (left) and winter (right) locations of tagged striped bass in Keystone Reservoir.

stocks of Hudson River–Long Island Sound striped bass. The summer distributions of striped bass in Cherokee Reservoir, Tennessee (Waddle et al. 1980; Schaich and Coutant 1980) were similar to those of Keystone Reservoir, with fish concentrated in the lower, deep-water regions of the reservoir in summer. The similarity of seasonal distribution and migratory patterns of anadromous and freshwater populations of striped bass, as shown in the present study, suggests an inherited behavioral pattern with concentration areas, such as staging areas, as part of this migratory pattern.

During their movement towards and while in areas of concentration, striped bass distribute themselves along inundated river and creek channels. Summerfelt and Mosier (1976) reported similar findings for pre-spawning striped bass in Keystone Reservoir. Summer areas of concentration were in the deep-water regions of the reservoir where striped bass continued to distribute themselves along the river channels associated with submerged islands and steep drop-offs from shallow flats.

The presence of preferred summer areas in Keystone Reservoir may be related to water temperature as well as inherited behavior patterns. Coutant and Carroll (1980) found that temperature was a greater influence on habitat selection by striped bass than water depth or light intensity, with the preferred temperature being 22 C. In Cherokee Reservoir, Waddle et al. (1980) found that the summer ranges of striped bass in the lower reservoir corresponded to the presence of springs containing cool, oxygenated water. Fish concentrated in these thermal refuges in order to avoid summer ambient temperatures greater than 27 C. This concept is supported by Dudley et al. (1977) for Savannah River striped bass. After spawning, these fish moved upstream to remain until the following spring. This movement apparently is temperature-related because temperatures in the upper Savannah River are cooler in the summer months than surrounding coastal waters where temperatures reach 26–30 C. Scruggs (1955) found that striped bass in the Cooper River, South Carolina spent the summer months in the upper part of the Cooper River, presumably to avoid excessive summer temperatures. With the nearly homothermous state of Keystone Reservoir, thermal refuges probably do not exist, although the fish did distribute themselves in the deeper limnetic areas of the lower reservoir. The normally homothermous waters in excess of 30 C probably confine striped bass to the deep-water areas of Keystone Reservoir in the summer.

The existence of racial subpopulations of striped bass in Chesapeake Bay, where discrete populations exist in tributary rivers, has been reported by Massmann and Pacheco (1961), Nichols and Miller (1967), Hollis (1967), and Morgan et al. (1973). Clark (1968) found four distinguishable contingents of striped bass in the Long Island Sound and coastal waters of the New York Bight. Raney and de Sylva (1953) discussed racial differences between the Hudson River and Chesapeake Bay stocks, as well as the existence of upstream and downstream populations in the Hudson River. Raney and Woolcott (1954) differentiated endemic races of striped bass along the southeastern Atlantic coast from Albemarle Sound, North Carolina; Santee-Cooper, South Carolina; and the Saint Johns River, Florida. Striped bass introduced into Oklahoma waters were procured from endemic stocks in Virginia, North Carolina, and South Carolina. These introductions of geographical subpopulations and the apparent segregation of the Arkansas River and Cimarron River fish during the spring and summer months suggest the presence of at least two subpopulations in Keystone Reservoir. The Arkansas River is considered to be the primary spawning area for Keystone Reservoir striped bass. Low flows in the Cimarron River are thought to inhibit successful striped bass spawning although successful reproduction was documented in 1973 and 1978–1980 by personnel from the Oklahoma Department of Wildlife Conservation. Periodic spawning success in the Cimarron River may be sufficient to maintain a separate stock of fish in that river.

In summary, the present study helped narrow the existing knowledge gap of freshwater populations of striped bass by: (1) confirming the existence of annual migrations between the reservoir and its tributary streams much like the anadromous stocks from which these freshwater populations originated; (2) determining seasonal concentration areas in the reservoir from which striped bass migrate; (3) proposing that the concentration of stocks is an inherited behavior among both freshwater and anadromous stocks; and (4) proposing the existence of segregated striped bass populations of differing racial qualities in Keystone Reservoir.

References

Calhoun, A. J. 1952. Annual migrations of California striped bass. California Fish and Game 38:391–403.

Chadwick, H. K. 1967. Recent migrations of the Sacramento-San Joaquin striped bass population. Transactions of the American Fisheries Society 96:327–342.

Chapotan, R. B., and J. E. Sykes. 1961. Atlantic coast migration of large striped bass as evidenced by fisheries and tagging. Transactions of the American Fisheries Society 90:13–20.

Clark, J. R. 1968. Seasonal movements of striped bass contingents of Long Island Sound and the New York Bight. Transactions of the American Fisheries Society 97:324–343.

Coutant, C. C., and D. S. Carroll. 1980. Temperatures occupied by ten ultrasonic-tagged striped bass in freshwater lakes. Transactions of the American Fisheries Society 109:195–202.

Dudley, R. G., A. W. Mullis, and J. W. Terrell. 1977. Movements of adult striped bass (*Morone saxatilis*) in the Savannah River, Georgia. Transactions of the American Fisheries Society 106:314–322.

Grant, G. C., V. G. Burrell, Jr., C. E. Richards, and E. B. Joseph. 1969. Preliminary results from striped bass tagging in Virginia, 1968–1969. Proceedings of the Annual Conference Southeastern Association Game and Fish Commissioners 23:558–570.

Hollis, E. H. 1967. Investigation of striped bass in Maryland. Maryland Department of Game and Inland Fisheries, Final Report F-003-R-12, Annapolis, Maryland, USA.

Mansueti, R. J. 1961. Age, growth and movements of the striped bass, *Roccus saxatilis*, taken in size selective fishing gear in Maryland. Chesapeake Science 2:9–36.

Massmann, W. H., and A. L. Pacheco. 1961. Movements of striped bass in Virginia waters of Chesapeake Bay. Chesapeake Science 2:37–44.

Mensinger, G. C. 1970. Observations on the striped bass, *Morone saxatilis*, in Keystone Reservoir, Oklahoma. Proceedings of the Annual Conference Southeastern Association Game and Fish Commissioners 24:447–463.

Moore, C. J., and D. T. Burton. 1975. Movements of striped bass, *Morone saxatilis*, tagged in Maryland waters of Chesapeake Bay. Transactions of the American Fisheries Society 104:703–709.

Morgan, R. P., II, T. S. Y. Koo, and G. E. Krantz. 1973. Electrophoretic determination of populations of the striped bass, *Morone saxatilis*, in the upper Chesapeake Bay. Transactions of the American Fisheries Society 102:31–32.

Nichols, P. R., and R. V. Miller. 1967. Seasonal movements of striped bass, *Roccus saxatilis* (Walbaum), tagged and released in the Potomac River, Maryland, 1959–61. Chesapeake Science 8:102–124.

Orsi, J. J. 1971. The 1965–1967 migrations of the Sacramento-San Joaquin estuary striped bass population. California Fish and Game 57:257–267.

Raney, E. C., and D. P. de Sylva. 1953. Racial

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investigation of the striped bass, *Roccus saxatilis* (Walbaum). Journal of Wildlife Management 17:495–509.

RANEY, E. C., AND W. S. WOOLCOTT. 1954. Races of striped bass, *Roccus saxatilis* (Walbaum), in Southeastern United States. Proceedings of the Annual Conference Southeastern Association of Fish and Game Commissioners 8:60–64.

SCHAICH, B. A., AND C. C. COUTANT. 1980. A biotelemetry study of spring and summer habitat selection by striped bass in Cherokee Reservoir, Tennessee, 1978. ORNL/TM-7127. Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA.

SCRUGGS, G. D., JR. 1955. A migration study of the Cooper River populations of striped bass, *Roccus saxatilis* (Walbaum). Report in South Carolina Academy of Science, Columbia, South Carolina, USA.

SUMMERFELT, R. C., AND D. MOSIER. 1976. Evaluation of ultrasonic telemetry to track striped bass to their spawning grounds. Final Report, Dingell-Johnson Project F-29-R, Segment 7. Oklahoma Department of Wildlife Conservation, Oklahoma City, Oklahoma, USA.

WADDLE, H. R., C. C. COUTANT, AND J. L. WILSON. 1980. Summer habitat selection by striped bass, *Morone saxatilis*, in Cherokee Reservoir, Tennessee, 1977. ORNL/TM-6927, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA.

#15

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Striped Bass, Temperature, and Dissolved Oxygen: A Speculative Hypothesis for Environmental Risk[1,2]

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Abstract

Striped bass *Morone saxatilis* has a paradoxical record of distribution and abundance, including population declines in coastal waters and variable success of freshwater introductions. This record is analyzed for consistency with a hypothesis that striped bass are "squeezed" between their thermal and dissolved oxygen preferences or requirements. A commonality among diverse field and laboratory observations supports an inherent thermal niche for the species that changes to lower temperatures as fish age. This shift can cause local conditions, especially warm surface strata and deoxygenated deep water, to be incompatible with the success of large fish. Crowding due to temperature preferences alone or coupled with avoidance of low oxygen concentrations can lead to pathology and overfishing, which may contribute to population declines. Through a mixture of evidence and conjecture, the thermal niche–dissolved oxygen hypothesis is proposed as a unified perspective of the habitat requirements of the species that can aid in its study and management.

The striped bass *Morone saxatilis* presents a paradox. Stocked populations have expanded dramatically in fresh water since the late 1950s when this anadromous species was recognized as capable of a freshwater life cycle. However, its coastal stocks, including both native ones along the east and south coasts of North America and those introduced to the west coast (where they flourished initially) in the late 1800s, are in dramatic decline. The Gulf of Mexico strain has had its once-distinct gene pool blurred by introduction of east coast fish meant to rehabilitate stocks. Despite the general and often spectacular success of stocking and managing striped bass in freshwater reservoirs, there have been some puzzling inconsistencies. For example, there have been instances of midsummer mortalities among the largest adults. At several locations, the fish have failed to attain the large sizes hoped for by trophy anglers. In some reservoirs, however, introduced striped bass seem to have done so well as to overcrop the food supply, and their populations subsequently declined. Dams on southeastern coastal rivers and inland waters have not only created physical barriers to migratory movements, but have otherwise changed characteristic seasonal movement patterns in odd ways, particularly by attracting striped bass to tailwaters in summer. The recent ascendance of a hatchery-bred hybrid between white bass *Morone chrysops* and striped bass in many waters where the striped bass has experienced difficulty adds a new genetic facet to the enigmatic mix of striped bass successes and problems. Accounts of many of these situations are provided in detail by other authors in this issue.

Interpretation of the diverse and often contradictory observations of striped bass populations in both marine and freshwater habitats has run through two phases, and we now may be experiencing the beginning of a third. In the first phase, local conditions were emphasized. This approach fostered independent local and regional speculation about the causative roles of site-specific environmental and biological factors. Data were gathered (often the classical data of fisheries practice) for empirical correlations. Blame for population declines or observed mortalities was attributed to (in one reference or another) pollution, power-plant entrainment or impingement, spawning barriers, predation, irrigation diversions, toxicant bioaccumulation, overfishing, and most other conceivable influences. In the second phase, emphasis was placed on the dynamics of juvenile striped bass in their environment. Efforts were more focused on food availability, feeding, survival, and growth during the

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[2] Publication 2426, Environmental Sciences Division, Oak Ridge National Laboratory.

early juvenile distribution, energetics, and survival for establishing year-class strength of striped bass populations (for example, Chadwick et al. 1977; Ulanowicz and Polgar 1980), I wish to devote this paper to discussion of similar relationships that have been neglected in later parts of the life cycle. Even in the general synopsis just presented, one should be struck by major changes in habitats occupied by striped bass of different ages. These habitat shifts may not merely be responses peculiar to the stimuli of coastal waters and estuaries, but may reflect the species' age-specific, genetic limits of adaptation. It is my working presumption that the life cycle "strategy" developed through natural selection in east coast estuaries has fixed the species' environmental requirements. These requirements would then be manifested in other environments wherever the species is transplanted, although some genetic selection may have diversified today's regional stocks to a limited extent. Because the new environments do not completely reproduce the environmental conditions of native estuaries, but rather offer a wide range of environmental conditions, they have constituted a grand experiment for obtaining more detailed knowledge of the species' habitat requirements. I have used these new environments, particularly eastern Tennessee freshwater reservoirs, to develop a hypothesis of thermal niche partitioning among striped bass age groups (Coutant 1980a). A thermal niche is the temperature range in which a fish performs best physiologically and that it selects, if available, in a gradient; consensus is developing that the two temperatures are nearly the same (for example, Coutant 1975; Beitinger and Fitzpatrick 1979; Magnuson et al. 1979; McCauley and Casselman 1980; Jobling 1981). I now extend this hypothesis to include its interaction with another major limiting factor in many environments—dissolved oxygen concentration—to explain the observed distribution of adult striped bass and many of the environmental problems of the species.

The Temperature-Oxygen Hypothesis

I believe that striped bass population sizes can be limited by summer restriction of suitable habitat for adults, which can be defined as having temperatures between about 18 and 25 C and dissolved oxygen concentrations above about 2 to 3 mg/liter. Populations can be limited by several mechanisms that operate in summer: (1) direct mortality (from thermal or respiratory stress) of adults that fail to occupy suitable habitat; (2) decreased fecundity of adults that must reside in marginal habitats for extended summer periods or that are crowded into small refuges; and (3) increased susceptibility to other forms of crowding stress in refuges that can lead to heightened mortality from starvation, toxicant exposure, overfishing, diseases, parasites, and other causes.

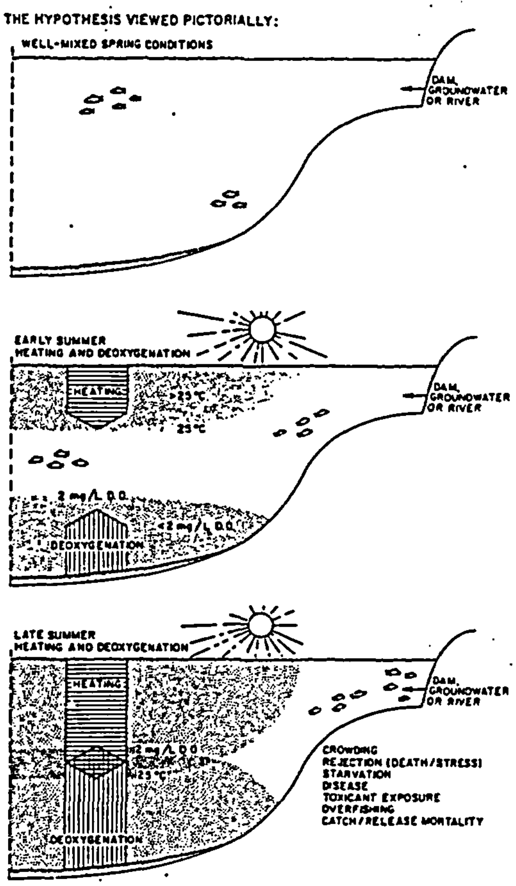

FIGURE 1.—*Hypothesized effects of warm temperature and low dissolved oxygen (D.O.) on habitat available for adult striped bass. The model is driven by seasonal warming, stratification, and deoxygenation of the water body, and conditioned by thermal (≤25 C) and oxygen (>2 mg/liter) tolerances of the fish. Adults are compressed into progressively smaller water volumes and ultimately into small refuges, where they are vulnerable to physiological stresses and overexploitation leading to excessive mortality.*

In effect, there can be a summertime "squeeze" of suitable habitat space, which can be visualized most easily for the well-known seasonal limnolmortality might be ascribed to the other stress more readily, the directive influence of thermal preference may be the crucial factor in determining exposure.

I have, for simplicity, presented the hypothesis in its extreme, emphasizing lethal or life-threatening sublethal temperatures and dissolved oxygen concentrations. However, a more appropriate and comprehensive view is of a continuum of behavioral responses all guided strongly by temperature preference. Whether striped bass reside in a warm, eutrophic reservoir in summer where survival alone is tenuous or in the broad thermal gradient of an estuary that is contiguous with cooler oceanic water, temperatures can pull them into aggregations vulnerable to fishing, toxicants, and other stresses. To this pull one must add the contrary stimulus of depressed oxygen concentration that often accompanies stratified cooler water in summer and limits available thermal habitat. Only by embracing the continuum of behavioral responses, between those at the lower range of preferred temperatures and those at high temperatures that directly or indirectly cause death, can the varied behaviors of the species be appreciated. Given that the temperature response takes precedence over most other responses to stimuli, as I suggest, the hypothesis allows us to realize that even preferred temperatures can exacerbate environmental risks to striped bass.

Evidence for the Hypothesis

The notion of a temperature–oxygen squeeze on striped bass arose from research done at and from Oak Ridge National Laboratory during the last dozen years, work that embraced freshwater habitats in eastern Tennessee, laboratory and field studies of temperature selection, and temperature-dependent growth rates of juveniles in controlled experiments. The hypothesis was developed to integrate these results, but it is consistent with data gathered in other studies as well. Support for the hypothesis is developed in this section with (1) a synopsis of the Oak Ridge observations; (2) background information on the juvenile thermal niche; (3) a summary of dissolved oxygen requirements of all ages from the literature; (4) evidence for an ontogenetic shift in thermal requirements; (5) a test of the hypothesis with published data on fresh water; and (6) extension of the test to studies on estuaries, principally San Francisco Bay–Delta, Chesapeake Bay, and Hudson River. The estuarine discussions progress from objective tests of the hypothesis to more speculative interpretations related to recent population declines. A following section outlines possible uses of the hypothesis for management of the species.

Oak Ridge Studies

Spatiotemporal Distributions

Radio and ultrasonic transmitter tags, especially those with temperature sensors, have given the most precise information about the orientation of striped bass to environmental variables in lakes and reservoirs. In 1974 and 1975, tagged subadults were placed in small quarry lakes on the Oak Ridge Reservation (Coutant and Carroll 1980). These lakes have strong thermal stratification in summer but oxygen is not depleted except for a few centimeters above the bottom. As summer warming progressed, the fish remained at average temperatures near 20 to 22 C by descending with these isotherms to deeper strata, and rarely entered water that exceeded 25 C during observation periods of 1 to 27 hours.

During the same years, attempts were made to tag and monitor adults in Cherokee Reservoir, a 12,000-hectare, 87-km-long storage impoundment on the Holston River in Northeast Tennessee. All but one of these fish (noted in Coutant and Carroll 1980) died in about 2 hours after they had made rapidly repeated movements between the surface, where temperature was above 25 C, and depths where temperatures were 23–24 C. The successfully tagged fish remained in cool water near 21 C after its initial dive. This fish had been released close to the capture point, whereas the others had been released some distance from their capture (due to drift of the boat during tagging). We believe that the latter were displaced from their temperature–oxygen refuge and underwent rapid searching for suitable habitat, alternating between temperatures that were too warm and oxygen concentrations that were too low (0.5 to 2.5 mg/liter measured at the depth fish turned to return to the surface) until they succumbed (Coutant 1980b).

The first successfully tagged fish in Cherokee Reservoir did not exhibit the wide-ranging pelagic habit we had expected, but took up residence in a cove. Its location and temperature selection suggested residence in a small submerged creek channel that retained cool tributary water in a density underflow (Fig. 2). Midsum-

Striped bass–white bass hybrids, although present in the reservoir, were rarely caught with adult striped bass.

We further evaluated our temperature selection hypothesis in Watts Bar Reservoir, a 15,440-hectare mainstem reservoir on the Tennessee River. Watts Bar has a different hydrothermal regime from Cherokee Reservoir because it receives cool tailwaters of an upstream dam that form a horizontal thermal gradient in summer with the warmer main reservoir. Nevertheless, tagged adult striped bass followed the same pattern as in Cherokee Reservoir, leaving warm, deoxygenated waters for cooler tailwater and spring-fed refuges in summer, and dispersing again in autumn (Cheek et al. 1985, this issue).

Mortalities

A history of summer mortalities in Cherokee Reservoir is consistent with a pattern of progressive saturation of limited thermal refuges available to adults and with decreasing preferred temperatures as fish age. Major summer die-offs of large (>5 kg) striped bass occurred during our telemetry studies. Disoriented, moribund fish were often seen at the surface, and shorelines were littered with carcasses. We autopsied many of these fish, and also some caught by us and by anglers, and found poor condition factors (weight: length ratios) that worsened as summer progressed, uniformly empty stomachs (despite abundant young shad *Dorosoma* spp. in surface waters), swollen and dark gall bladders, yellow livers, and numerous red sores on the head and body. The gall bladders indicated lack of digestive activity for a considerable time prior to observation even though fish were capable of feeding. (As public knowledge of the thermal refuges spread during our study, angler catches rose; knowledgeable anglers were able to hook fish with nearly any live bait used in the cool oxygenated water, and often had to release fish to stay within the state limit of two fish per day.) The presence or absence of potential prey had little effect on habitats occupied by adult striped bass in our studies. In fact, apparently starving fish would not penetrate a thermocline to feed on dense schools of shad located only 2–3 m above them but in 28–29 C water.

Striped bass have been stocked in Cherokee since 1964, and at sustained high levels for the last 15 years (D. Bishop, cited in Coutant 1978). Growth rates of all age classes were excellent in early years. Deaths first were observed in summer 1971 and involved only larger fish. Major mortalities began in 1972 outside areas frequently fished and could not be attributed to angling activity. In August 1972, state fisheries biologists found an estimated 200 adult striped bass concentrated and dying near a spring in Cedar Hill Cove, the first evidence of a thermal refuge. Dead fish exhibited red sores, but evaluations of systemic diseases, pesticides, and mercury contamination by the state staff and their consultants were negative. After die-offs began, few fish in Cherokee exceeded 5 to 6 kg, a size commonly exceeded in nearby Norris Reservoir, which is cooler, oxygenated, and has had no die-offs. Juveniles have continued to grow well in Cherokee except during occasional years when food appears to have been limiting (Humphreys 1983). Production of maturing fish, through high stocking rates and good survival of juveniles, appears to have exceeded refuge capacity since 1971.

Physiological stress of adult striped bass in Cherokee Reservoir appears to be causing a de-

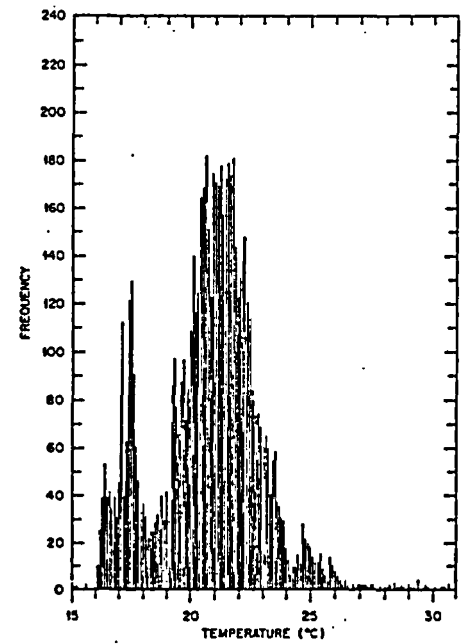

FIGURE 3.—*Frequency histogram of temperatures occupied by a 4.5-kg adult striped bass in Cherokee Reservoir tagged with an ultrasonic, temperature-sensing transmitter, summer 1977. The minor peak reflects entrance into Mossy Creek, a cool-water tributary (from Waddle et al. 1980).*

sueti (1961) was among the first to recognize the ability of striped bass to successfully tolerate waters having marginal water quality, a view supported by studies of respiratory metabolism (Neumann et al. 1981). Lewis (in press) found major summer concentrations of striped bass adults in the metalimnion of Lake Norman, North Carolina, where oxygen concentrations were as low as 0.2 to 3.0 mg/liter.

Several studies have attempted to define experimentally the limit of striped bass performance in reduced dissolved oxygen. Chittenden (1971b) observed restlessness at about 3 mg/liter (16–19 C), followed by inactivity, loss of equilibrium, and finally death as oxygen concentrations were lowered. Ventilation rate (gulps/second) was maximum at 2 to 3 mg/liter but declined at lower oxygen concentrations. Dorfman and Westman (1970) observed 80% survival among juvenile striped bass transferred to 2 mg/liter (20 C) and 3 mg/liter (25.6 C) from ambient concentrations. Krouse (1968) concluded from experiments in the 13 to 25 C range that striped bass are capable of surviving dissolved oxygen concentrations of 3 mg/liter but not of 1 mg/liter. Low dissolved oxygen adversely affects appetite (Hoff et al. 1966), and the effects of prolonged poor feeding become serious. Juvenile striped bass acclimated at 18 C generally avoided oxygen concentrations of 3.8–4 mg/liter (41 to 44% of saturation) in experimental gradients (Meldrim et al. 1974).

Ontogenetic Shift in Thermal Requirements

Having outlined the hypothesis of ontogenetic thermal niche partitioning and a potential thermal–oxygen squeeze for adult striped bass and supported it with our own field and laboratory studies and background information, I now test its validity and generality by examining other published studies of the species in both fresh water and estuaries. Many of these studies do not include direct temperature or dissolved oxygen data, but there are enough correlates that reasonable inferences can be made and a "weight of evidence" judgment can be derived.

Some data sets span the juvenile-to-adult habitat transition. Ontogenetic habitat shifts among fishes are common, but few studies have suggested a thermal relationship (Welcomme 1964); protection from predators (including cannibals) or specialized diets are the most often cited advantages. Growth comparisons for different ages across the striped bass latitudinal range are especially informative. When yearly length increments of striped bass from 46 studies are plotted against latitude, the pattern supports the hypothesis that optimum growth temperatures decrease as fish age (Fig. 4; there was considerable scatter among points, as would be expected due to thermal variability at any latitude, differing food availability, and water quality differences). First-year growth is more rapid in southern latitudes, but this trend disappears by age 3, and it is reversed at older ages if abnormally cool reservoir tailwaters in the south are excluded. From Tennessee to north Florida, older fish that have cool tailwaters available grow consistently faster than those without tailwaters (Fig. 5). At the species' southern limit in Florida, environmental stresses fall disproportionately on older fish. Young striped bass usually grow well for 1 or 2 years, but condition declines and mortality (often associated with parasites) increases thereafter; fisheries for large striped bass usually fail to develop despite high stocking rates (Ware 1971; Stevens 1975).

When waters have high thermal diversity and sufficient oxygen in summer, all sizes of striped bass grow well. In Alabama, the largest fish occur where the species has access to both warm reservoir surface waters and cool upstream tailwaters (Bryce 1982). In the thermally diverse river–reservoir system of the lower Colorado River, growth by year 6 exceeded other western populations by 20% (Edwards 1974). Particularly large striped bass develop in large cool water bodies such as Millerton Lake, California (Goodson 1966), and Norris Reservoir, Tennessee; such lakes have well-developed thermal stratification but the large hypolimnetic volume apparently precludes major deoxygenation.

A shift in suitable habitat by maturing striped bass is supported by scale analyses by Bryce (1982) and VEPCO (1983) for fresh water and Orsi (1970) for San Francisco Bay. False annuli indicated that growth slowed during mid- to late summer due to poor feeding, poor energetic performance, or both, but incidence varied among ages. In Bryce's study, Alabama striped bass (Atlantic stock) in the Tallapoosa River, downstream of Thurlow Dam, showed no false annuli during the first year (indicating generally satisfactory conditions for feeding and growth), 50% in the second year, and 100%, 73.5%, and 94.7% in years 3–5, respectively (false annuli were more trophic Lake Anna, Virginia, VEPCO (1983) similarly reported false annuli on scales of older fish, as did Orsi (1970) for scales of San Francisco Bay striped bass between the second and third year. Spawning probably was not the cause because false annuli began to appear before maturity.

Among physiological studies, Neumann et al. (1981) found that respiration rates of swimming striped bass increased more rapidly with weight at 25 C than at 15 C, suggesting that the large fish in the range of sizes tested (147–264 mm) were more sensitive to the higher temperature. No clear metabolic optimum was seen, however.

Freshwater Studies

Numerous studies in fresh water support the notion of an adult thermal niche for striped bass in the 18–25 C range, centering near 20 C for the largest ones. Some also provide evidence of a squeeze with low dissolved oxygen. Early observations of adult striped bass in Florida (1953–1955) are consistent with our observations in Cherokee Reservoir. McLane (1958) recognized the probable importance of temperature in establishing a divided striped bass distribution in north Florida between the St. Mary's, Nassau, and St. Johns river systems, which empty to the Atlantic Ocean, and rivers from the Ochlockonee to the Perdido, which drain to the Gulf of Mexico. The hiatus was hypothesized to be related to post-Pleistocene global warming. Striped bass occurred primarily in the northern third of the St. Johns River where catches were poor and irregular. No occurrences were recorded from coastal marine waters, which suggested a nonmigratory, riverine strain (racial differences between these and more northerly coastal stocks were determined by Raney and de Sylva 1953). A midsummer concentration of adult striped bass in Mill Log Creek, a tributary to the St. Johns River, resembles aggregations in thermal refuges of Cherokee Reservoir. A small spring-fed stream with a nearly constant temperature of 24.4 C attracted adult striped bass in the latter part of July and they disappeared at the end of October. Digestive tracts were empty and all fish were "thin with concave bellies, protruding skull bones, and lacking in vitality" (McLane 1958). Individuals were heavily parasitized and had poorly healed scars and bleeding ulcers on the body and head. Females had undeveloped gonads as late as October. Because of poor condition, attempts

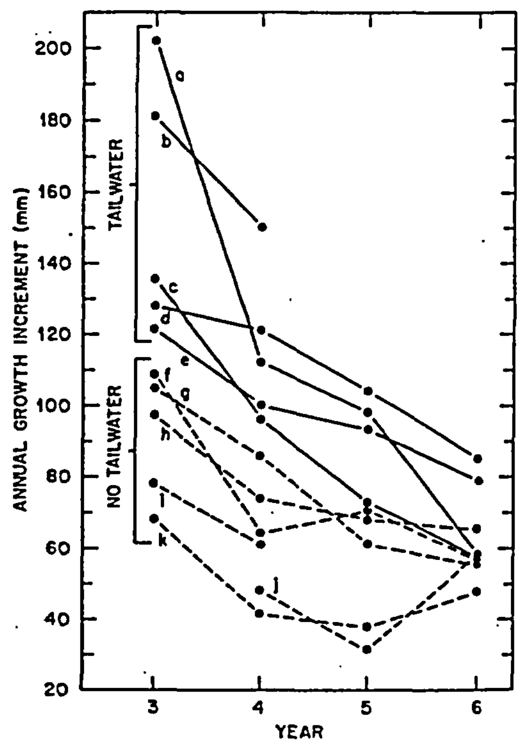

FIGURE 5.—*Annual increments of striped bass growth (mm) in years 3 to 6 in freshwater areas between latitudes 30 and 36.5°N where cool discharges from upstream reservoirs are, or are not, available in summer. Sources: (a) Edwards 1974 (females); (b) Higginbotham 1979; (c) Edwards 1974 (males); (d) Wooley and Crateau 1983; (e) Bryce 1982; (f) Scruggs 1957; (g) Erickson et al. 1972; (h) Stevens 1958; (i) Mensinger 1971; (j) Trent and Hassler 1968 (females); (k) Trent and Hassler 1968 (males).*

to tag these fish caused nearly 50% mortality. It was concluded that the species was barely maintaining itself at the extreme limit of physiological thermal tolerance.

In more recent Florida studies, Wooley and Crateau (1983) observed lower condition factors in adult striped bass when water temperatures in the Apalachicola River system rose above 26 C. Adult fish occupied thermal refuges at about 21 C where oxygenated water came from springs or spring-fed creeks, while surface water temperature rose to 31 C and dissolved oxygen fell to 5 mg/liter. Striped bass were essentially riverine in this system and exhibited two distinct "runs" when they were susceptible to fishermen. The first (mid-October to mid-November) was as-

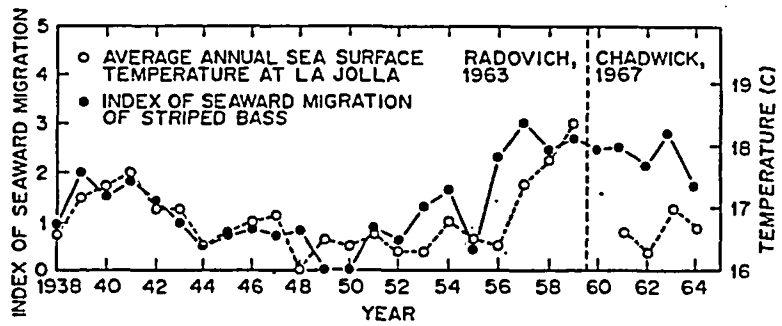

FIGURE 6.—*The index of seaward migration of adult striped bass from San Francisco Bay compared to the average annual sea surface temperature at La Jolla, California, 1938–1959 (per Radovich 1963), followed by 1960–1964 information from Chadwick (1967) that put the relationship in doubt.*

water from June through August, and were most abundant in July, but none were found there in January through April when they had access to the downstream reservoir. Older striped bass in Lake Powell, Arizona–Utah, ate progressively more benthic crayfish through spring and summer (but few in fall or winter) in studies by Hepworth et al. (1977), suggesting increased restriction of larger fish to a deep-water habitat without pelagic prey.

There are some freshwater studies that do not show a clear preference of adult striped bass for cooler water in summer, and a temperature–dissolved oxygen squeeze does not appear to occur. Lake Texoma, Texas–Oklahoma, is one such apparent exception, although more detailed studies there seem warranted (Matthews et al. 1985, this issue). It is popularly believed that adult striped bass survive in Santee–Cooper Reservoir, South Carolina, at temperatures as high as 30 C, and that no refuges are available (R. E. Stevens, personal communication). Telemetry studies comparable to those on Cherokee Reservoir may be needed to resolve fish behavior in these situations.

Estuarine and Coastal Studies

Having found support for a cool thermal niche for adult striped bass and likely examples of temperature–oxygen squeezes in the freshwater literature, I now extend the search for consistent data to estuaries and coastal waters, albeit with more speculation. Merriman's early (1941) records of striped bass distribution along the Atlantic coast indicate that adults generally are not found above the range of 25 to 27 C. This limit was substantiated by laboratory studies during which feeding declined and swimming behavior of subadults and adults became abnormal in seawater at temperatures over 26 C (Rogers and Westin 1978; Rogers et al. 1980). Sketchy laboratory studies have shown that adults avoid temperatures near 26.7 C (Gift 1970).

Some of the most fascinating examples of data that seem consistent with the hypothesis of a cool (18–25 C) thermal niche and a dissolved oxygen squeeze for adult striped bass come from the habitats (San Francisco Bay–Delta and Chesapeake Bay) where striped bass populations now are stressed and in precipitous decline. These consistencies seem more than circumstantial; they may indicate fundamental causes of population problems and suggest important remedial measures. In the discussions below, I will separate more straightforward supportive observations from my clearly speculative interpretations, and proffer testable hypotheses.

San Francisco Bay–Delta

Supportive observations. Temperature appeared to Hubbs and Schultz (1929, in Radovich 1961) to be influencing the location of adult striped bass in the San Francisco Bay–Delta and adjacent coastal waters. They linked the first notable northward movement of striped bass to Oregon (Coos Bay) in the summer of 1925 to abnormally high coastal water temperatures. Radovich (1961) observed a similar correlation between elevated seawater temperatures and an upsurge in catches of large fish near the mouth of San Francisco Bay in 1957, 1958, and 1959. He further solidified the coastal temperature relationship in a later paper (Radovich 1963) that tightly correlates 22 years (1938–1959) of data conclusion consistent with thermal niche partitioning. Returns from Carquinez Strait–San Pablo Bay were highest for 38- to 51-cm individuals, those from San Francisco Bay proper were highest for 52- to 61-cm fish, and those from the Pacific Ocean were highest for 62-cm and larger fish. During this period of warm summers, the smallest fish were in the Sacramento River, and the vast majority of large fish were downstream of Suisun Bay. It was then that most ocean returns occurred (nearly all of which were close to the Golden Gate). Fall tag returns showed an upstream movement, and fish tags were returned from throughout the system during winter.

Tagging studies by Orsi (1971) in 1965–1967 confirmed the 1958–1961 pattern of movement and demonstrated a clear size dependence. The largest fish moved farthest downstream into San Francisco Bay and into the adjacent Pacific Ocean, and they did so only in summer and fall; fall signaled a return to the upstream delta area. The smallest of the tagged fish (38 to 51 cm long) tended to remain in fresh water during summer. Sexual differences in migration were actually functions of size, because females had a larger average size than males. Supporting evidence that striped bass avoid cold water along the Pacific coast comes from Coos Bay, Oregon, where they move within the bay but do not generally exit to the ocean (Morgan and Gerlach 1950), probably because appropriate temperatures are found within the cool bay.

It has been difficult to correlate these movements of striped bass with temperatures in the bay-delta system because of a lack of thermal data. Radovich's (1963) use of ocean temperatures at La Jolla provided a poor substitute for more local information. When recent temperatures (Smith et al. 1979; Smith and Herndon 1980, 1983; Dedini et al. 1981; Fig. 8) are compared to Calhoun's summer fish distributions (Fig. 7), however, one sees a striking overlap of tag recoveries with the general thermal preference zone (18–21 C) hypothesized here for large adults.

It was previously thought that striped bass oriented primarily to the salinity gradient in the

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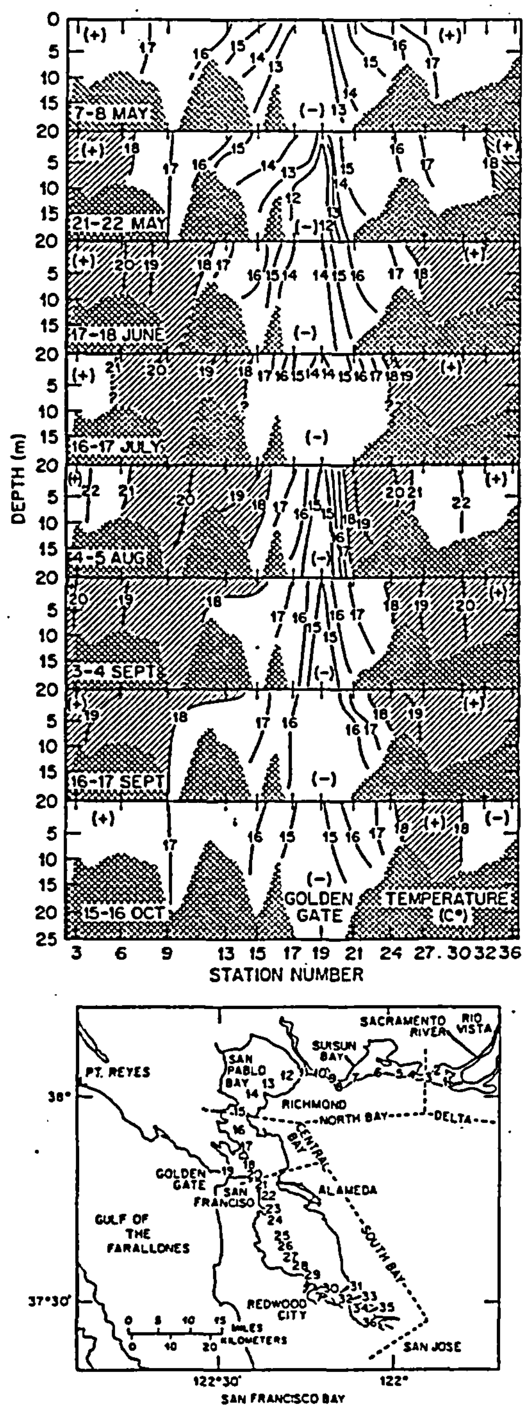

FIGURE 8.—*Temperature patterns in the San Francisco Bay region in 1980 as derived from sampling stations numbered on the bottom panel (after Dedini et al. 1981). Crosshatch represents the bottom contour. Diagonals indicate temperatures in the range 18 to 21 C, roughly corresponding to lower and upper temperatures occupied by the largest adults in Cherokee Reservoir studies.*

bined with warm river flows probably would yield the smallest habitat space for adult striped bass. Water temperatures reflect not only climatic variations but also changes in water inflow to the bay–delta (the lower the flow, the longer the time estuarine water is subject to solar heating); therefore, major flow diversions to several irrigation projects may now exert a substantial indirect influence on habitat for adult striped bass.

This horizontal temperature squeeze may be detrimental through localized interactions with other factors. Dissolved oxygen, which was so important in Cherokee Reservoir, may not be a problem here; synoptic surveys (Smith and Herndon 1980, 1983) indicate adequate oxygen to 20 m in most of the bay that was sampled. However, striped bass may be exposed to toxic materials, which may be concentrated in the same zone for hydrodynamic reasons (Arthur and Ball 1979). Field results summarized by Whipple (1982) indicate the importance of toxicants to striped bass in the bay–delta system. High body burdens of pollutants correlate positively with elevated parasite burdens, poor body conditions, poor liver condition, and, most importantly, with impaired egg and gonad condition. Fish from the San Francisco Bay–Delta have higher and more damaging parasite loads than fish from Coos Bay (Oregon), Lake Mead (Nevada), and Hudson River (New York), all of which are fairly coolwater systems.

Decreases in fecundity could form an especially important link between adult stress and reduced indices of juvenile abundance. Although many aspects of habitat selection behavior in the field are difficult to evaluate, increased stress effects on fecundity of older, larger fish should be testable. Most studies of female striped bass seem to agree that older, larger females spawn or contain more mature eggs in their ovaries than do younger, smaller females (Hollis 1967; McFadden 1977). If the largest striped bass have the smallest thermal niche, which would subject them to the greatest direct and indirect stress from crowding, this size-related fecundity pattern should be reversed. Fish exposed to chronic pollutant stress in San Francisco Bay exhibited reduction in reproductive capacity, fecundity, and gamete viability; a 45% overall reduction in viable eggs in 1978 was variously associated with lack of gonad development, complete egg resorption, egg death, and reduction in numbers of eggs (Whipple 1982). Older fish were in poorest condition, with lower fecundity, higher parasite loads, and greater concentrations of polychlorinated biphenyls and metals.

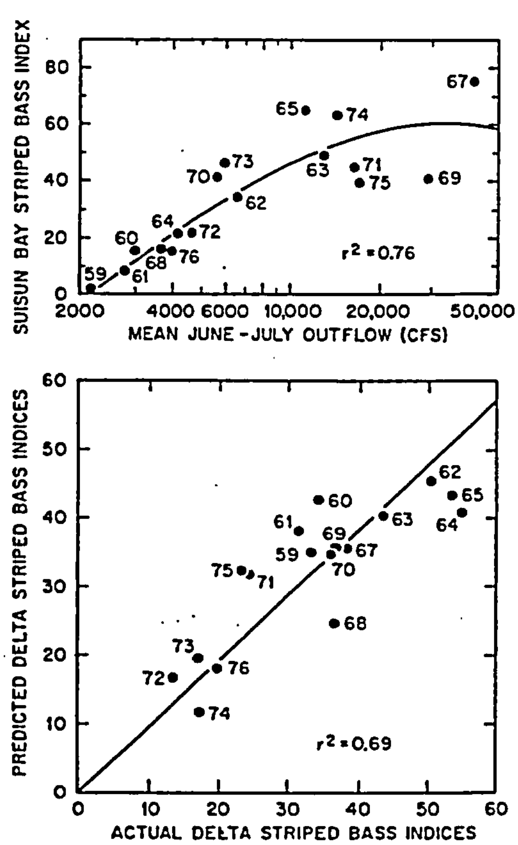

FIGURE 9.—*Predictions of juvenile striped bass abundance in the San Francisco Bay-Delta system (1959–1976), based on water outflow from the delta. Upper: the Suisun Bay striped bass index obtained from field collections compared to mean June–July outflow. Lower: a comparison between predicted and actual indices. (After California State Water Resources Control Board 1982.)*

Although water flow and diversions in the delta traditionally have been identified as major factors affecting juvenile survival, Whipple (1982) has advanced the case for strong interactions of pollutants on maintenance of populations as well. The thermal niche hypothesis (even without an oxygen squeeze) provides a mechanism to explain the high degree of toxicant exposure when coupled with entrapment of toxicants in the same zones occupied by striped bass.

Speculations about striped bass populations in the San Francisco Bay-Delta area need to take

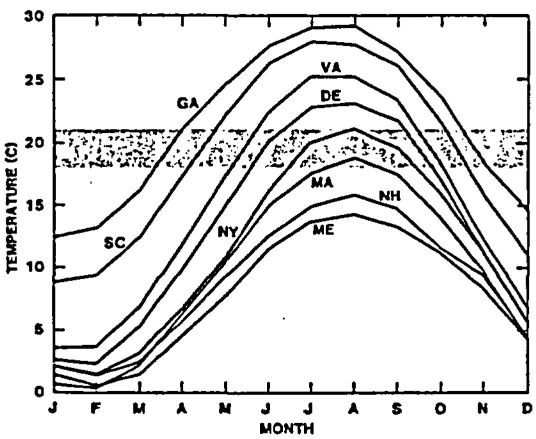

FIGURE 10.—*Atlantic coastal water temperatures (monthly averages: United States Department of Commerce 1973). Adult striped bass migrate northerly along the coast in summer and southerly in winter, and may be following their preferred temperatures near 18–21 C (stippled). Stations are Brunswick, Georgia (GA); Myrtle Beach, South Carolina (SC); Kiptopeke Beach, Virginia (VA); Breakwater Harbor, Delaware (DE); Montauk, New York (NY); Cape Cod Canal, Massachusetts (MA); Portsmouth, New Hampshire (NH); and Bar Harbor, Maine (ME).*

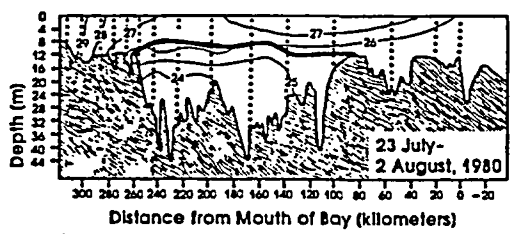

FIGURE 11.—*Temperature profiles (24–29 C) and the 2 mg/liter contour (heavy line) for dissolved oxygen in a longitudinal transect of Chesapeake Bay, July 23–August 2, 1980 (after Price et al. 1985, this issue; vertical columns of dots represent sampling stations).*

responsible for the pronounced decreases in the striped bass population in the drought years of 1976 and 1977, one would expect to see especially marked differences in survivorship among age classes in the fall of 1976 and spring of 1977. Fish hatched in the springs of 1975 and 1976 would, under this hypothesis, have been too young during the drought summers of 1976 and 1977 to have experienced a drop in thermal preferences; thus, they would have shown little of the decline in numbers seen in the stressed year classes of 1974 and before. A detailed report of age-specific striped bass abundance in the bay–delta system does not seem to be available; however, there is some evidence that transition age classes have managed relatively well even as the whole population is declining (California State Water Resources Control Board 1980).

To advance a working hypothesis even further, one might expect males to survive relatively better than females in the advanced (3+) ages, for at about this stage, female size at a given age increases faster than male size (Scofield 1931; Robinson 1960; Mansueti 1961). Our only basis for judging temperature preference of adults in the field is for size (Coutant 1980a), but the sexual differences in growth rate make it likely that females will exhibit stress and possible increased mortality at earlier ages than males. A shift in sex ratios toward males in the older stressed population should be readily testable. Because there is a general increase in percentage of females in older ages of a population, the difference should be sought in a changing ratio of females to males during and after stressful years, not in a numerical dominance by males.

Summer crowding in the bay–delta area and such consequences as restriction of readily available food resources should be reflected in summer scale "checks" (false annuli). False annuli have an advantage as a test of the behavioral hypothesis in that they provide a retrospective measure of conditions in past years. It should be possible now to obtain data on conditions that affected bay–delta striped bass in past years by analyzing scales from fish collected today, and from archived scale collections. Orsi's (1970) observation of false annuli appearing on scales and operculi between the second and third year suggests that this technique may be fruitful.

Chesapeake Bay

Supportive observations. Along the east coast, the general movements of striped bass have been known for many years, and they are consistent with an adult thermal niche that is cooler than that for juveniles. Younger fish remain in Chesapeake Bay and river tributaries and do not migrate out until in their third year (unless there is high population pressure from especially large year classes) (Mansueti 1961; Mansueti and Hollis 1963; Clark 1968; Austin and Hickey 1978). Larger individuals travel longer distances outside their natal Chesapeake Bay and undertake coastal migrations more frequently than do

The fish are almost certainly squeezed between warming surface waters and deoxygenating deep waters, just as they were in our Cherokee Reservoir studies. In principle, all of the large fish with low temperature preferences still should be able to leave the bay in late spring, as they apparently did historically with no detrimental effects on the population. Young fish would remain in the surface waters, whereas the fate of the subadults that traditionally stayed in the bay is most uncertain. Two factors, increased severity of oxygen depletion in a time frame that matches poor striped bass recruitment, and increased fishing exploitation of the subadult striped bass, may explain recent changes from the historic pattern.

The temperature–oxygen squeeze now develops each spring and summer in Chesapeake Bay over a larger area and at an earlier date (on average) than before 1972 (see evidence presented by Correll 1981, Officer et al. 1984, and Price et al. 1985). While it develops, there are undoubtedly fine-scaled differences in temperature and dissolved oxygen concentration that provide alternative migration routes and temporary refuges for subadult and adult striped bass. These modified migration patterns and refuges may affect survival or physiological condition. Notably, the Chesapeake and Delaware Canal, which links the upper Chesapeake Bay to Delaware Bay, is now considered a major migratory pathway for postspawning adults (J. Boreman, personal communication). The fish thus avoid deoxygenated conditions near Baltimore which, by 1980, were worse at the end of May than those that had prevailed in midsummer prior to 1970 (Officer et al. 1984).

Some refuges may be temporary. Adults or subadults may, for example, descend into bottom depressions as the surface waters warm only to find themselves in a vertical "box canyon," as warm water descends from above, deoxygenated water rises from below, and bottom topography blocks lateral movement. There may be no escape to coastal waters once the fish have committed themselves to a small refuge basin. Direct mortality could result (although mass mortalities have not been reported for Chesapeake Bay), or there may be decreased physiological condition and fecundity (in adults). Recent localized increases in anoxia could have created these traps where none existed previously, or increased biological and chemical oxygen demand could have extended the duration of anoxia and thus the duration of physiologically damaging crowding in refuges. The subadults that typically remain in the bay over summer may be the most affected by this scenario. Evidence of it should be sought through studies of spatial and temporal distribution of fish and of their condition.

Fishing mortality may have increased above historic levels in zones where striped bass are more concentrated because of thermal and dissolved oxygen preferences. This has happened in freshwater reservoirs. One would expect the commercial fishery in Chesapeake Bay to be adept at locating and exploiting concentrated striped bass, more so than would the sports fishery. There are data that indicate the commercial fishery harvest is gaining an increasing share of the total catch (less than half in Maryland prior to 1976 but 66% in 1979 and 83% in 1980: Sport Fishing Institute 1984). Overfishing of subadults in their zones of concentration may be contributing to the population decline in Chesapeake Bay and coastal waters even though, historically (1929–1976), less than 10% of the Maryland commercial catch (by weight) has come during the July–September period (Clark and Baldrige 1984). An evaluation of fishing mortality directed toward factors that would change with altered temperature and dissolved oxygen patterns (such as catchability, size selectivity, timing) may be fruitful for explaining and reversing population declines.

As discussed for San Francisco Bay, the shifting thermal niche with increasing fish size would allow young fish to survive well, perhaps even better than previously, because of the probable relaxation of density-dependent population controls when spawning is depressed. The numbers of subadults (if known) would, therefore, remain positively correlated with first-year juvenile abundance indices, as would the commercial landings that are increasingly composed of subadults. Goodyear (1985, this issue) has demonstrated the statistical correlation between juvenile indices and commercial landings; the correlations since 1973 have been controlled by ages 2 to 3. If there was abnormal, stress-related mortality of young adults (thus keeping them out of the fishery), one would expect to see the relationship between catch and juvenile indices deteriorate with increasing fish age, as Goodyear has shown. It is impossible without more data, however, to distinguish between stress-related ygenated zone in western Long Island Sound, but its continuity with favorable habitat to the east may prevent a damaging squeeze.

Interpretations. Because of its more northerly latitude, the Hudson River–Long Island Sound system seems unlikely to experience the temperature preference problems I hypothesize for Chesapeake Bay. Even if deep-water deoxygenation that now occurs in the western end of the sound should become more extensive, large volumes of near-optimal thermal habitat still would extend well into coastal waters of New England. Unlike Pacific waters off San Francisco Bay, the Atlantic Ocean temperatures off Long Island are sufficiently warm that they would not provide a barrier to seaward movement in summer.

Gulf Coast Estuaries

The Gulf coastal stocks are riverine. This exception to the typical pattern of estuarine habit seems to confirm the species' need (as adults) for 18–25 C water in summer. Such water has not been available in the Gulf of Mexico since Pleistocene glaciation, and large river springs apparently have maintained adult stocks. Hydroelectric sites now offer an alternative source of cool water (in dam tailwaters) that is being used by adult striped bass and they appear to be sustaining important upriver stocks.

Use of the Thermal Niche-Oxygen Squeeze Hypothesis

Managing Reservoir Stocks

There are many reasons why the introduction of striped bass to freshwater reservoirs has been desirable. The species' large size, photogenic coloration, fighting qualities, and palatable flesh have endeared it to a growing group of anglers. Ecologically, the introduced striped bass has filled an underutilized niche in pelagic zones of large water bodies. Striped bass feed largely on clupeids (mostly *Dorosoma* species) that themselves have been of concern for tying up much of a lake's productivity in unused biomass. The effects of striped bass on resident sport fish through predation or competition generally have been considered negligible or even positive (except in a few cases involving trout). Striped bass in reservoirs reduce forage fish populations and improve energy flow, especially to humans. Despite the general success with striped bass, and because research and management should lead to more successes and fewer failures, the observed summer mortalities and other signs of stress are disturbing.

What are some implications of this thermal niche–dissolved oxygen squeeze hypothesis for striped bass stocking programs in reservoirs? It would seem from actual experience and from our understanding of reservoir limnology that the limiting habitats for the species in the southeast are most likely to be the cool oxygenated zones needed by large fish. If trophy angling is the major objective for the fishery, then reservoirs that offer this habitat in abundance should be selected for stocking. On the other hand, warm eutrophic reservoirs offer superb habitat for juveniles up to about age 2, which in themselves offer fine angling. Is there a management strategy that can optimally use this productive capacity? I believe so.

With young fish thriving in the warm productive surface layers of eutrophic reservoirs, and their rapid growth fed by abundant clupeids, it is readily seen that recruitment to older age classes could outstrip available adult habitat. The limited amount of cool oxygenated water available and the pressure of additional maturing juveniles crowding into it each year must cause a point to be reached at which the adult population exceeds carrying capacity. Mortality from some cause will necessarily occur, and this prospect offers opportunities for creative fishery management. There may be several options.

One management option is to continue a high rate of juvenile stocking that saturates available adult habitat and leads to spontaneous summer mortalities or, on a less severe scale, to slow adult growth rates and poor condition often complicated by disease or parasites. Experience suggests that this option is undesirable.

A second option is to reduce juvenile stocking rates to levels that allow only a limited recruitment of adults and undersaturation of temperature–oxygen refuges. This alternative would provide a low-level angling opportunity for both young fish and adults, but the few adults taken would be in better condition and there should be no summer die-offs. However, the small catches may not justify the stocking effort.

A third alternative is to encourage the harvest of adults so that their mortality rates (most of it due to fishing) would balance recruitment rates while still maintaining a high juvenile stocking program that effectively uses the abundant juvenile habitat and food supply. This alternative effects of coastal water temperatures would need to be incorporated into monitoring and management plans. It would seem prudent to manage both the fishery and habitat to ensure an adult population size large enough to saturate the spawning grounds with eggs. Because these arguments are largely speculative in the absence of direct evidence linking thermal preferences to the striped bass problems in the bay–delta, a logical first step would be to test the thermal niche hypotheses.

Chesapeake Bay

The recent call for size and catch restrictions on the striped bass fishery may help stem the rapid decline of Chesapeake Bay stocks, but such restrictions may miss the mark for solving the problem. Indeed, size restrictions that limit catches of younger fish may aggravate the problem by overpopulating refuges with maturing fish and putting additional stress on the fish that are most important for reproduction. The younger fish are more capable of handling the warmer temperatures of surface waters and are more apt to survive without our help. Alternatively, total catches might be limited, the zones of any late spring and summer concentrations might be located and placed off limits to commercial fishing, and the deeper (cooler) water zones might be managed as critical thermal refuges for resident subadults, with attention being directed to pollution control that would improve oxygen resources.

For the long-term health of Chesapeake Bay striped bass, efforts to control deoxygenation by limiting nutrient loading may be the most critical, as further discussed by Price et al. (1985), in this issue. The thermal preferences of striped bass and the limitations on normal habitat selection imposed by increased deoxygenation appear to place the species, particularly subadults, at a high risk in Chesapeake Bay. Physiological stresses and heightened exploitation may be the immediate causes of increased mortality. Although exceedingly speculative, this scenario appears consistent with other observations and seems testable.

Other Estuaries

The Hudson River has continuity with cool water and generally favorable striped bass habitat in Long Island Sound and coastal waters. It would seem important, however, that deoxygenation in the New York City area and in the access routes to Long Island Sound not become so severe in late spring and early summer as to block access from the Hudson River estuary to the sound. On the Gulf coast, the species decline in recent years was probably an inevitable consequence of industrialization and other estuary and river alterations. The importance of traditional (spring-fed) and new (reservoir-fed) cool-water riverine zones in summer should be recognized for their management importance and should be protected or enhanced.

Conclusion

Finally, I return to the paradox wherein the striped bass exhibits a spectrum of successes and declines across the United States that seems inexplicable by traditional fishery or water quality correlations. Careful examination of local conditions in many studies only lengthened the list of potential contributing factors. Emphasis on the juvenile stages that were presumed to be most sensitive to perturbations also has failed to explain many major population trends. This paper hypothesizes a unifying factor that seems to explain, in general and simple terms, most of the diverse observations.

I feel that size-dependent thermal preferences of striped bass define acceptable thermal habitats in the field, and that the cool-water requirements of adults provide a basic mechanism that explains much of the species' behavior and distribution. When the required cool temperatures for adults are unavailable, a condition that often results from deoxygenation of cooler strata in lakes and estuaries, the populations undergo remarkably similar stresses: direct mortality, heavy fishing mortality in refuges, increased disease incidence, reduced fecundity, and poor physical condition; increased toxicant uptake also occurs if refuges are polluted. The degree to which these symptoms are manifested, which depends on local conditions, is directly related to the duration of the temperature–dissolved oxygen squeeze. Even when such extreme conditions do not occur, the species shows a continuum of preference and avoidance responses that may increase its risk from one or more of the stresses just listed.

The scenarios presented provide testable hypotheses with which the overall scheme can be supported, rejected, or modified as necessary; such is the way of science. The hypotheses also provide management agencies with potential directions to pursue in the urgent business of pre-

CHEEK, T. E., M. J. VAN DEN AVYLE, AND C. C. COUTANT. 1985. Influences of water quality on distribution of striped bass in a Tennessee River impoundment. Transactions of the American Fisheries Society 114:67–76.

CHITTENDEN, M. E., JR. 1971a. Status of striped bass, *Morone saxatilis*, in the Delaware River. Chesapeake Science 12:131–136.

CHITTENDEN, M. E., JR. 1971b. Effects of handling and salinity on oxygen requirements of striped bass, *Morone saxatilis*. Journal of the Fisheries Research Board of Canada 28:1823–1830.

CLARK, G. H. 1936. A second report on striped bass tagging. California Fish and Game 22:272–283.

CLARK, J. R. 1968. Seasonal movements of striped bass contingents of Long Island Sound and the New York Bight. Transactions of the American Fisheries Society 97:320–343.

CLARK, W., AND M. BALDRIGE. 1984. Emergency striped bass research study, report for 1982–1983. Report to Congress by the Secretaries of Interior and Commerce, Washington, D.C., USA.

COLLINS, B. W. 1982. Growth of adult striped bass in the Sacramento–San Joaquin Estuary. California Fish and Game 68:146–159.

COMBS, D. L. 1982. Fish population changes in Keystone Reservoir fourteen years after striped bass introductions. Proceedings of the Annual Conference Southeastern Association of Fish and Wildlife Agencies 34:167–174.

CORRELL, D. L. 1981. Eutrophication trends in water quality of the Rhode River (1971–1978). Pages 425–435 *in* B. J. Neilson and L. E. Cronin, editors. Estuaries and nutrients. Humana Press, Clifton, New Jersey, USA.

COUTANT, C. C. 1975. Temperature selection by fish—a factor in power plant impact assessments. Pages 575–597 *in* Environmental effects of cooling systems at nuclear power plants. International Atomic Energy Agency, Vienna, Austria.

COUTANT, C. C. 1978. A working hypothesis to explain mortalities of striped bass, *Morone saxatilis*, in Cherokee Reservoir. Oak Ridge National Laboratory, ORNL/TM-6534, Oak Ridge, Tennessee, USA.

COUTANT, C. C. 1980a. Environmental quality for striped bass. Pages 179–187 *in* H. Clepper, editor. Marine recreational fisheries 5. Sports Fishing Institute, Washington, D.C., USA.

COUTANT, C. C. 1980b. Abortive tagging makes sense. Underwater Telemetry Newsletter 10(1):13.

COUTANT, C. C., AND D. S. CARROLL. 1980. Temperatures occupied by ten ultrasonic-tagged striped bass in freshwater lakes. Transactions of the American Fisheries Society 109:195–202.

COUTANT, C. C., K. L. ZACHMANN, D. K. COX, AND B. L. PEARMAN. 1984. Temperature selection by juvenile striped bass in laboratory and field. Transactions of the American Fisheries Society 113:666–671.

COX, D. K., AND C. C. COUTANT. 1981. Growth dynamics of juvenile striped bass as functions of temperature and ration. Transactions of the American Fisheries Society 110:226–238.

DAVIES, W. D. 1973. Rates of temperature acclimation for hatchery-reared striped bass fry and fingerlings. Progressive Fish Culturist 35:214–217.

DAVIS, R. H. 1966. Population studies of striped bass, *Roccus saxatilis* (Walbaum), in Maine based on age distribution and growth rate. Master's thesis. University of Maine, Orono, Maine, USA.

DEDINI, L. A., L. E. SCHEMEL, AND M. A. TEMBREULL. 1981. Salinity and temperature measurements in San Francisco Bay waters, 1980. United States Geological Survey, Open-file report 82-125, Menlo Park, California, USA.

DEPPERT, D. L. 1978. The effect of striped bass predation and water quality on the rainbow trout fishery of the lower Illinois River. Master's thesis. University of Oklahoma, Norman, Oklahoma, USA.

DEPPERT, D. L., AND J. B. MENSE. 1980. Effect of striped bass predation on an Oklahoma trout fishery. Proceedings of the Annual Conference Southeastern Association of Fish and Wildlife Agencies 33:384–392.

DOMROSE, R. J. 1963. Warmwater fisheries management investigations—striped bass study. Virginia Department of Game and Inland Fisheries, Federal Aid in Fish Restoration Project F-5-R-8, Job Completion Report, Richmond, Virginia, USA.

DORFMAN, D., AND J. WESTMAN. 1970. Responses of some anadromous fishes to varied oxygen concentrations and increased temperatures. Rutgers University, Water Resources Research Institute, Partial completion and termination report, New Brunswick, New Jersey, USA.

DOROSHEV, S. I. 1970. Biological features of the eggs, larvae, and young of the striped bass, *Roccus saxatilis* (Walbaum), in connection with the problem of its acclimatization in the U.S.S.R. Journal of Ichthyology 10:235–248.

DUDLEY, R. G., A. W. MULLIS, AND J. W. TERRELL. 1977. Movements of adult striped bass (*Morone saxatilis*) in the Savannah River, Georgia. Transactions of the American Fisheries Society 106:314–322.

EDWARDS, G. B. 1974. Biology of the striped bass, *Morone saxatilis* (Walbaum), in the lower Colorado River (Arizona–California–Nevada). Master's thesis. Arizona State University, Tempe, Arizona, USA.

ERICKSON, K. E., J. HARPER, G. C. MENSINGER, AND D. HICKS. 1972. Status and artificial reproduction of striped bass from Keystone Reservoir, Oklahoma. Proceedings of the Annual Conference Southeastern Association of Game and Fish Commissioners 25:513–522.

FRISBIE, C. M. 1967. Age and growth of the striped bass, *Roccus saxatilis* (Walbaum), in Massachusetts coastal waters. Master's thesis. University of Massachusetts, Amherst, Massachusetts, USA.

and Agriculture Organization, European Inland Fisheries Advisory Commission Symposium 80/ E76, Rome, Italy.

McFadden, J. T., editor. 1977. Influence of Indian Point Unit 2 and other steam electric generating plants on the Hudson River estuary, with emphasis on striped bass and other fish populations. Report for Consolidated Edison Company of New York, New York, New York, USA.

McGie, A. J., and R. E. Mullen. 1979. Age, growth, and population trends of striped bass, *Morone saxatilis*, in Oregon. Oregon Department of Fish and Wildlife, Information Report Series, Fisheries 79-8, Charleston, Oregon, USA.

McLane, W. M. 1958. Striped bass investigations. Florida Game and Freshwater Fish Commission, Federal Aid in Fish Restoration Project F-4-R, Completion Report, Tallahassee, Florida, USA.

Meldrim, J. W., and J. J. Gift. 1971. Temperature preference, avoidance, and shock experiments with estuarine fishes. Ichthyological Associates, Bulletin 7, Ithaca, New York, USA.

Meldrim, J. W., J. J. Gift, and B. R. Petrosky. 1974. The effect of temperature and chemical pollutants on the behavior of several estuarine organisms. Ichthyological Associates, Bulletin 11, Ithaca, New York, USA.

Mensinger, G. 1971. Observations on the striped bass, *Morone saxatilis*, in Keystone Reservoir, Oklahoma. Proceedings of the Annual Conference Southeastern Association of Game and Fish Commissioners 24:447–463.

Merriman, D. 1937. Notes on the life history of the striped bass, *Roccus lineatus*. Copeia 1937:15–36.

Merriman, D. 1941. Studies on the striped bass (*Roccus saxatilis*) of the Atlantic Coast. United States Fish and Wildlife Service Fishery Bulletin 50(35).

Miller, L. W., and J. J. Orsi. 1969. Growth of striped bass (*Morone saxatilis*) in the Sacramento–San Joaquin estuary from 1961–1965. California Department of Fish and Game, Anadromous Fisheries Administrative Report 69-6, Sacramento, California, USA.

Moore, C. J., and D. T. Burton. 1975. Movements of striped bass, *Morone saxatilis*, tagged in Maryland waters of Chesapeake Bay. Transactions of the American Fisheries Society 104:703–709.

Morgan, A. R., and A. R. Gerlach. 1950. Striped bass studies on Coos Bay, Oregon, in 1949 and 1950. Oregon Fish Commission Contributions 14: 1–31.

Moss, J. L. 1985. Summer selection of thermal refuges by striped bass in Alabama reservoirs and tailwaters. Transactions of the American Fisheries Society 114:77–83.

Neumann, D. A., J. M. O'Connor, and J. A. Sherk, Jr. 1981. Oxygen consumption of white perch (*Morone americana*), striped bass (*Morone saxatilis*), and spot (*Leiostomus xanthurus*). Comparative Biochemistry and Physiology A, Comparative Physiology 69:467–478.

Neville, W. C. 1940. Conservation of striped bass. *In* A study of certain marine fishery problems of Suffolk County, Long Island, New York. United States Bureau of Fisheries Survey with Board of Supervisors, Suffolk County, New York, USA.

Nifong, S. C. 1982. Growth and food habits of adult striped bass in Cherokee Reservoir, Tennessee. Master's thesis. University of Tennessee, Knoxville, Tennessee, USA.

Officer, C. B., R. B. Biggs, J. L. Taft, L. E. Cronin, M. A. Tyler, and W. R. Boynton. 1984. Chesapeake Bay anoxia: origin, development, and significance. Science (Washington, D.C.) 223:22–27.

Orsi, J. J. 1970. A comparison of scales, otoliths, and operculae in striped bass aging. California Department of Fish and Game, Anadomous Fisheries Administrative Report 70-15. Sacramento, California, USA.

Orsi, J. J. 1971. The 1965–1967 migrations of the Sacramento–San Joaquin estuary striped bass population. California Fish and Game 57:257–267.

Otwell, W. S., and J. V. Merriner. 1975. Survival and growth of juvenile striped bass, *Morone saxatilis*, in a factorial experiment with temperature, salinity, and age. Transactions of the American Fisheries Society 104:560–566.

Pearson, J. C. 1938. The life history of the striped bass or rockfish, *Roccus saxatilis* (Walbaum). United States Bureau of Fisheries Bulletin 49:825–851.

Price, K. S., and seven coauthors. 1985. Nutrient enrichment of Chesapeake Bay and its impact on the habitat of striped bass: a speculative hypothesis. Transactions of the American Fisheries Society 114:97–106.

Radovich, J. 1961. Relationships of some marine organisms of the northeast Pacific to water temperatures, particularly during 1957 through 1959. California Department of Fish and Game, Fish Bulletin 12.

Radovich, J. 1963. Effect of ocean temperature on the seaward movements of striped bass, *Roccus saxatilis*, on the Pacific coast. California Fish and Game 49:191–207.

Raney, E. C. 1952. The life history of the striped bass *Roccus saxatilis* (Walbaum). Bulletin of the Bingham Oceanographic Collection, Yale University 14(1):5–97.

Raney, E. C. 1954. The striped bass in New York waters. New York Conservationist 8(4):14–16.

Raney, E. C., and D. P. de Sylva. 1953. Racial investigations of the striped bass *Roccus saxatilis* (Walbaum). Journal of Wildlife Management 17: 495–509.

Rathjen, W. F., and L. C. Miller. 1957. Aspects of the early life history of the striped bass (*Roccus saxatilis*) in the Hudson River. New York Fish and Game Journal 4:43–60.

Robinson, J. B. 1960. The age and growth of striped

Ocean Survey Publication 31-1, 4th edition, Rockville, Maryland, USA.
VAN DEN AVYLE, M. J., B. J. HIGGINBOTHAM, B. T. JAMES, AND F. J. BULOW. 1983. Habitat preferences and food habits of young-of-the-year striped bass, white bass, and yellow bass in Watts Bar Reservoir, Tennessee. North American Journal of Fisheries Management 3:163–170.
VEPCO (VIRGINIA ELECTRIC AND POWER COMPANY). 1983. Environmental study of Lake Anna and the lower North Anna River. Environmental Services Department, North Anna Power Station Annual Report, January 1–December 31, 1982, Richmond, Virginia, USA.
VLADYKOV, V. D., AND D. H. WALLACE. 1952. Studies of striped bass *Roccus saxatilis* (Walbaum), with special reference to the Chesapeake Bay region during 1936–1938. Bulletin of the Bingham Oceanographic Collection, Yale University 14(1): 132–177.
WADDLE, H. R., C. C. COUTANT, AND J. L. WILSON. 1980. Summer habitat selection by striped bass, *Morone saxatilis*, in Cherokee Reservoir, Tennessee, 1977. Oak Ridge National Laboratory, ORNL/TM-6927, Oak Ridge, Tennessee, USA.
WARE, F. J. 1971. Some early life history of Florida's inland striped bass, *Morone saxatilis*. Proceedings of the Annual Conference Southeastern Association of Game and Fish Commissioners 24:439–447.
WELCOMME, R. L. 1964. The habitats and habitat preferences of the young of the Lake Victoria *Tilapia* (Pices, Cichlidae). Revue de Zoologie et de Botanique Africaines 70:1–28.
WESTIN, D. T., AND B. A. ROGERS. 1978. Synopsis of biological data on the striped bass, *Morone saxatilis* (Walbaum) 1792. University of Rhode Island, Marine Technical Report 67, Kingston, Rhode Island, USA.
WHIPPLE, J. A. 1979. The impact of estuarine degradation and chronic pollution on population of anadromous striped bass *Morone saxatilis* in San Francisco Bay–Delta, California. National Marine Fisheries Service, Tiburon Laboratory, Progress report, Tiburon, California, USA.
WHIPPLE, J. A. 1982. Impacts of pollutants on striped bass in the San Francisco Bay–Delta, California. National Marine Fisheries Service, Tiburon Laboratory, Project summary, Tiburon, California, USA.
WIGFALL, M., AND M. M. BARKULOO. 1976. A preliminary report on the abundance and biology of stocked striped bass in the Choctawatchee River system, Florida. Proceedings of the Annual Conference Southeastern Association of Game and Fish Commissioners 29:152–161.
WOOLEY, C. M., AND E. J. CRATEAU. 1983. Biology, population estimates, and movement of native and introduced striped bass, Apalachicola River, Florida. North American Journal of Fisheries Management 3:383–394.

Selected Coolwater Fishes of North America

Robert L. Kendall
Editor

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1978

Preface

This Symposium did not just happen; the idea for it emerged and caught fire nearly four years ago. It received its first official sponsorship from the North Central Division of the American Fisheries Society. Subsequently, the AFS Fish Culture Section, the Freshwater Institute, the Sport Fishing Institute, and the U.S. Fish and Wildlife Service agreed to cosponsor the symposium, and the result was an interesting and comprehensive mix of professional and governmental support. With sponsorship assured, the Steering Committee was formed, and it worked for two and a half years to bring the Coolwater Symposium to a climax.

The term "coolwater fishes" is not rigorously defined, but it refers generally to those species which are distributed by temperature preference between the "coldwater" salmonid communities to the north and the more diverse, often centrarchid-dominated "warmwater" assemblages to the south. We decided to concentrate, though not exclusively, on five species for the Symposium, hence the title, "Selected Coolwater Fishes of North America." These five—walleye, sauger, yellow perch, northern pike, and muskellunge—are of major recreational and commercial importance on this continent. Increasingly, they are cultured and stocked far beyond their native ranges in every geographical direction. Our planning, then, was international in scope. Our aim was to bring academic scientists together with agency biologists, hatchery engineers, and fisheries managers for an exchange of perspectives on the ecology, production, and enhancement of these significant resources. It is a measure of the great interest in this young field that we had no difficulty in filling such an ambitious program.

The Keynote Speaker was Richard J. Myshak, Deputy Assistant Secretary for Fish, Wildlife and Parks in the U.S. Department of the Interior. I want to offer a synopsis of his remarks, which set the Symposium's tone and context.

I find it reassuring that this is an international symposium, with U.S., Canadian, and European participants. It is a splendid example of the creative synergism that can occur when interested, dedicated people work together.

"Coolwater fishes" is a new term which has evolved in the last ten years, and which promises new quality angling experiences to many people. Advances in research, development, and management still are needed in the coolwater area. Many methods of spawning, culturing, and management being applied today are at the same stage of understanding and procedure they were 75 to 100 years ago. What advancement there has been to date has been largely the result of trial and error. Compliments are in order to those who have made significant strides, but these advances only signal what *can* be done. It remains now for us to pick up on those signals and *do* it. Perhaps 70 to 80 percent of the cultural and management concepts now used for trout and salmon can be applied in some way to the coolwater fishes, provided the research and development facilities are made available. The success of the northern pike-muskellunge hybrid is justification enough to explore other coolwater crosses. The public will continue to demand advances of this nature.

Coolwater fish scientists and managers have been a rather small group within the fishery community. You have enjoyed a comradeship that comes with this kind of smallness and closeness. This symposium says to me that you are no longer a small group, either in numbers or in knowledge. It is my hope that as you grow and gain in prominence and recognition, you also manage to hang onto the sense of togetherness that has paid off in spirited cooperation and communication—and a steadily improving fishery resource.

The Symposium met Mr. Myshak's expectations. It revealed new scientific information about coolwater fishes and important advances in their practical management and culture. Major knowledge gaps were identified, and the basis was laid for rapid progress in research and its application. The Symposium Proceedings which comprise this volume document the breadth and depth of the program, but they cannot convey the excitement, enthusiasm, and intense discussions of over 500 people during those three days in St. Paul. The prospects for coolwater fisheries now are brighter than ever before.

The Coolwater Symposium and the publication of its Proceedings could not have happened without the support of our sponsors and contributors. They are listed elsewhere in this volume, but I would like to thank them again here. The Symposium was hosted with grace and skill by the Minnesota Department of Natural Resources. Among the Minnesota staff, we are particularly grateful to Warren Scidmore, Floyd Hennagir, Charles Burrows, Henry Swanson, Howard Krosch, William Nye, Bernham Philbrook, Donald Carlson, Andrew Brewer, David Vesall, Oliver Jarvenpa, William Longley, James Schneider, Sandra Brothen, and Elaine Heinze for their contributions of time and money.

I hold a special reserve of appreciation and esteem for my Steering Committee coworkers and advisors. They worked hard and diligently over a long time to create this Symposium, and its great success reflects the quality of their efforts. Ward Falkner was the Steering Committee's Canadian Cochairman. Richard Sternberg handled all the complex local arrangements. Bernard Griswold put together the outstanding program. Shyrl Hood maintained our accounts and our solvency. Jack Hammond and Robert Martin promoted and publicized the Symposium; John Klingbiel saw that its contributions were published. Herbert Lawler, Dale Henegar, Richard Stroud, and Richard Ryder, our Special Advisors, kept our visions high but out of the clouds. It was the dedication of all these people that really made the Symposium happen. With the perogatives that stem from my initial involvement in the Symposium concept and my position as U.S. Cochairman, and with much pleasure and satisfaction, I dedicate these Proceedings to them.

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U.S. Fish and Wildlife Service
Spearfish Fisheries Center
Spearfish, South Dakota 57783

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Transactions of the American Fisheries Soc 5–202, 1980

Temperatures Occupied by Ten Ultrasonic-Tagged Striped Bass in Freshwater Lakes

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Abstract

Subadult striped bass, *Morone saxatilis*, tagged with temperature-sensing ultrasonic transmitters in April–October and monitored in freshwater lakes generally occupied waters of 20–24 C, when these temperatures were available. When they were not (spring and fall), fish occupied nearly the warmest water available at depths >1.5 m. Excursions of less than 2 minutes duration to warmer and to cooler water than was generally occupied were common in spring and summer. A thermal niche for subadult striped bass of 20–24 C centering near 22 C, as suggested by these results, would have important implications for managing this species in fresh water.

Little quantitative information is available about the temperature preference of striped bass, *Morone saxatilis*, either in its native estuaries and coastal zones or in fresh water where it has been introduced (Pfuderer et al. 1975). Merriman (1941) concluded from field distribution records that striped bass would not be found above the range 25–27 C. Gift (1970) noted that five 4-year-old striped bass exhibited an upper avoidance temperature of 26.7 C in an experimental apparatus, although two other fish avoided 28.9 and 29.4 C. Dudley et al. (1977) observed postspawning adults moving upstream in the Savannah River, Georgia toward reservoir tailwaters at less than 26 C rather than seaward where coastal temperatures were in the vicinity of 27–30 C. Most striped bass ascend coastal rivers to spawn in spring when water temperatures reach 15–19 C (Raney 1952; Stevens 1964). Striped bass apparently avoid cool sea temperatures (<18.5 C) after spawning by remaining in warmer Pacific coast streams (Radovich 1963). Other studies of temperature-related striped bass behavior have used juveniles in the laboratory and have concentrated on temperature differentials required to cause short-term avoidance of heated water (Meldrim 1970; Meldrim and Gift 1971; Meldrim et al. 1974). While concepts of thermal preference and avoidance by fish are well developed from laboratory experiments (for example, Coutant 1975; Richards et al. 1977), there are few quantitative field data that approach the detail of controlled laboratory determinations (but see Norris 1963; Neill and Magnuson 1974; Stauffer et al. 1974; Magnuson et al. 1979).

Questions about temperature-related movements and preferred temperatures of striped bass have been raised because of (1) the importance of this species for sports fisheries in both fresh and salt water and (2) concerns over effects of electric power plant cooling systems on all phases of their life cycle. Introduction of this species into freshwater reservoirs has opened new habitats of questionable suitability. Knowledge of thermal requirements of the species is necessary for managers to discriminate between freshwater habitats that are satisfactory for stocking and those that are not.

Methods

We monitored water temperatures occupied April–October by 10 free-roaming, subadult fish (43–68 cm) that were tagged with temperature-sensing, ultrasonic transmitters in relation to available water temperatures (Table 1). Principal research sites were two approximately 2-hectare, 20-m-deep rock quarry lakes (Lambert and Union Valley quarries) on the United States Department of Energy's Oak Ridge (Tennessee) Reservation. We also tracked a single fish in Cherokee Lake, a 12,260-hectare Tennessee Valley Authority reservoir on the Holston River, Tennessee. The quarry lakes provided small, deep, spring-fed, thermally stratified (but well oxygenated) experimental lakes in which a tagged fish was nearly always

TABLE 1.—*Striped bass studied for thermal habitat occupancy, with indication of figure or table which summarizes data for each fish.*

Study location	Fish identification	Dates	Total length (cm)	Weight (g)	Tagging method	Source[a]	Data summary
Union Valley Quarry (1974)	71	1 May–14 Jun	62.6	3,515	Surgery	C	Fig. 2 legend
	53	14 May–4 Jun	47.5	1,476	Surgery	C	Fig. 2 legend
Lambert Quarry (1975)	100a	9 Apr–20 May	44	940	Surgery	L	Fig. 1, Table 2
	111a	29 Apr–3 May	47	1,030	Surgery	L	Fig. 1 legend
	100b	27 May–12 Jun	43	907[b]	Stomach	L	Fig. 1, Table 2
	111b	27 May–18 Jun	43	907[b]	Stomach	L	Fig. 1, Table 2
	117	8 Jul–18 Jul	45	1,004	Stomach	L	Fig. 1, Table 2
	122	18 Aug–20 Oct	54	1,719	Stomach	L	Fig. 1, Table 2
	123	18 Aug–29 Oct	58	2,815	Stomach	L	Fig. 1, Table 2
Cherokee Reservoir (1975)	102	17–22 Jul	68	2,268	Stomach	C	text

[a] C = Cherokee Reservoir, L = Laboratory raised from Cherokee Reservoir Stock.
[b] Visual estimation (2 pounds).

within reception distance. Cherokee Reservoir, on the other hand, represents the type of large freshwater reservoir having thermal and oxygen stratification into which striped bass juveniles are currently being stocked by fish management agencies throughout the southeast. Our Cherokee fish was tracked wholly in Mossy Creek Cove, at the southwest end of the reservoir. Because Union Valley Quarry was heavily used by fishermen and bathers in summer, fish were tracked there only in May and June 1974. Temperature and oxygen vertical profiles were determined periodically throughout the study.

The ultrasonic transmitters (70–120 kilohertz), which were developed and built in our laboratory (Rochelle and Coutant 1973), were inserted either into the coelomic cavity (by surgical procedures similar to those of Hart and Summerfelt 1975) or into the stomach through the esophagus (similar to Koo and Wilson 1972). In each case, the thermistor remained exterior, protruding through the incision or extending up the esophagus into the pharynx. Internal temperatures would be subject to unwanted damping, and we felt that this would not represent the fish's sensory environment. Only fish tagged in spring tolerated the heavy anesthesia (MS-222 Sandoz) and handling of the surgical technique; summer tagging relied on the less stressful stomach-insertion (after light anesthesia). Tags regurgitated or otherwise lost from some fish were reused on others. We recovered lost tags by scuba diving in deep water or wading in shallow water after locating tags.

The 1.8 × 4-cm cylindrical tag had a temperature-coding pulse rate that varied from one to three beats per second with an accuracy at a constant temperature of about 0.2 C. The mounted thermistor had a time constant of about 3 seconds. Tags operated 1–2 months before the batteries were exhausted or failed.

Ultrasonic sound pulses from the tags were received by either portable equipment (for short-duration records and location tracking) consisting of a handheld, directional hydrophone (Smith-Root SR70-H), tuneable ultrasonic receiver (Smith-Root TA-60), and digital pulse-interval counter (Hewlett-Packard System 5300), or by a fixed system (for long-duration recording) using an omnidirectional hydrophone system (Gould System CS-3200-200) connected to a receiver, a counter, and a standard laboratory punched-paper tape recorder mounted in a shoreline-based trailer. The automatic recording system (which recorded data every 10 seconds for periods of varying length), supplemented occasionally by manual recording, was used for data collection at the two quarries. Round-the-clock manual tracking from a boat (data taken once per minute) was used in Cherokee Reservoir where both location and temperature were determined for one continuous period of 32 hours.

Static, often of unknown origin, introduced spurious data into some recordings (especially early in the study in Lambert Quarry) and made some recorded data sets unusable. Hand-recorded data were generally available at these times. Even a few spurious data prevented us from defining maximum and minimum values for some data sets (Fig. 1). Rain, swimming activity, falling rocks along the shoreline, and corrosion of hydrophone materials (Rochelle 1979) were partly responsible for static.

Data sets consisting of pulse intervals obtained either by hand or by recorder were transformed to temperatures by pulse rate–temperature calibration data obtained for each tag in the laboratory before fish release. Best fits to calibration data (±0.1 C) were obtained with second-order or logarithmic equations. These sets of temperature data for each fish, amounting to over 7,000 observations in any continuous 24-hour recording, were reduced to a variety of statistics for the recording period with a HP-65 hand calculator (short data sets) or the Statistical Analysis System (SAS-76) statistics package on an IBM 360/91 computer (Barr et al. 1976).

Statistics used in our analyses were arithmetic mean, standard deviation, range, and frequency distributions at 0.1 C intervals. Frequency distributions yielded a visual image of the normality of the data and median, mode, and ranges of temperatures encompassing selected time percentages of occupancy (we tabulated 50, 66, 75, and 95% of all observations). These statistics were obtained for each hour and for the full length of each data set. Values of mean temperature and standard deviation were plotted by hour for visual search for diel periodicities of occupied temperature and activity, respectively. We also examined graphs of tag temperature versus time for each fish to identify temporal details of thermal variability. Durations of abrupt temperature changes (≥2 C) away from the temperature generally occupied were measured in midsummer recordings that were least encumbered by static (which introduced spurious data that could be misinterpreted as brief excursions).

All fish were of stock from Cherokee Reservoir, originally derived from the James River, Virginia. Two fish studied in Union Valley Quarry (May–June 1974) were captured by electroshocking in the Holston River in the headwaters of Cherokee Reservoir and transported first to our laboratory for surgical tagging and then to the quarry lake (2 days). Their ages were estimated to be 3–4 years. At Lambert Quarry, fish in their third year were studied that had been raised in our laboratory from larvae of Cherokee Reservoir brood stock supplied by the Tennessee state hatchery at Morristown. At Cherokee Reservoir, the one fish (estimated by size to be 3–4 years old) was caught by rod and reel, tagged in the stomach, and released at the point of collection within 5 minutes without use of anesthesia.

Results

Fish in Lambert Quarry occupied a temperature band of about 20–24 C, centering near 22–23 C, during summer months when there was the greatest range of available temperatures (Fig. 1a; Table 2). Similar central tendency is apparent whether one examines arithmetic means, modes, or medians for the data sets (Table 2). Frequency distributions of occupied temperatures were often close to normal, but some were clearly skewed and some showed multiple modes. Modes were often slightly higher than means. A temperature band of about 4 C is defined generally in Fig. 1 by standard deviation bars (one SD on each side of the mean for each data set) and by analysis of frequency distributions for percentage occurrence of occupied temperatures (Table 2; 75% of the time was spent generally between about 20 and 24 C). This same general temperature band and midpoint were also occupied by the one fish tracked in Cherokee Reservoir (mean 22.6 C, SD 1.10 C, mode 22.8 C, median 22.6 C, 75% occupancy 21.5–24.1 C).

In spring when the maximum temperature was below about 22 C, fish in both quarries occupied nearly the warmest water available at depths greater than about 1.5 m (Figs. 1 and 2). Fish showed little thermal variation in recordings of 10, 13, and 23 hours in October when the epilimnion was deep and nearly homothermal at temperatures less than 22 C. Through spring and summer, fish in Lambert Quarry moved progressively deeper, maintaining a generally consistent mean temperature in the thermocline (Fig. 1b).

The temperature range occupied by quarry fish, however briefly, extended from 13 to 14 C (Lambert) and from about 9 C (Union Valley) to maximum surface temperatures (Figs. 1 and 2). Dissolved oxygen was high at all quarry depths (7.0 mg/liter at bottom on 8 August

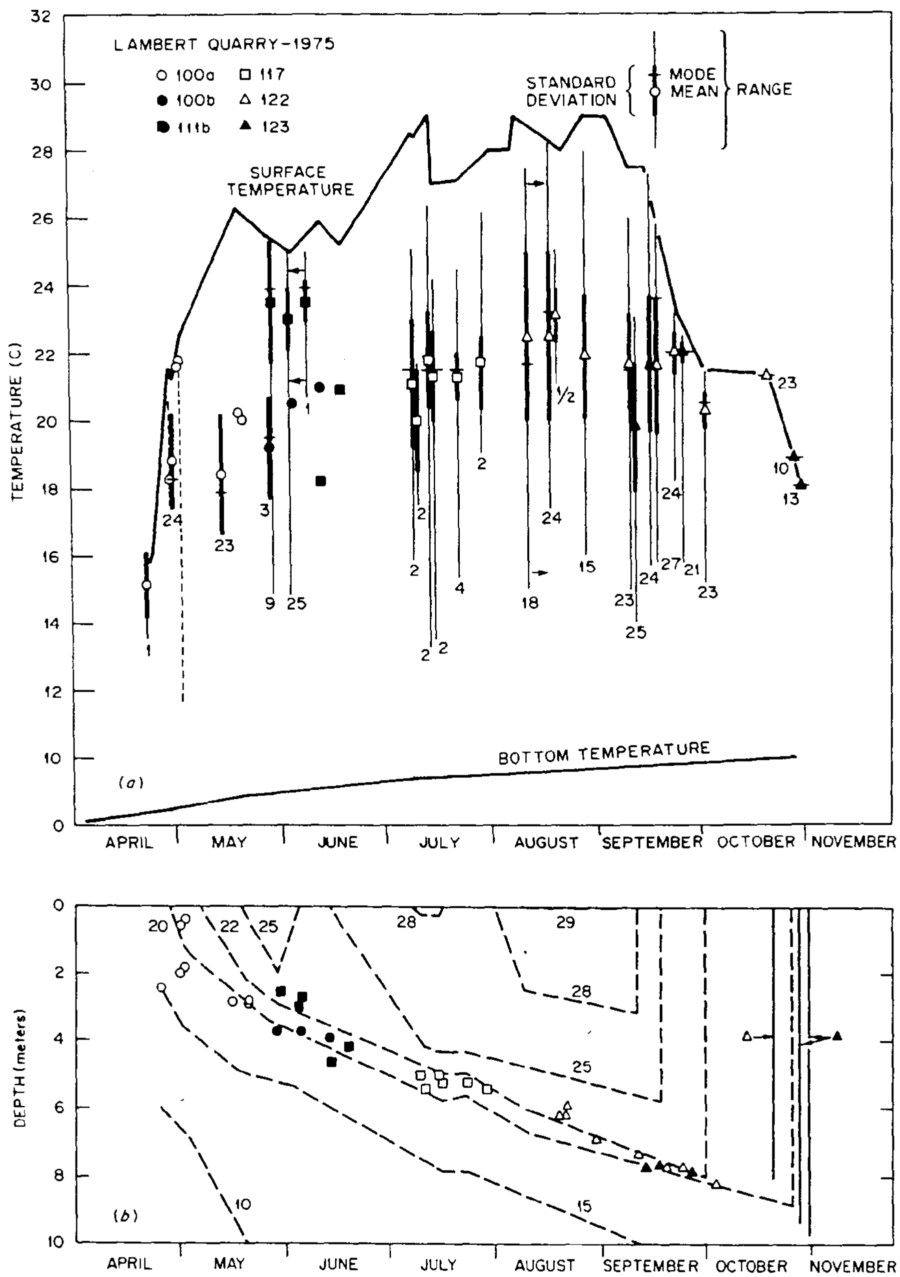

FIGURE 1.—*(a) Mean, mode, standard deviation, and range of temperatures occupied by six subadult striped bass in the range of available temperatures in Lambert Quarry, Oak Ridge, Tennessee, April–October 1975. Lengths of records (hours) are given below each data summary. Means of short manual observations are given for some dates in May and June. Not shown are means of 20.0, 20.4, and 20.4 C for fish 111a on April 30–2 May, respectively. Numerous brief excursions into cool water were made by fish 100a in early May (vertical dashed line). Standard deviation and range in late October were <0.2 C. A combined mode is shown for manual records in mid-July. For some dates there was no clear mode. (b) Mean occupied temperatures plotted at the depths where temperatures occurred. Isothermal conditions of the epilimnion in late October prevented designating discrete depths (zones that could have been occupied are designated by bars).*

1975) and did not limit distribution. Excursions into water temperatures above, and more often below, the zone usually occupied were short. For example, durations of 93 excursions (≥2 C) in the 24-hour record of fish 122 from 18 to 19 August 1975 extended from 20 to 180 seconds, with a mode of 60 seconds.

Visual inspection of graphed temperature-time data showed no pattern of diel change in temperatures occupied hourly or of their standard deviations (indicative of activity) by quarry fish that were examined either individually or lumped together. The fish tracked in Cherokee Reservoir did show a diel pattern, however, that was similar to changes in water surface temperature. This fish was located in a submerged stream channel that was fed by a cool tributary. Minimum temperatures available to the fish (about 17–18.5 C) changed in a diel cycle, controlled apparently by daytime warming of both the stream and the reservoir cove with which the tributary flow mixed.

Tagged fish were active horizontally as well as vertically. Location tracking indicated that quarry fish rarely remained in one spot and cruised the entire shoreline. Cessation of this cruising behavior signalled a lost tag. The Cherokee fish roamed the submerged stream channel but also showed quiescent periods (hours) in zones that were just downstream of submerged, low waterfalls (1–3 m as measured when exposed by reservoir drawdown in fall).

Recreational swimmers in Union Valley Quarry on 23 May and in early June were associated with fish data showing occupied temperatures much lower than surface temperatures and lower than data taken later in the

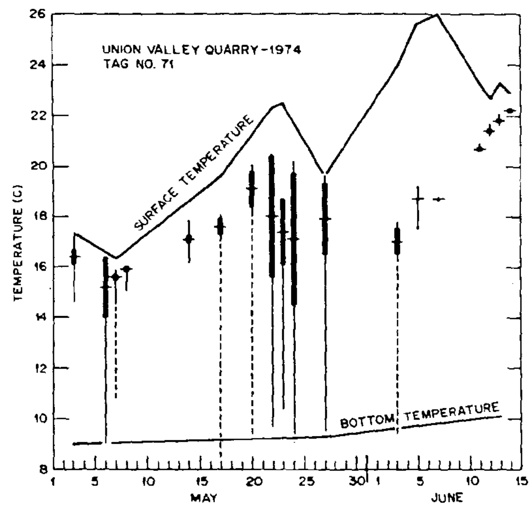

FIGURE 2.—*Mean, standard deviation, and range of temperatures selected each 10 seconds over half-hour periods by a subadult striped bass in the range of available temperatures in Union Valley Quarry, Oak Ridge, Tennessee, 1 May–14 June 1974. Single excursions to deep water are indicated by a dashed line, but the excursion is not included in the statistics. A second fish not shown (Number 53) had means and standard deviations of 19.8 (0.8), 16.6 (0.7), 20.2 (<0.1), 14.8 (<0.1), and 21.5 (<0.1) C on 24 and 27 May and 2, 5, and 11 June, respectively.*

TABLE 2.—*Frequency analysis of temperatures (C) occupied by striped bass in Lambert Quarry during >2-hour data sets when maximum available temperatures exceeded 25 C (≈no constraint on selection). Mean is given parenthetically for comparison. Temperature bands for 50, 66, 75, and 95% occupancy are centered about the median.*

Date	Tag number	Hours	Median (mean) temperature	Modal temperature	Occupancy of temperature bands 50%	66%	75%	95%
May 14	100a	23	18.3 (18.4)	17.9	17.0–19.9	16.5–20.4	16.2–20.7	15.4–21.4
28	100b	3	18.9 (19.2)	19.5	18.1–19.6	17.8–20.0	17.6–20.5	17.2–23.6
29	111b	9	23.8 (23.4)	23.9	23.0–24.5	22.5–24.7	21.9–24.8	17.8–25.6
Jun 3	111b	25	23.1 (23.0)	23.2	22.7–23.5	22.5–23.6	22.2–23.7	20.2–24.2
mid-July	117	12	21.5 (21.5)	21.5	21.2–22.0	20.8–22.3	20.7–22.5	17.2–24.0
Aug 18	122	18	22.3 (22.5)	21.7	21.0–23.7	20.4–24.3	20.0–24.7	17.6–27.1
19	122	24	22.9 (22.7)	23.2	21.5–23.9	20.8–24.3	20.4–24.6	18.7–26.0
28	122	15	22.1 (23.7)	23.6	20.5–23.4	20.2–23.6	19.7–23.6	18.2–24.3
Sep 10	122	23	21.6 (21.7)	21.5	21.0–22.6	20.7–23.0	20.4–23.2	18.8–24.0
11	123	25	19.9 (19.8)	[a]	18.7–21.2	18.1–21.6	17.5–21.9	15.2–22.8
16	123	24	22.2 (21.6)	21.6	19.7–23.8	18.1–24.4	17.7–24.5	16.4–24.7
18	122	27	22.4 (21.6)	23.6	19.8–23.4	19.3–23.5	19.0–23.5	17.6–23.6

[a] Mode indistinct between 18.8 and 21.8 C.

month without swimmers (Fig. 2). There were frequent, deep excursions by the fish at these times that were not included in the numerical data.

Discussion

Our data on occupied temperatures represent the "realized" thermal niche of striped bass in the waters in which they were studied (see Magnuson et al. 1979, for a discussion of thermal niche). Interspecies interactions or physiochemical restrictions in the field may alter the pattern of occupied temperatures away from the "fundamental" (or noninteractive; Hutchinson 1957) thermal niche as determined in the laboratory. Reynolds and Casterlin (1978) made this point clearly for another niche axis, pH. The simple ecosystems of quarry lakes were selected for the study, however, to minimize nonthermal variables. The small populations of mostly bluegills (*Lepomis macrochirus*) and largemouth bass (*Micropterus salmoides*) in each quarry lake offered minimal competition for space or food resources and were the principal prey available for the striped bass. The physicochemical environment was stable and predictable. Thus, a realized thermal niche of 20–24 C indicated here may represent fairly closely the fundamental niche, which is difficult to define in the laboratory for such a large fish. If so, then subadult striped bass fall into the cool-water thermal guild of Magnuson et al. (1979) or the "temperate mesotherm" category of Hokanson (1977).

The breadth of our fishes' realized thermal niche (in summer when the thermal axis was unrestricted by maximum or minimum water temperatures) is about the same as the breadth of 4 C for the fundamental niche identified by Magnuson et al. (1979) from laboratory studies of many species. Exact breadth depends upon the criterion used to calculate it. One standard deviation on either side of the mean generally defined a band of 2–4 C for any multiple-hour recording, and a band of about 4 C for the aggregate of all recordings. Frequency distributions of 66% of all records centered about the median (as recommended by Magnuson et al. 1979, because it encloses the same number of observations as the standard deviation), or of 75%, did not differ greatly from 4 C.

There is a suggestion of a time lag in attaining the field equivalent of the "final preferendum" in both quarries in the spring (Figs. 1 and 2). With the exception of fish 111b, records show gradually increasing temperatures occupied from the beginning of May through mid-June, while surface temperatures rose rapidly. This would be in accordance with (although somewhat slower than expected) most laboratory data that show an acclimation response in which the final preferendum is attained only after gradual biochemical acclimation to progressively warmer temperatures (Cherry et al. 1975, 1977; Richards et al. 1977).

The absence of diel patterns in temperature selection, despite the presence of the fish in the steep thermal gradient of the thermocline, suggests that daily light levels played no special role in distribution or activity of these fish. The seasonal pattern of selecting ever greater depths as the thermocline descended in the water column ties the depth distribution clearly to temperature or some other factor rather than to light.

An alternative hypothesis for apparent temperature selection is that the striped bass are orienting to the discontinuity of the thermocline rather than to temperature per se. B. L. Olla (National Marine Fisheries Service, personal communication) has observed bluefish (*Pomatomus saltatrix*) orienting to steep thermal gradients in laboratory tanks rather than to any particular temperature. Thermoclines offer potential advantages other than temperature, including density gradients, less water turbulence than in the epilimnion, and accumulations of planktonic organisms and detritus. The two hypothesized behaviors are indistinguishable in our spring and summer data. The October data, however, show the fish distributed in the isothermal (nearly) epilimnion (range and SD < 0.2 C) when temperatures there were below the apparent preferred temperatures near 22 C rather than in the cooler discontinuity zone (Fig. 1).

Potential biases could have resulted from various methods employed in this study. The use of telemetry to monitor temperature selection by fish is a relatively new approach and the validity of the results should be judged by comparison with studies using other accepted methods. The effects of transplanting fish from lake and laboratory to quarries are unknown. Although it is common practice to surgically implant or to "force feed" transmitters, the effects of such procedures have not been quantitatively defined. It is only through indirect observations (for example, tracking active movements, observing feeding) that the side effects are judged minimal. The general consistency of our results, despite differing techniques, lends credence to their validity. The observed variabilities among fish and time periods warrant further field study to determine if they are artifacts of technique or real biological differences. Further work in the complex environments of open reservoirs such as Cherokee is clearly needed before distributional generalizations can be made.

The thermal distributions of our fish in summer support Merriman's (1941) early observations that about 25–27 C is an upper avoidance range. There were some rapid excursions above it, but only one data set had a standard deviation that exceeded 25 C. Our data also lend credence to the hypothesis by Dudley et al. (1977) that the postspawning behavior of their fish in the Savannah River was influenced largely by temperature. Fish preferring temperatures near 22 C, as suggested in our study, would tend to move in the direction of cool hypolimnetic reservoir discharges upstream rather than toward temperatures of 26–30 C in the marine waters along the coast of Georgia. Movement of adult striped bass in Watts Bar Reservoir, Tennessee toward cool waters of the Clinch River below Melton Hill Dam near Oak Ridge has been observed by fishermen in September for several years (E. Means, newspaper articles in *The Oak Ridger*, Oak Ridge, Tennessee) but has never been carefully studied. Our data on lower temperatures being occupied also support the conclusion by Radovich (1963) that cold ocean temperatures were responsible for striped bass remaining in warmer San Francisco Bay during cool years, while they emigrated normally when ocean temperatures were higher.

A thermal niche for adult striped bass in fresh water of 20–24 C, as suggested by our data, can have several ecological implications. One is a potential conflict between thermal preferences and available dissolved oxygen in warm, eutrophic lakes. Summer deoxygenation of hypolimnetic and metalimnetic waters may make the preferred thermal habitat unusable. Mortalities could result, as happened to cisco (*Coregonus artedii*) that were reported killed by a temperature–dissolved oxygen squeeze in Michigan lakes by Colby and Brooke (1969). Indeed, late summer mortalities of adult striped bass have occurred annually in eutrophic Cherokee Reservoir since 1972 (D. Bishop, Tennessee Wildlife Resources Agency, personal communication). Restriction to temperatures above the fundamental thermal niche by low dissolved oxygen or power-plant cooling may cause reduced growth rates (Magnuson et al. 1979), leading to emaciated fish, also commonly reported by fishermen in Cherokee Reservoir in late summer and fall. Small water volumes having both low temperatures and high dissolved oxygen such as the cool, submerged stream channel in which our Cherokee fish was tracked could be expected to be frequented by striped bass under simultaneous high temperature and low dissolved oxygen stress in open waters. Because the thermal structure of a lake is dynamic and seasonally transitory, the duration of stressful conditions and the availability of suitable refuges may determine population survival.

Another implication relates to predator-prey interactions. Many common prey species—for example, threadfin (*Dorosoma petenense*) and gizzard shad (*D. cepedianum*), freshwater drum (*Aplodinotus grunniens*), juvenile carp (*Cyprinus carpio*), and sunfishes (*Lepomis* spp.)—have high thermal preferenda (Coutant 1977) and may be thermally isolated in summer from feeding adult striped bass. Conversely, native species with apparently similar thermal niches—for example, yellow perch (*Perca flavescens*), white crappie (*Pomoxis annularis*), black crappie (*P. nigromaculatus*), rainbow trout (*Salmo gairdneri*), walleye (*Stizostedion vitreum*), and sauger (*S. canadense*)—could congregate with introduced striped bass leading to competition for prey and high levels of predation by the larger individuals. These interactions could be intense if the thermal–dissolved oxygen refuges discussed above are small. Accelerated predation forced by advanced eutrophication could logically cause the large striped bass predators to overtake populations of smaller game fish.

Acknowledgments

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References

Barr, A. J., J. H. Goodnight, J. P. Sall, and J. T. Helwig. 1976. A user's guide to SAS 76. SAS Institute, Raleigh, North Carolina, USA.

Cherry, D. S., K. L. Dickson, and J. Cairns, Jr. 1975. Temperatures selected and avoided by fish at various acclimation temperatures. Journal of the Fisheries Research Board of Canada 32:485–491.

Cherry, D. S., K. L. Dickson, J. Cairns, Jr., and J. R. Stauffer. 1977. Preferred, avoided, and lethal temperatures of fish during rising temperature conditions. Journal of the Fisheries Research Board of Canada 34:239–246.

Colby, P. J., and L. T. Brooke. 1969. Cisco (*Coregonus artedii*) mortalities in a southern Michigan lake, July 1968. Limnology and Oceanography 14:958–960.

Coutant, C. C. 1975. Temperature selection by fish—a factor in power plant impact assessments. Pages 575–597 *in* Environmental effects of cooling systems at nuclear power plants. International Atomic Energy Agency, Vienna, Austria.

Coutant, C. C. 1977. Compilation of temperature preference data. Journal of the Fisheries Research Board of Canada 34:739–745.

Dudley, R. G., A. W. Mullis, and J. W. Terrell. 1977. Movements of adult striped bass (*Morone saxatilis*) in the Savannah River, Georgia. Transactions of the American Fisheries Society 106:314–322.

Gift, J. J. 1970. Responses of some estuarine fishes to increasing thermal gradients. Doctoral dissertation. Rutgers University, New Brunswick, New Jersey, USA.

Hart, L. G., and R. C. Summerfelt. 1975. Surgical procedures for implanting ultrasonic transmitter into flathead catfish (*Pylodictus olivaris*). Transactions of the American Fisheries Society 104:56–59.

Hokanson, K. E. F. 1977. Temperature requirements of some percids and adaptations to the seasonal temperature cycle. Journal of the Fisheries Research Board of Canada 34:1524–1550.

Hutchinson, G. E. 1957. Concluding remarks. Cold Spring Harbor Symposium on Quantitative Biology 22:415–427.

Koo, T. S. Y., and J. S. Wilson. 1972. Sonic tracking striped bass in the Chesapeake and Delaware Canal. Transactions of the American Fisheries Society 101:453–462.

Magnuson, J. J., L. B. Crowder, and P. A. Medvick. 1979. Temperature as an ecological resource. American Zoologist 19:331–343.

Meldrim, J. W. 1970. An experimental study of the behavior of estuarine fishes to a proposed thermal effluent. Processed report, Ichthyological Associates, Middletown, Delaware, USA.

Meldrim, J. W., and J. J. Gift. 1971. Temperature preference, avoidance and shock experiments with estuarine fishes. Ichthyological Associates Bulletin 7, Middletown, Delaware, USA.

Meldrim, J. W., J. J. Gift, and B. R. Petrosky. 1974. The effect of temperature and chemical pollutants on the behavior of several estuarine organisms. Ichthyological Associates Bulletin 11, Middletown, Delaware, USA.

Merriman, D. 1941. Studies on the striped bass (*Roccus saxatilis*) of the Atlantic Coast. United States Fish and Wildlife Service Fishery Bulletin 50:1–77.

Neill, W. H., and J. J. Magnuson. 1974. Distributional ecology and behavioral thermoregulation of fishes in relation to heated effluent from a power plant at Lake Monona, Wisconsin. Transactions of the American Fisheries Society 103:663–710.

Norris, K. S. 1963. The functions of temperature in the ecology of the percoid fish *Girella nigricans* (Ayers). Ecological Monographs 33:23–62.

Pfuderer, H. A., S. S. Talmage, B. N. Collier, W. Van Winkle, and C. P. Goodyear. 1975. Striped bass—a selected, annotated bibliography. ORNL-EIS-75-73, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA.

Radovich, J. 1963. Effect of ocean temperature on the seaward movements of striped bass, *Roccus saxatilis*, on the Pacific coast. California Fish and Game 49:191–207.

Raney, E. C. 1952. The life history of the striped bass, *Roccus saxatilis* (Walbaum). Bulletin of the Bingham Oceanography College 14:5–177.

Reynolds, W. W., and M. E. Casterlin. 1978. Reactions of blue crabs to low pH. Transactions of the American Fisheries Society 107:868–869.

Richards, F. P., W. W. Reynolds, and R. W. McCauley, editors. 1977. Temperature preference studies in environmental impact assessments: an overview with procedural recommendations. Journal of the Fisheries Research Board of Canada 34:728–761.

Rochelle, J. M. 1979. Observations of excess acoustic noise caused by metallic corrosion. Underwater Telemetry Newsletter 9(1):9–10.

Rochelle, J. M., and C. C. Coutant. 1973. Temperature sensitive ultra-sonic fish tag, Q-5099. ORNL/TM-4438, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA.

Stauffer, J. R., Jr., K. L. Dickson, and J. Cairns, Jr. 1974. A field evaluation of the effects of heated discharges on fish distribution. Water Resources Bulletin 10:860–876.

Stevens, R. E. 1964. A final report on the use of hormones to ovulate striped bass, *Roccus saxatilis* (Walbaum). Proceedings of the Annual Conference of the Southeastern Association of Game and Fish Commissioners 18:525–538.

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#19

Influences of Water Quality on Distribution of Striped Bass in a Tennessee River Impoundment

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Abstract

Telemetry techniques were used to evaluate relationships between water quality and distribution of adult striped bass *Morone saxatilis* during an 18-month period in Watts Bar Reservoir, Tennessee. Distribution and movements of fish were influenced by water temperature and dissolved oxygen concentration. During winter and early spring, temperature was vertically and horizontally uniform, and striped bass were relatively mobile and occurred in both tributary arms as well as in the main body of the reservoir. As the reservoir warmed in summer, fish were less mobile and progressively limited to areas in the tributary arms where temperature was less than 24 C and dissolved oxygen exceeded 4 mg/liter. Parts of the tributary arms of Watts Bar Reservoir provided such areas due to hypolimnetic discharges from upstream impoundments and groundwater inflows. Striped bass were restricted to these areas until late fall, when the entire reservoir cooled and again was nearly isothermal. Knowledge of relationships between striped bass habitat use and water quality is useful for fishery management and resource protection for reservoirs; an example is provided for Watts Bar Reservoir.

Since it was first discovered that striped bass *Morone saxatilis* could complete their life cycles in fresh water (Scruggs 1957), the species has been introduced into impoundments throughout the United States. These populations usually are maintained by annual stocking of young hatchery fish or, more rarely, by natural reproduction. Angler harvest of striped bass has been localized and seasonal in some reservoirs, leading to concern that management practices or habitat conditions have been inadequate for establishment of more-extensive fisheries. Particular concern has surrounded summer mortalities of large striped bass valued by sport fishermen. Die-offs in Kentucky (Axon 1979), Kansas (McCloskey and Stevens 1980), Tennessee (Schaich and Coutant 1980; Waddle et al. 1980), and Oklahoma (Summers 1982) exemplify the need for information on habitat requirements and behavior of adult striped bass in reservoirs.

A few studies of adult striped bass movements and habitat use in reservoirs have been reported. Schaich and Coutant (1980) and Waddle et al. (1980) related water temperature, dissolved oxygen, and cool summer "refuge" areas to striped bass habitat selection in Cherokee Reservoir, Tennessee. Summerfelt and Mosier (1976) studied prespawning movements during spring, and Combs and Peltz (1982) followed the seasonal distribution of adults in Keystone Reservoir, Oklahoma. Information on striped bass distribution in Lake Texoma, Oklahoma–Texas, was obtained primarily in the main basin of the reservoir during periods of stratification (Summers 1982; Matthews et al. 1985, this issue). None of these studies was able to relate water quality to habitat use by striped bass throughout a year for a whole reservoir.

In this paper, we present the results of an 18-

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(TVA 1967) and that pronounced differences occurred among inflows. The Clinch River arm generally is higher in dissolved oxygen, warmer in winter, and cooler in summer than the Tennessee River arm due to upstream releases from Melton Hill Reservoir (unpublished data for 1974–1978 provided by TVA Water Quality Branch, Chattanooga, Tennessee). Prior to closure of Tellico Dam, inflowing water from the Little Tennessee River was considerably cooler than the majority of water in the Tennessee River channel during summer and fall (also due to upstream storage reservoir releases from Fontana Reservoir), and this discharge exerted a 1–2 C cooling effect as far as 5 km downstream of the confluence. A steam electric generating station (1,600-megawatt capacity) on the lower Clinch River uses river water for condenser cooling, and the heated discharge forms a stratified surface layer from the facility to the mouth of the Clinch River.

Watts Bar Reservoir supports a diverse assemblage of warm- and coolwater fishes with an average biomass of about 240 kg/hectare for all species combined (unpublished data for 1949–1978 provided by TVA Office of Natural Resources, Norris, Tennessee). The reservoir was initially stocked with striped bass eggs and larvae in 1964, and annual stockings of young of the year began in 1971 (Van Den Avyle and Higginbotham 1980). Higginbotham (1979) indicated that growth, food habits, maturation, and other aspects of striped bass life history in Watts Bar Reservoir were similar to those reported for other freshwater impoundments.

Methods

The distribution of striped bass was monitored with several types of location-indicating or temperature-sensing transmitters. Most (51) of the ultrasonic transmitters (35 g in water, longevity > 1 year) allowed location of the fish only and were built at Tennessee Technological University. Seven ultrasonic transmitters fabricated at Oak Ridge National Laboratory (16–26 g, >6 months; Rochelle and Coutant 1973), four Smith-Root Model SR69A ultrasonic transmitters (20.5 g, 45 days), and two radio tags built at the University of Minnesota (15 g, >6 months) indicated water temperature as well as location.

Transmitter frequencies and pulse rates were selected to allow individual recognition, and pulse rates of temperature-indicating transmitters were calibrated in a laboratory prior to field use. Most transmitters were attached externally in a "backpack" fashion similar to the techniques used by Winter (1976) and Schaich and Coutant (1980). Some of the smaller transmitters were surgically implanted (Rochelle and Coutant 1973; Hart and Summerfelt 1975). Thermistors of temperature-indicating transmitters were allowed to protrude to measure water temperature.

Striped bass were collected for transmitter attachment throughout most of the July 1979–December 1980 study period. We attempted to tag equal numbers of fish from the two upstream arms and the main body of the reservoir, but sampling efforts were adjusted according to known locations of tagged fish and past collecting success. Most striped bass were captured by electrofishing in the upper reaches of the Clinch River and Tennessee River arms, and others were obtained from gill and trammel nets in the lower reservoir during late fall and winter. Fish were selected for transmitter attachment only if the transmitter's weight in water was less than 1.25% of the fish's weight in air (Winter et al. 1978). Tagged fish were released immediately at the capture site; Schaich and Coutant (1980) reported poor survival of striped bass that were displaced after capture during summer.

Tracking trips were made weekly from July 1979 through December 1980 to locate tagged fish. Receiving equipment included a directional, hand-held hydrophone (Smith-Root SR70-H) and a multiple channel ultrasonic receiver (Smith-Root TA-70) or a directional, hand-held yagi antenna and a multiple channel radio receiver (Wildlife Materials TRX-24A). Searching was done by cruising sections of the reservoir and stopping at short intervals to listen for signals; the entire reservoir was searched at least monthly. River position and water temperature and dissolved oxygen profiles were recorded each time a fish was located, and pulse intervals for temperature sensing transmitters were recorded (Hewlett-Packard 5300A Universal Counter) every 10 seconds for 30 minutes to obtain an average interval read against a calibration curve.

Water quality data were collected monthly at 17 stations (Fig. 1) to provide information on possible uplake–downlake gradients of water temperature and dissolved oxygen concentrations. Vertical profiles were measured at 1-m depth intervals with a YSI Model 51B Temp/DO meter. These data, along with those obtained much more distinct and stable in tributary embayments of the lower reservoir, where conditions were less affected by water currents.

The Clinch River arm was considerably cooler during August and September than the Tennessee River arm or the main reservoir but not markedly warmer in winter. The highest water temperature measured in the Clinch River, except for the localized effluent of the Kingston Steam Plant, was 20.5 C in September. Underflows of cool water were common in the Clinch River during summer from the confluence of the Emory River to the area immediately downstream of the confluence with the Tennessee River. This local vertical stratification was due to the combined influences of the Kingston Steam Plant's heated discharge and the warmer conditions of the Tennessee River at the confluence. The closure of Tellico Dam on the Little Tennessee River in September 1979 halted a similar summer flow of cool water into the Tennessee River arm.

Minimum dissolved oxygen concentrations for all stations in the Tennessee and Clinch River arms were 3.7 and 6.2 mg/liter, respectively. Dissolved oxygen concentrations were less than 3.0 mg/liter in the main body of the reservoir only during August and September at depths greater than 10 m. Concentrations were lower, commonly less than 2.0 mg/liter at depths exceeding 6 m, in tributary embayments off the main reservoir.

Water quality measurements taken near tagged fish generally conformed to the results of reservoir-wide sampling. A major exception occurred at an unsuspected underwater spring (22 C) in the Tennessee River (Sugarlimb, Tennessee River kilometer 954.8) to which striped bass were attracted in August–October when surrounding temperatures were higher. Catches of tagged fish by anglers in the Kingston Steam Plant discharge during winter suggested that the elevated temperatures there (up to 10 C above ambient) may be an important winter feature.

Fish Distribution

Seventy-one striped bass were tagged and monitored between July 1979 and December 1980. Of these, 29 were tagged in the Tennessee River arm (including the Little Tennessee River), 25 in the Clinch River arm, and 17 in the main body of the reservoir. Externally attached ultrasonic transmitters were used on 61 fish, internally attached ultrasonic transmitters on 8, and externally attached radio transmitters on 2. Tagged fish weighed 2.0 to 13.5 kg (mean = 6.3 kg), ranged from 55 to 107 cm total length (mean = 78 cm), and were 3 to 7 years old (mean = 4.8 years); sizes and ages did not differ significantly among the three main tagging sites. Fifty-eight fish were relocated (detailed histories of tagged fish are given in Cheek 1982).

Evidence for fish distribution within Watts Bar Reservoir comes mainly from collections of fish to tag (netting and electrofishing) and searches for tagged individuals. Both the positive evidence of fish interception and the negative evidence of fruitless effort serve to compile a record of fish presence or absence.

Searching effort (river kilometers covered) was fairly even in each of the three major zones of the reservoir, but the observed distribution of striped bass was not equally even (Fig. 2). In January through May, most fish observed were in the main reservoir. Fish moved actively enough that we could catch them in passive nets for tagging. Few remained in the main reservoir tagging area, however. In June, and for the remainder of the summer, fish became more abundant in the Tennessee and Clinch River arms. Each arm displayed its own pattern of distribution. Tagged fish in the Clinch River arm generally moved throughout the 30-km reach between Melton Hill Dam and the Emory River. Fish found in the Tennessee River arm, however, became progressively restricted to either the Little Tennessee River confluence (in 1979) or to the groundwater source at Sugarlimb (in 1980), where they remained until late October. We are unable to evaluate the distribution of fish in the main reservoir during June due to lack of tracking effort there; intensive searching in July revealed some fish, but continued searching efforts into early September yielded only one interception in the main reservoir in early August (Fig. 2). November and December appeared to be a period of dispersal; fish occurred in both arms and the main reservoir in 1979 and 1980.

Discontinuities in fish distribution over time were associated with specific temperature ranges and dissolved oxygen concentrations (Fig. 2). Temperatures during the winter and early spring, when most fish contacts were made in the main reservoir, were nearly uniform vertically and horizontally throughout the reservoir. As observations of fish in the tributary arms increased

June and low mobility within relatively cool habitats during July–October (mobility at this time being affected by the size of the coolwater zone).

The striped bass we captured or tracked appeared to prefer certain physical characteristics of the river–reservoir habitat when high temperature and low dissolved oxygen were not limiting factors. In the main reservoir, upper edges of the old river channel were most frequented. In riverine sections, fish occupied structured shorelines, such as rock banks, and oriented to features that created eddies, such as fallen trees or submerged deltas of small tributaries. There was often little or no detectable movement of a fish for several hours along a channel margin or similar habitat. At other times, fish moved rapidly along channel edges or (rarely) along the channel bottom.

Discussion

Information about striped bass distribution and water quality in Watts Bar Reservoir provides a basis for evaluating the consistency of data from previous studies and developing general predictions of striped bass behavior in reservoirs. Past studies in fresh water have indicated that distribution patterns are influenced by water temperature, dissolved oxygen concentrations, spawning cycles, water flow, and a variety of additional factors. In our work, the most apparent responses to water quality included movement to uplake areas during late spring and highly predictable, restricted distributions during summer.

Frequent occurrence of striped bass in upstream areas of Watts Bar Reservoir where water temperatures were 15–19 C during June may have been the result of attempted spawning migration. Mature fish in reservoirs typically move up major tributaries during spring and have been reported to spawn at 14–15 C in Santee-Cooper Reservoir, South Carolina (Scruggs 1957), and 15.5–18.5 C in J. Percy Priest Reservoir, Tennessee (Stooksbury 1977). Anadromous striped bass usually spawn during spring when water temperatures are 15–19 C (Raney 1952; Barkuloo 1967; Kornegay and Humphries 1976). The prolonged occurrence of 15–19 C temperatures in the Clinch River arm may be responsible for the unusually long striped bass spawning period noted by Higginbotham (1979) in Watts Bar Reservoir.

After spawning, adults in anadromous stocks usually move downstream to coastal bays and the ocean (Massman and Pacheco 1961; Chadwick 1967; Orsi 1971; Moore and Burton 1975); similar postspawning movements to downlake areas have been reported for Keystone Reservoir (Summerfelt and Mosier 1976; Combs and Peltz 1982), J. Percy Priest Reservoir (Stooksbury 1977), and Lake Texoma (Matthews et al. 1985). We observed no pronounced downstream movement of fish following the spawning season in Watts Bar Reservoir, which may have been due to the relatively rapid increase of surface temperature and decrease in deepwater oxygen in the main reservoir at this time. Unusual postspawning migrations have been noted in rivers when temperatures were too low or too high. Striped bass in the Sacramento–San Joaquin river system, California, ceased their downstream postspawning migration when coastal waters were cooler than 18.5 C (Radovich 1963). In the Savannah River, Georgia–South Carolina, striped bass moved upstream after spawning when coastal waters were 26–30 C, and some fish apparently spent their entire lives in the cooler river (Dudley et al. 1977). Scruggs (1957) concluded that striped bass in the Cooper River, South Carolina, also remained in upstream sections of the river throughout most of the year.

Temperature and dissolved oxygen concentrations at sites occupied by striped bass during summer in Watts Bar Reservoir were similar to those for most impoundments. In Watts Bar Reservoir, tagged striped bass occurred in areas where the average water temperature was 20 C (SD = 2.1; N = 141) and dissolved oxygen concentrations exceeded 4 mg/liter. Coutant (1978), Waddle et al. (1980), and Schaich and Coutant (1980) reported that adult striped bass in Cherokee Reservoir moved into isolated, 21–22 C, spring-fed areas having 5 mg/liter dissolved oxygen when other areas were warmer or anoxic. These "refuge" areas were occupied until other parts of the reservoir cooled. Coutant and Carroll (1980) observed that subadult striped bass in a quarry lake preferred 20–24 C during the summer, but when surface temperatures were less than 21 C, the fish preferred the warmest available water at depths exceeding 1.5 m. Striped bass in the main pool of Lake Texoma moved to the coolest available water strata (about 25 C) having more than 2 mg/liter oxygen when surface layers were 28–29 C and the hypolimnion was anoxic (Matthews et al. 1985).

striped bass were low, presumably because distributions of commercial effort and striped bass did not overlap to a great extent (Heitman and Van Den Avyle 1979). Our present study largely confirms this explanation—commercial fishing effort was concentrated in the main reservoir during summer, when striped bass were in upstream areas; when fishing was concentrated in tailwaters during fall and winter, striped bass were dispersed throughout the reservoir. Knowledge of water quality patterns could be used to protect reservoir striped bass populations from excessive incidental commercial harvest by prohibiting netting in areas having preferred temperatures and dissolved oxygen concentrations.

Knowledge of general patterns of habitat use and of restricted distribution patterns could help stimulate angler interest in striped bass fishing in reservoirs. In Watts Bar Reservoir, angling should be encouraged in tailwaters and the river arms during spring, summer, and early fall and concentrated along the submerged Tennessee River channel in the main reservoir at other times. Nearly all fish we collected or tracked in the main part of the reservoir were located near the river channel. In Cherokee Reservoir, Tennessee, fishermen have become adept at locating concentrations of adult striped bass in thermal refuges during summer (Schaich and Coutant 1980; Waddle et al. 1980).

Extensive cool thermal refuge areas in reservoirs should be viewed as valuable resources and protected as such. It is likely that closure of Tellico Dam and the resulting loss of the Little Tennessee River's cooling effect on Watts Bar Reservoir reduced the summer carrying capacity for adult striped bass. Maintenance of cool, oxygenated conditions in the Clinch River arm of Watts Bar Reservoir during the summer provides an extensive thermal refuge without the adverse effects of crowding and mortalities noted by Waddle et al. (1980) and Schaich and Coutant (1980) in Cherokee Reservoir. Studies of effects of industrial development and other habitat alteration on water temperatures of reservoir tributaries should consider impacts on the thermal regime available to striped bass, especially during summer.

Acknowledgments

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References

AXON, J. R. 1979. An evaluation of striped bass introductions in Herrington Lake. Kentucky Department of Fish and Wildlife Resources Fisheries Bulletin 63.

BARKULOO, J. M. 1967. The Florida striped bass (*Roccus saxatilis*). Florida Game and Fresh Water Fish Commission, Federal Aid in Fish Restoration Project F-10-R, Tallahassee, Florida, USA.

CHADWICK, H. K. 1967. Recent migrations of the Sacramento–San Joaquin striped bass population. Transactions of the American Fisheries Society 96:327–342.

CHEEK, T. E. 1982. Distribution and habitat selection of adult striped bass, *Morone saxatilis* (Walbaum), in Watts Bar Reservoir, Tennessee. Master's thesis. Tennessee Technological University, Cookeville, Tennessee, USA.

COMBS, D. L., AND L. R. PELTZ. 1982. Seasonal distribution of striped bass in Keystone Reservoir, Oklahoma. North American Journal of Fisheries Management 2:66–73.

COUTANT, C. C. 1978. A working hypothesis to explain mortalities of striped bass (*Morone saxatilis*) in Cherokee Reservoir. Oak Ridge National Laboratory ORNL/TM-6534, Oak Ridge, Tennessee, USA.

COUTANT, C. C. 1983. Striped bass and the management of cooling lakes. Pages 389–396 *in* S. Sengupta and S. S. Lee, editors. Waste heat utilization and management. Hemisphere, Washington, D.C., USA.

COUTANT, C. C. 1985. Striped bass, temperature, and dissolved oxygen: a speculative hypothesis for environmental risk. Transactions of the American Fisheries Society 114:31–61.

COUTANT, C. C., AND D. S. CARROLL. 1980. Temperature selection by ten ultrasonic-tagged striped bass in fresh water lakes. Transactions of the American Fisheries Society 109:195–202.

DUDLEY, R. G., A. W. MULLIS, AND J. W. TERRELL. 1977. Movements of adult striped bass (*Morone saxatilis*) in the Savannah River, Georgia. Trans-

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#19

Seasonal Distribution of Striped Bass in Keystone Reservoir, Oklahoma

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ABSTRACT

Sixteen striped bass (*Morone saxatilis*) from Keystone Reservoir, Oklahoma, were successfully implanted with ultrasonic transmitters and located periodically during a 337-day monitoring period. A total of 220 sightings were plotted, 154 (70%) of which occurred during the summer months (June–August). Striped bass exhibited seasonal migratory and distributional patterns, showing areas of concentration in the headwaters of the reservoir during the spring and fall with summer concentrations in the main body of the reservoir.

Striped bass (*Morone saxatilis*) were introduced into Oklahoma waters in 1965 both as an additional sport fish and as a biological management tool to control over-abundant clupeid populations. Keystone Reservoir, a 10,643-hectare hydro-electric impoundment on the Arkansas River, was stocked from 1965 through 1969 with fingerling striped bass. Natural reproduction was identified in 1970 (Mensinger 1970) and has occurred for 12 consecutive years.

Seasonal distributions and movement patterns of anadromous striped bass stocks have received much attention. Chesapeake Bay stocks of striped bass have been studied by Mansueti (1961), Massmann and Pacheco (1961), Chapotan and Sykes (1961), Hollis (1967), and Moore and Burton (1975). Movements of striped bass found in Long Island Sound were studied by Clark (1968). Striped bass populations in the Sacramento-San Joaquin Estuary were investigated by Calhoun (1952), Chadwick (1967), and Orsi (1971). These authors found discernible migratory patterns for mature striped bass but little or no movement of immature fish.

Movement patterns of striped bass in freshwater have been studied by Scruggs (1955) in the Cooper River, South Carolina; Dudley et al. (1977) in the Savannah River, Georgia; Coutant and Carroll (1980) in quarry lakes in Tennessee; Waddle et al. (1980) and Schaich and Coutant (1980) in Cherokee Reservoir, Tennessee; and Summerfelt and Mosier (1976) in Keystone Reservoir, Oklahoma. Summerfelt and Mosier (1976) investigated pre-spawning movement in Keystone Reservoir and showed that striped bass preferred both the Cimarron and Arkansas River headwater areas plus Salt Creek Cove during the spring season.

Striped bass distributional studies throughout the year have not been conducted although striped bass have been widely introduced into reservoirs in southeastern states. The objective of this study was to examine the seasonal distribution of striped bass in Keystone Reservoir to help fill the knowledge gap that exists for striped bass distribution in reservoirs.

METHODS

Striped bass used for telemetry implants were captured by gill nets (0.08 m × 2.4 m × 91.4 m, bar mesh) during the fall of 1976 and spring of 1977. Ultrasonic transmitters were implanted in 16 striped bass: five from the Arkansas River, seven from the Cimarron River, and four from the Salt Creek areas of Keystone Reservoir during November 1976 and March 1977 (Table 1). These fish ranged from 597 to 780 mm in total length and weighed from 2.7 to 6.0 kg.

Transmitters (74 kHz) used in the study had varying identifiable pulse rates, were 16 × 65 mm, and weighed 20 g in air and 8 g in water. These transmitters were surgically implanted into the body cavity following the procedures of Summerfelt and Mosier (1976). Recovery from

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Table 1. Tagging and tracking information from striped bass bearing ultrasonic transmitters in Keystone Reservoir, 1976–1978.

Date tagged	Tag number	Total length (mm)	Weight (g)	Sex	Location of capture[a]	Date of last sighting	Total time tracked
24 November 1976	12	625	2,722	M	S	17 November 1977	260.4[b]
1 March 1977	20	697	4,423	F	S	13 October 1977	227.0
7 March 1977	11	780	5,959	F	S	10 December 1977	277.4
7 March 1977	10	700	4,086	F	S	25 May 1977	79.0
10 March 1977	22	634	3,600	M	C	31 March 1977	20.7
10 March 1977	14	661	3,405	M	C	18 August 1977	160.7
11 March 1977	18	681	3,405	F	C	13 March 1977	1.9
11 March 1977	21	617	2,898	M	C	31 January 1978	326.1
11 March 1977	16	634	3,008		C	29 August 1977	171.0
12 March 1977	17	597	3,178	M	C	31 March 1977	18.9
12 March 1977	15	644	3,348	M	C	1 September 1977	172.8
14 March 1977	25	730	4,682	F	A	7 June 1977	85.1
14 March 1977	9	644	3,292	M	A	16 November 1977	246.3
14 March 1977	29	710	4,881	F	A	17 August 1977	155.8
16 March 1977	19	708	4,082	F	A	21 November 1977	249.8
16 March 1977	13	722	4,082	M	A	30 November 1977	259.8

[a] S = Salt Creek Area; C = Cimarron River arm; A = Arkansas River arm.
[b] Tracking started 1 March 1977. Actual time at large was 357.4 days.

surgery took place in a 1–4 hour furacin bath (100 mg/liter) in a 1-m circular stock tank with a recirculating system.

Striped bass distributions were monitored approximately 15 days each month in Keystone Reservoir from 1 March 1977 to 31 January 1978. Locating was conducted throughout the reservoir. Starting locations generally were at the confluence of the Cimarron and Arkansas River arms of the reservoir, but as distributions became apparent, daily starting locations were determined from the last sightings of previous monitoring days. Locating continued either until all fish were located or until the entire reservoir was searched.

Results

Seasonal distributions of Keystone Reservoir striped bass were determined from a total of 220 sightings during the 337-day study period (Table 2). During the spring season (March–May), locating effort and sightings were limited because most tagged fish were ascending tributary streams to spawn. Distribution patterns (Fig. 1) were determined from a total of 35 sightings made during the spring. Re-locations of tagged striped bass during the spring were made primarily in March, within the 2-week period following implantation and release. In March, 14 of the 16 tagged fish were re-located, but in April and May only three and six tagged fish were located, respectively, during a total of 12 sightings. Spring distributions showed major concentrations of tagged fish in the upper portion of the Cimarron River arm of the reservoir, with additional sightings made on fish as they moved between the Cimarron tributary and the lower portion of the reservoir. Although striped bass were tagged and released in the upper Arkansas River arm of the reservoir, no tagged fish were re-located in that area or in the Arkansas tributary during the spring months. In March, two fish tagged in the upper Arkansas arm were located shortly after release in the concentrations of fish in the upper Cimarron arm. As spring progressed (April–May), one of these two tagged fish was located again in the Arkansas arm of the reservoir along with two fish tagged in the Cimarron arm and one from the Salt Creek area. Similar occurrences of fish moving from the Arkansas River arm to the Cimarron River arm and back were reported by Summerfelt and Mosier (1976).

Summer distributional patterns (June–August) were determined from 154 observations or 70% of the total sightings (Fig. 1). Following spawning runs into the tributary streams, primarily the Arkansas River (Mensinger 1970), tagged fish descended into the main body of the reservoir during the summer. There were three concen-

Table 2. Seasonal summaries of tagged striped bass sightings by major area of Keystone Reservoir.

Tag number	Location[a]																Total sightings
	Spring				Summer				Fall				Winter				
	A	C	S	Σ	A	C	S	Σ	A	C	S	Σ	A	C	S	Σ	
12					7	1	1	9	2			2					11
20		4		4	2	13	1	16			1	1					21
11	2			2	10	4	2	16		1		1		1		1	20
10		5		5		1[b]		1									6
22		2[b]		2													2
14		1		1	2	2		4									5
18		1[b]		1													1
21	2	1		3	8	2	4	14		9		9		8		8	34
16	1	3		4	17	1		18									22
17		2		2													2
15		3		3	14	2		16	1			1					20
25	1[b]			1													1
9		1		1	12			12									13
29		2		2	5	8		13									15
19					1	15	2	18		8		8					26
13	2	2		4	9	1	7	17									21
Totals				35				154				22				9	220

[a] A = Arkansas River arm; C = Cimarron River arm; S = Salt Creek area.
[b] = Confirmed death of tagged fish.

tration areas: (1) the Arkansas River arm around the U.S. 64 highway bridge; (2) the mouth of Salt Creek Cove in the Cimarron River arm; and (3) a submerged island in Salt Creek Cove.

Early in the summer, tagged fish were located in the Arkansas River arm of the reservoir. These fish gathered in the lower portion during June prior to their segregation in late summer into areas of concentration. Eleven of the 13 tagged fish at large during the summer months were located in the Arkansas arm during the early summer. By late summer (July–August) tagged fish had moved into areas of concentration in the lower end of the reservoir. These tagged fish segregated themselves into distinct summering groups, with individuals of those groups occasionally intermingling in another area of concentration. Fish tagged in the Cimarron River arm (Fig. 2) showed a preference for the lower Arkansas arm and the main body of the reservoir near the U.S. 64 bridge during the summer, with 78% of the sightings in this area. Only nine sightings were made in the Cimarron River arm (12%) or the Salt Creek Cove (11%) areas. Conversely, figh tagged in the Arkansas River arm (Fig. 3) used the Cimarron River arm and Salt Creek area extensively (61%). The Arkansas River arm near the U.S. 64 bridge also was frequented (39%), primarily by one individual (10 sightings), but not as much as other areas of concentration. Distribution patterns of fish tagged in Salt Creek Cove (Fig. 4) were extensive. They used the same summer areas as fish tagged in the Cimarron and Arkansas arms. Areas of preference were not as apparent as for fish tagged in other areas, with sightings distributed among the Arkansas arm, Cimarron arm and the Salt Creek area (43, 47, and 11% of the sightings, respectively). When concentrated, these tagged fish distributed themselves along inundated river and creek channels. These concentration areas are characterized by steep drop-offs, submerged islands, heavy rock riprap, submerged trees, and tree stump beds in the summer.

Fall distributions (Fig. 5) of tagged fish were scattered throughout the reservoir after the summer concentrations of fish broke up and moved toward the headwaters. During fall (September–November), only six of 12 tagged fish at large were located during 22 sightings. Tagged fish randomly distributed themselves about the reservoir during early fall. By late October–November, they apparently moved towards the confluence of each arm of the reservoir and concentrated there. Three tagged fish were located in the upper Cimarron River arm during 18 sightings, two fish were located in the upper Arkan-

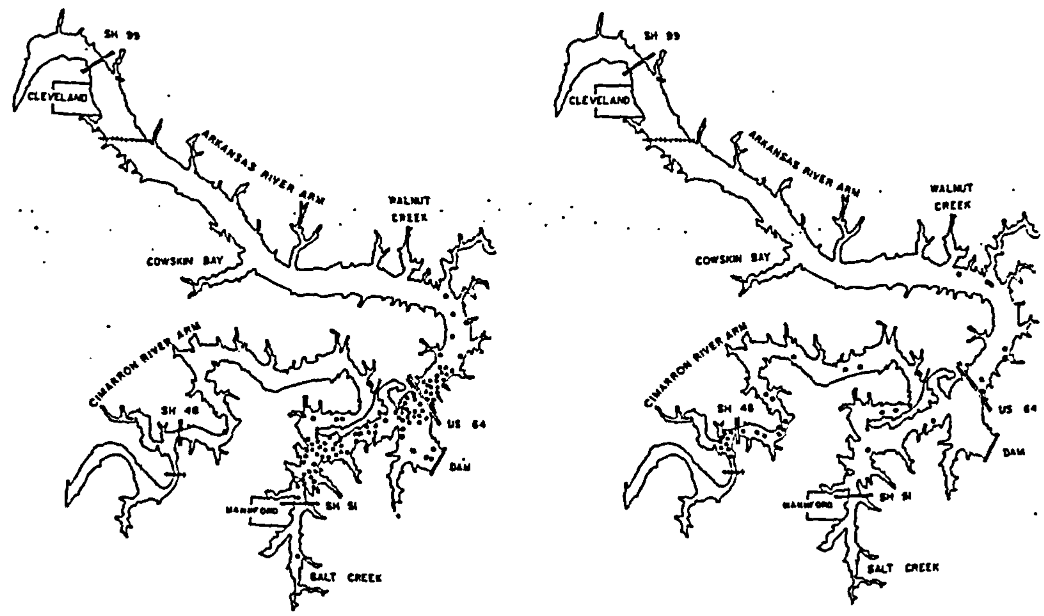

Figure 1. Spring (left) and summer (right) locations of tagged striped bass in Keystone Reservoir.

sas River arm (three sightings), and one tagged fish remained in Salt Creek Cove.

Information on the distribution of fish during the winter (December–February) was restricted to two of the 12 tagged fish at large that were located nine times (Fig. 5). Most sightings were in the headwater region of the Cimarron River arm of the reservoir, where one tagged fish remained for the winter. Standard search procedures for tagged fish were terminated in January 1978 due to heavy ice cover on the reservoir. Tracking of fish No. 21 continued through the ice until February on the upper Cimarron arm. Further work through the ice was precluded by winter drawdowns that produced unstable ice. In March 1978, when ice cover broke up on Keystone Reservoir, tagged fish No. 21 was relocated in the upper Cimarron River arm where apparently it had remained for the winter near its original release point of the previous year.

Discussion

Mature striped bass in Keystone Reservoir exhibit a yearly migratory pattern. Previous research had shown that mature striped bass concentrate at the confluence of the main tributaries of the reservoir in March (Summerfelt and Mosier 1976). These areas of concentration are known as staging areas and are defined as sites where congregations or temporary gatherings of pre-spawning fish occur prior to upstream movement. Tagging operations during the present study took place within or immediately downstream of these staging areas reported in Summerfelt and Mosier (1976). In March subsequent to tagging, striped bass were located in one of the two staging areas on Keystone Reservoir. Concentrations of fish in staging areas in the Arkansas River tributary, as reported by Summerfelt and Mosier (1976), were not located during the present study. Heavy siltation in this area of the Arkansas River prevented passage by boat from the reservoir into the river staging area. Background static caused by physical conditions of the river also interfered and made locating tagged fish nearly impossible in the river. Failure to locate tagged fish in the upper Arkansas River arm in the spring, and again during fall months, probably was caused by our inability to locate tags due to physical conditions in the area rather than a reflection of the usage of the area by striped bass. Only six tagged fish were located in the reservoir during April and May, indicating that most mature fish had already ascended the river systems on their spawning runs. Tagged fish began appearing in the main

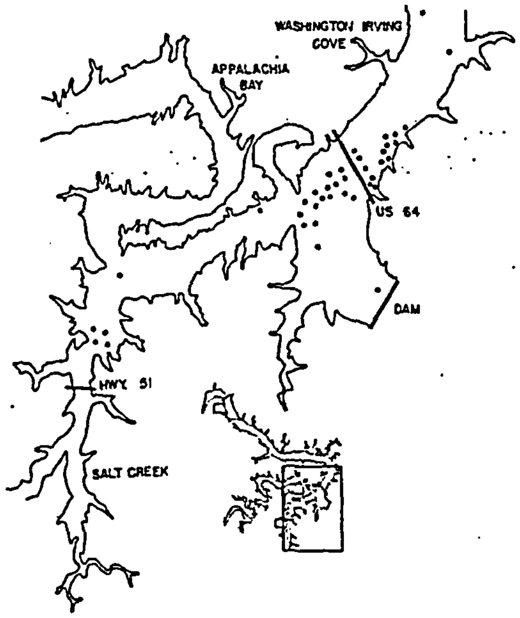

Figure 2. Summer locations (July–August) of striped bass tagged in the Cimarron River arm of Keystone Reservoir.

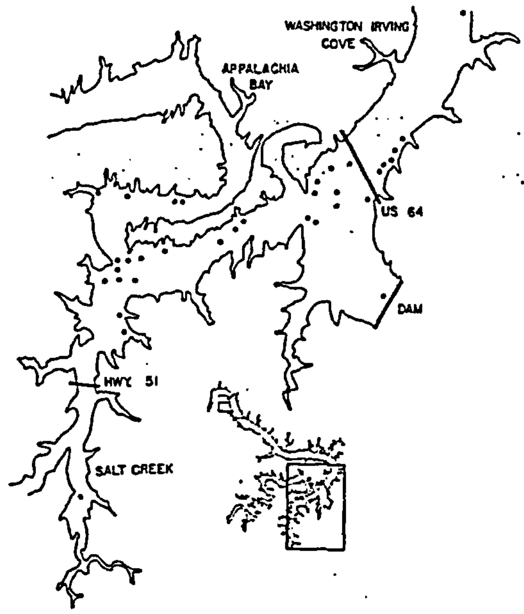

Figure 4. Summer locations (July–August) of striped bass tagged in the Salt Creek area of Keystone Reservoir.

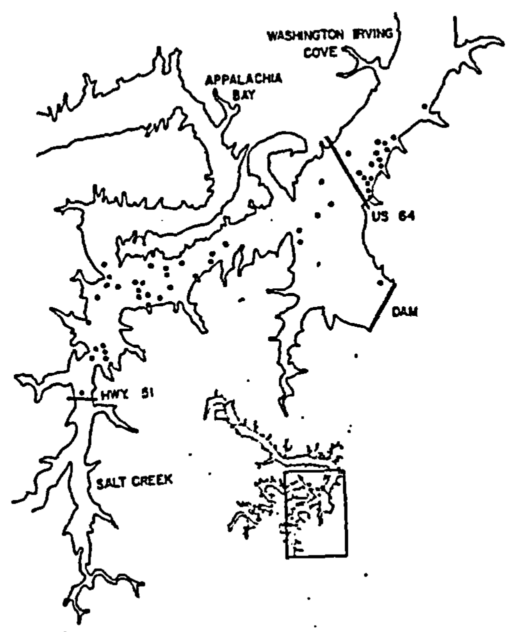

Figure 3. Summer locations (July–August) of striped bass tagged in the Arkansas River arm of Keystone Reservoir.

body of the reservoir early in June and remained concentrated around the confluence of the Arkansas and Cimarron rivers; Salt Creek and the Cimarron River through July and August. During the fall, tagged striped bass migrated back to the staging areas in the upper end of the reservoir where they remained until the spawning run in the spring.

The migratory pattern of striped bass in Keystone Reservoir closely resembles that of anadromous striped bass stocks. In Calhoun's (1952) study of the migratory habits of striped bass in the Sacramento-San Joaquin Delta, fish moved downstream following the spring spawning run into the lower bays and ocean for the summer months. The fish then moved back upstream into the Delta in the fall, where they remained until the spring spawning run. Further studies by Chadwick (1967) and Orsi (1971) revealed a similar pattern, although more extensive summer migrations and a shift of the overwintering area downstream were noted. Massmann and Pacheco (1961), Chapotan and Sykes (1961), Nichols and Miller (1967), and Grant et al. (1969) observed similar seasonal migratory patterns for Chesapeake Bay stocks of striped bass. Clark (1968) also noted a similar migratory pattern for three

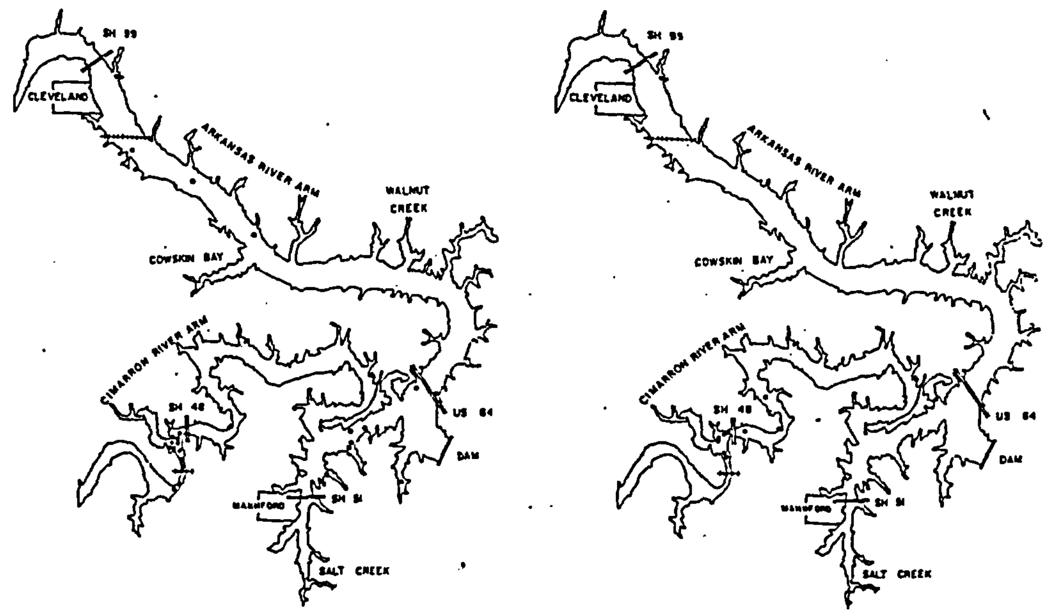

Figure 5. Fall (left) and winter (right) locations of tagged striped bass in Keystone Reservoir.

stocks of Hudson River–Long Island Sound striped bass. The summer distributions of striped bass in Cherokee Reservoir, Tennessee (Waddle et al. 1980; Schaich and Coutant 1980) were similar to those of Keystone Reservoir, with fish concentrated in the lower, deep-water regions of the reservoir in summer. The similarity of seasonal distribution and migratory patterns of anadromous and freshwater populations of striped bass, as shown in the present study, suggests an inherited behavioral pattern with concentration areas, such as staging areas, as part of this migratory pattern.

During their movement towards and while in areas of concentration, striped bass distribute themselves along inundated river and creek channels. Summerfelt and Mosier (1976) reported similar findings for pre-spawning striped bass in Keystone Reservoir. Summer areas of concentration were in the deep-water regions of the reservoir where striped bass continued to distribute themselves along the river channels associated with submerged islands and steep drop-offs from shallow flats.

The presence of preferred summer areas in Keystone Reservoir may be related to water temperature as well as inherited behavior patterns. Coutant and Carroll (1980) found that temperature was a greater influence on habitat selection by striped bass than water depth or light intensity, with the preferred temperature being 22 C. In Cherokee Reservoir, Waddle et al. (1980) found that the summer ranges of striped bass in the lower reservoir corresponded to the presence of springs containing cool, oxygenated water. Fish concentrated in these thermal refuges in order to avoid summer ambient temperatures greater than 27 C. This concept is supported by Dudley et al. (1977) for Savannah River striped bass. After spawning, these fish moved upstream to remain until the following spring. This movement apparently is temperature-related because temperatures in the upper Savannah River are cooler in the summer months than surrounding coastal waters where temperatures reach 26–30 C. Scruggs (1955) found that striped bass in the Cooper River, South Carolina spent the summer months in the upper part of the Cooper River, presumably to avoid excessive summer temperatures. With the nearly homothermous state of Keystone Reservoir, thermal refuges probably do not exist, although the fish did distribute themselves in the deeper limnetic areas of the lower reservoir. The normally homothermous waters in excess of 30 C probably confine striped bass to the deep-water areas of Keystone Reservoir in the summer.

The existence of racial subpopulations of striped bass in Chesapeake Bay, where discrete populations exist in tributary rivers, has been reported by Massmann and Pacheco (1961), Nichols and Miller (1967), Hollis (1967), and Morgan et al. (1973). Clark (1968) found four distinguishable contingents of striped bass in the Long Island Sound and coastal waters of the New York Bight. Raney and de Sylva (1953) discussed racial differences between the Hudson River and Chesapeake Bay stocks, as well as the existence of upstream and downstream populations in the Hudson River. Raney and Woolcott (1954) differentiated endemic races of striped bass along the southeastern Atlantic coast from Albemarle Sound, North Carolina; Santee-Cooper, South Carolina; and the Saint Johns River, Florida. Striped bass introduced into Oklahoma waters were procured from endemic stocks in Virginia, North Carolina, and South Carolina. These introductions of geographical subpopulations and the apparent segregation of the Arkansas River and Cimarron River fish during the spring and summer months suggest the presence of at least two subpopulations in Keystone Reservoir. The Arkansas River is considered to be the primary spawning area for Keystone Reservoir striped bass. Low flows in the Cimarron River are thought to inhibit successful striped bass spawning although successful reproduction was documented in 1973 and 1978–1980 by personnel from the Oklahoma Department of Wildlife Conservation. Periodic spawning success in the Cimarron River may be sufficient to maintain a separate stock of fish in that river.

In summary, the present study helped narrow the existing knowledge gap of freshwater populations of striped bass by: (1) confirming the existence of annual migrations between the reservoir and its tributary streams much like the anadromous stocks from which these freshwater populations originated; (2) determining seasonal concentration areas in the reservoir from which striped bass migrate; (3) proposing that the concentration of stocks is an inherited behavior among both freshwater and anadromous stocks; and (4) proposing the existence of segregated striped bass populations of differing racial qualities in Keystone Reservoir.

References

Calhoun, A. J. 1952. Annual migrations of California striped bass. California Fish and Game 38:391–403.

Chadwick, H. K. 1967. Recent migrations of the Sacramento-San Joaquin striped bass population. Transactions of the American Fisheries Society 96:327–342.

Chapotan, R. B., and J. E. Sykes. 1961. Atlantic coast migration of large striped bass as evidenced by fisheries and tagging. Transactions of the American Fisheries Society 90:13–20.

Clark, J. R. 1968. Seasonal movements of striped bass contingents of Long Island Sound and the New York Bight. Transactions of the American Fisheries Society 97:324–343.

Coutant, C. C., and D. S. Carroll. 1980. Temperatures occupied by ten ultrasonic-tagged striped bass in freshwater lakes. Transactions of the American Fisheries Society 109:195–202.

Dudley, R. G., A. W. Mullis, and J. W. Terrell. 1977. Movements of adult striped bass (*Morone saxatilis*) in the Savannah River, Georgia. Transactions of the American Fisheries Society 106:314–322.

Grant, G. C., V. G. Burrell, Jr., C. E. Richards, and E. B. Joseph. 1969. Preliminary results from striped bass tagging in Virginia, 1968–1969. Proceedings of the Annual Conference Southeastern Association Game and Fish Commissioners 23:558–570.

Hollis, E. H. 1967. Investigation of striped bass in Maryland. Maryland Department of Game and Inland Fisheries, Final Report F-003-R-12, Annapolis, Maryland, USA.

Mansueti, R. J. 1961. Age, growth and movements of the striped bass, *Roccus saxatilis*, taken in size selective fishing gear in Maryland. Chesapeake Science 2:9–36.

Massmann, W. H., and A. L. Pacheco. 1961. Movements of striped bass in Virginia waters of Chesapeake Bay. Chesapeake Science 2:37–44.

Mensinger, G. C. 1970. Observations on the striped bass, *Morone saxatilis*, in Keystone Reservoir, Oklahoma. Proceedings of the Annual Conference Southeastern Association Game and Fish Commissioners 24:447–463.

Moore, C. J., and D. T. Burton. 1975. Movements of striped bass, *Morone saxatilis*, tagged in Maryland waters of Chesapeake Bay. Transactions of the American Fisheries Society 104:703–709.

Morgan, R. P., II, T. S. Y. Koo, and G. E. Krantz. 1973. Electrophoretic determination of populations of the striped bass, *Morone saxatilis*, in the upper Chesapeake Bay. Transactions of the American Fisheries Society 102:31–32.

Nichols, P. R., and R. V. Miller. 1967. Seasonal movements of striped bass, *Roccus saxatilis* (Walbaum), tagged and released in the Potomac River, Maryland, 1959–61. Chesapeake Science 8:102–124.

Orsi, J. J. 1971. The 1965–1967 migrations of the Sacramento-San Joaquin estuary striped bass population. California Fish and Game 57:257–267.

Raney, E. C., and D. P. de Sylva. 1953. Racial investigation of the striped bass, *Roccus saxatilis* (Walbaum). Journal of Wildlife Management 17:495–509.

RANEY, E. C., AND W. S. WOOLCOTT. 1954. Races of striped bass, *Roccus saxatilis* (Walbaum), in Southeastern United States. Proceedings of the Annual Conference Southeastern Association of Fish and Game Commissioners 8:60–64.

SCHAICH, B. A., AND C. C. COUTANT. 1980. A biotelemetry study of spring and summer habitat selection by striped bass in Cherokee Reservoir, Tennessee, 1978. ORNL/TM-7127. Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA.

SCRUGGS, G. D., JR. 1955. A migration study of the Cooper River populations of striped bass, *Roccus saxatilis* (Walbaum). Report in South Carolina Academy of Science, Columbia, South Carolina, USA.

SUMMERFELT, R. C., AND D. MOSIER. 1976. Evaluation of ultrasonic telemetry to track striped bass to their spawning grounds. Final Report, Dingell-Johnson Project F-29-R, Segment 7. Oklahoma Department of Wildlife Conservation, Oklahoma City, Oklahoma, USA.

WADDLE, H. R., C. C. COUTANT, AND J. L. WILSON. 1980. Summer habitat selection by striped bass, *Morone saxatilis*, in Cherokee Reservoir, Tennessee, 1977. ORNL/TM-6927, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA.

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Influence of Water Quality and Season on Habitat Use by Striped Bass in a Large Southwestern Reservoir

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Abstract.—A large, multiyear (1981–1986) gillnetting data set was used to assess patterns of seasonal habitat use by striped bass *Morone saxatilis* in Lake Texoma, Oklahoma–Texas. Large (>2.27 kg), medium (1.36–2.27 kg), and small (<1.36 kg but not including age-0 individuals) fish exhibited different patterns of seasonal abundance in a study area about 40 km uplake from the dam. Large fish were never taken in the study area in June, July, August, or September, or when surface water temperatures exceeded 22°C. Abundance of medium-sized fish was significantly lower during June–September and when temperatures were above 22°C than in other months and at cooler temperatures. Small fish remained abundant in the uplake area all year but were almost never collected at dissolved oxygen concentrations less than 6.0 mg/L in summer. Substantial numbers of small fish were collected at temperatures as high as 29°C, but their catch per unit effort dropped from a mean of 11.8/net at 28°C to 1.9/net at 30°C. Our results supported the thermal niche hypothesis for striped bass, and the response of small striped bass to high temperatures was similar to that reported previously.

Habitat use by striped bass *Morone saxatilis* is highly seasonal in its native marine, estuarine, and riverine environments (Moore and Burton 1975; Dudley et al. 1977). Tagging studies (Chadwick 1967; Clark 1968; Coutant 1985) in both marine and fresh waters have shown various populations of striped bass differ in their annual movements. Some remain largely within freshwater rivers, and others make substantial movements from and to marine waters in distinct seasonal patterns.

Since the 1960s, striped bass have been stocked in more than 100 freshwater reservoirs of the southern USA (Axon and Whitehurst 1985; Matthews 1985), but relatively few studies have been published on seasonal habitat use by striped bass in reservoirs. Information is available on populations in Watts Bar and Cherokee reservoirs, Tennessee (Cheek et al. 1985), Lake Jordan and Millers Ferry Lake, Alabama (Moss 1985), Lake Norman, North Carolina (Siler et al. 1986), and Keystone and Texoma reservoirs, Oklahoma (Combs and Peltz 1982; Summers 1982). In the two Oklahoma reservoirs, large adult striped bass were concentrated downlake near dams in summer (Combs and Peltz 1982; Summers 1982). However, sample sizes in these studies were 16 and 20 fish, respectively, and only large fish were included. Combs and Peltz (1982) located only two individuals in winter, and Summers (1982) did not determine fish locations in winter. Summers (1982) showed that adult striped bass (mean weight, 6.9 kg) were downlake in the main basin from June through October or November. Thereafter, they dispersed and were not relocated in the main basin until the next May. Cheek et al. (1985) and Siler et al. (1986) provided year-round data on seasonality of striped bass habitat use in southeastern reservoirs, but those reservoirs are very different in morphometry and basic water quality characteristics from shallow southwestern reservoirs like Lake Texoma. Only Coutant and Carroll (1980) provided direct information about habitat use by juvenile striped bass other than young of the year in freshwater lakes.

Striped bass were introduced into Lake Texoma from 1965 to 1974 and since have established a self-sustaining reproductive population (Harper and Namminga 1986). Lake Texoma is a large (36,000-hectare), shallow impoundment of the Red and Washita rivers on the Texas–Oklahoma border (Matthews 1984; Matthews et al. 1985). The Red and Washita river arms of Lake Texoma (Figure 1) have a maximum depth of about 18 m, and water quality is influenced strongly by inflows from the river mainstreams (Matthews 1984). The two arms converge to form a deep (22–26 m) main basin downlake near the dam (Figure 1). This downlake basin strongly stratifies in most years (Matthews et al. 1985; Matthews and Hill 1988) so that warm surface waters overlie an anoxic hy-

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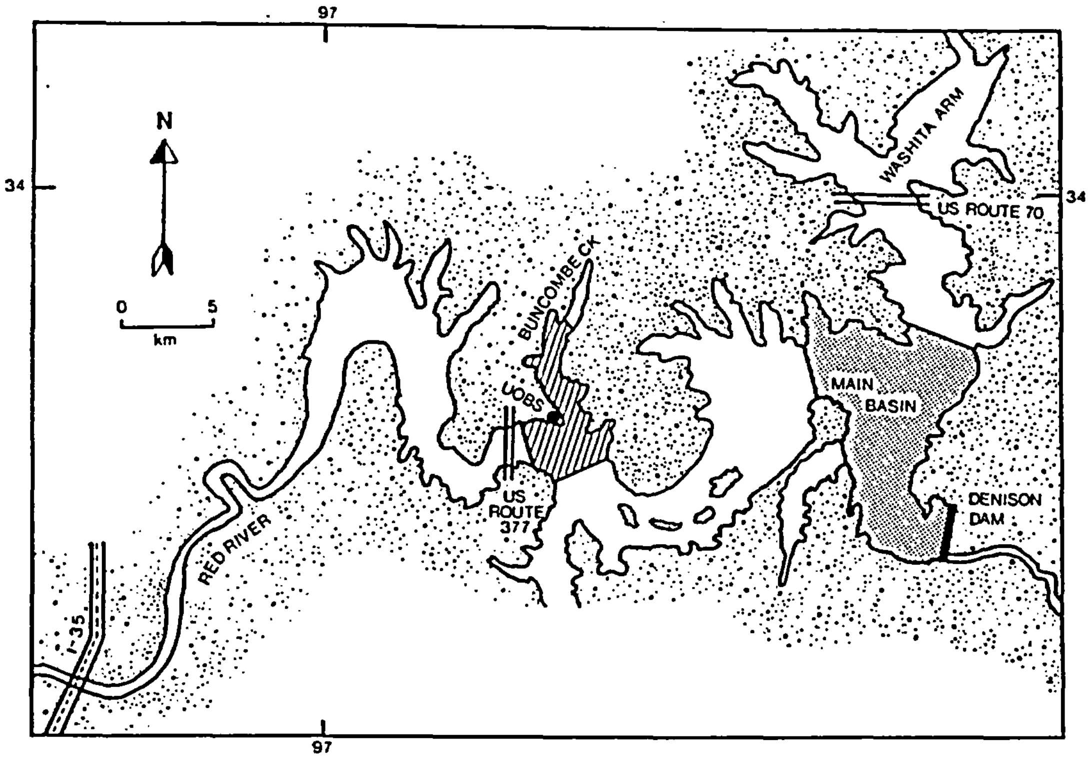

FIGURE 1.—Map of the study area, Lake Texoma, Oklahoma–Texas. Gillnetting occurred in crosshatched area, 1981–1986. Stippled area (main basin) was the downlake area studied by Summers (1982). UOBS = University of Oklahoma Biological Station; CK = creek.

polimnion. We documented the seasonality of occurrence of striped bass of various sizes and measured the water quality in a study area about 40 km uplake from the dam in the Red River arm of Lake Texoma (Figure 1). Our research had three goals. First, we wanted to test for statistically significant seasonality of striped bass abundance in the uplake area. Second, we wanted to evaluate patterns in water quality and habitat use by Lake Texoma striped bass (yearlings to adults) from the perspective of Coutant's (1985) temperature–oxygen hypothesis, which states that striped bass population size is limited by the summer restriction of suitable adult habitat (i.e., water temperature at 18–25°C and dissolved oxygen levels at 2–3 mg/L). Third, we wanted to combine our observed patterns with information from Summers (1982) to infer seasonal patterns in habitat use by large striped bass in uplake and downlake parts of the large reservoir.

Methods

In the study area, the reservoir is 2–3 km wide and has a maximum depth of about 18 m at normal power pool level (Matthews 1984). Fish were collected by gillnetting from April 1981 through October 1986. All collections were made with experimental gill nets 61 m long × 1.83 m deep. Each net had eight successive 7.62-m panels of monofilament mesh with bar measures of 19, 25, 38, 51, 64, 76, 89, and 102 mm. This net design was similar to the pattern recommended by Hubert (1983) to reduce size selectivity. As reviewed by Hubert (1983), the optimum girth of fish to be caught in a given mesh size is about 1.25 times the mesh perimeter. Our net design thus provided for optimal capture girths ranging form 96 to 512 mm. The nets efficiently captured fish whose girths were as much as 20% above or below the optimum, so there was overlap in the size of fish caught by different mesh sizes. A study of over 5,000 striped bass by Trent and Hassler (1968) yielded a regression equation that estimated mean fork lengths (FL) of striped bass captured in gill nets of various mesh sizes. According to this equation, our mesh-size range should result in mean capture lengths of 187–750 mm FL for striped bass. Therefore, whether Hubert's (1983) or Trent and Hassler's (1968) guidelines are used, the mesh sizes we used seemed to be efficient across the range of fish sizes that we studied. Passive gear, such as gill nets, give reasonable estimates of relative abundance and have been used in studies of migratory patterns or distribution of fish within a body of water (Hubert 1983).

Nets typically were set near midday and retrieved between 0900 and 1200 hours the next day. In all months, from April 1981 through July 1984 (except January 1984, for logistical reasons), six gill nets were set at fixed locations either twice (28 months) or once monthly (13 months). On each date, one net was set about 0.5 m below the surface and one was set on the bottom at each of three locations: the main channel of the reservoir (14–18 m deep), 1 km south of the University of Oklahoma Biological Station; the main channel of a major tributary, Buncombe Creek, which forms a north–south bay (8–10 m deep and 1 km wide) northeast of the station; and a shallow cove (3–4 m deep) known as Mayfield Flats (Patten 1975), which is immediately west of the station on the north shore of Lake Texoma (Figure 1). Catch per unit effort was defined as catch of fish in one net, set overnight (one net-night). There were 402 net-nights on 67 different collecting dates in 1981–1984. No collections were made from August 1984 through February 1985. From March 1985 through October 1986, gill nets were set overnight on 20 dates in 15 different months; all months but November were sampled at least once. In 1985–1986, three to five experimental nets were set near the surface in Buncombe Creek and Mayfield Flats on each collecting date, for a total of 82 net-nights. The midchannel site was omitted during 1985 and 1986.

All striped bass collected in gill nets were measured and weighed. For this analysis, three size-classes were considered: small (<1.36 kg), medium (1.36–2.27 kg), and large (>2.27 kg). We intentionally avoided the use of terms, such as juvenile, subadult, or adult, that imply information about sexual maturity because it was not feasible to examine the gonads of all fish in this study. Because of the mesh sizes used, most of the small fish in this study were 150 mm or more in total length and were at least yearling (age-1) fish. Our small category, therefore, does not include young of the year.

Analyses of collection data were by the Kruskal–Wallis nonparametric analysis of variance (Siegel 1956) because data were not normally distributed and were not normalized by log transformation.

On each collection date, temperature was measured near the surface in the study area. Surface temperatures at our fixed netting locations rarely differed more than 1°C on a given date. Thus, for interpretation of general patterns, our report is based on the average surface temperature within the study area (nearest whole degree) on each collection date. In summer 1982 and 1983, a Hydrolab Surveyor II (Hydrolab Corporation, Austin, Texas) was used to measure vertical profiles of temperature and oxygen from surface to bottom at each gillnetting location. Throughout summer 1982 and 1983, vertical profiles of temperature and oxygen also were documented in the downlake deep basin, as reported by Matthews et al. (1985) and Matthews and Hill (1988).

Results

Altogether, 3,813 striped bass were collected, including 3,428 small fish, 270 medium individuals, and 115 large individuals. There were no significant differences among years for mean catch per unit effort for any of the three size classes (H = 3.43, 7.03, and 3.23 and P = 0.63, 0.23, and 0.66 for small, medium, and large size-classes, respectively). Therefore, within each size-class, data were pooled across years in subsequent analyses.

Gill-net catches of all sizes of striped bass decreased in the warmest months (June–September) of all years (Figure 2). No large striped bass were taken in the study area in June–September of any study year (198 net-nights; Figure 2A). Although substantial numbers of large striped bass frequently were collected during October–May, the catch of large individuals was highly variable during those months.

Medium-sized fish also had a marked annual pattern of abundance in gill-net collections (Figure 2B). Mean catch per unit effort of medium striped bass in the study area was significantly lower in June–September than in October–May across all years (H = 19.20, df = 1, $P < 0.001$).

The annual pattern of abundance of small striped bass was similar to that of medium and large fish, but was less pronounced. Mean catch per unit effort of small fish (Figure 2C) was significantly lower in June–September than in the rest of the year (H = 19.62, df = 1, $P < 0.001$), but despite the statistical strength of the pattern (due in part to the larger sample size for small fish), substantial numbers of small fish were caught in gill nets in the study area in all months (Figure 2C). Mean catch per unit effort of small striped bass was 7.2 in June, 3.3 in July, 2.8 in August, and 5.5 in September for all years, but a mean catch of 9.0

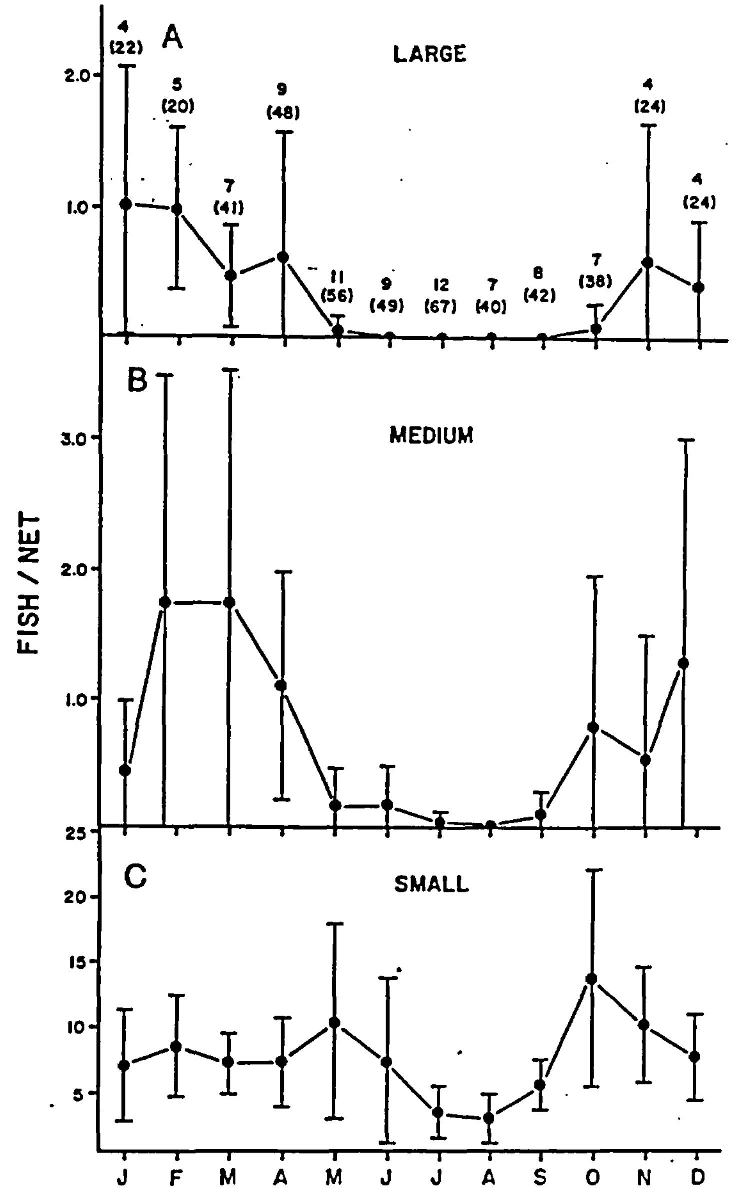

FIGURE 2.—Catch per unit effort (fish caught per single gill net fished overnight) for all months of all years 1981–1986 for large (A), medium (B), and small (C) striped bass in the uplake study area on Lake Texoma. The number of collecting dates in each month and the number of net-nights (in parentheses) are given in A. Error bars represent ±SD about the mean.

individuals per net-night was obtained in the other 8 months of all years (Figure 2C).

Large striped bass were never collected during our study when surface temperature was higher than 22°C (Figure 3A). At temperatures above 22°C, medium striped bass were collected (Figure 3B) on 13 of 47 netting dates. Mean catch per unit effort for medium-sized striped bass was significantly less above 22°C than at lower temperatures ($H = 25.26$, df = 1, $P < 0.001$). Small striped bass were caught in large numbers at most ambient temperatures, and as many as 10–20 individuals were caught per net when surface temperatures exceeded 22°C (Figure 3C). The mean number of small striped bass per net was 5.5 when the temperature was above 22°C and 9.2 at or below 22°C.

Although this difference was highly significant ($H = 15.42$, df = 1, $P < 0.001$), many small striped bass remained in the study area at temperatures well above 22°C.

Small striped bass were collected in only 3 of 27 nets set where the dissolved oxygen concentration was less than 6.0 mg/L in summer 1982 and 1983 (Figure 4). Small striped bass were collected in 37 of 50 nets set where dissolved oxygen equalled or exceeded 6.0 mg/L. Many small striped bass were taken in gill nets at temperatures from 22 to 30°C, or higher, in summer 1982 and 1983, but there was a substantial decrease in catch per unit effort from 11.8 small fish per net at 28°C to 3.0 at 29°C and 1.9 at 30°C. Coutant (1985) and Cox and Coutant (1981) suggested a thermal niche for juvenile striped bass with an upper limit at about 26°C. We therefore tested whether the catch of small fish decreased when temperatures at the location of gill nets were 27°C or higher, as suggested by the thermal squeeze hypothesis (Coutant 1985). Significantly more small striped bass were collected per net at temperatures less than 27°C (mean = 6.5) than at 27°C or higher (mean = 3.8) ($H = 3.84$, df = 1, $P < 0.05$).

To evaluate the response of the small fish to temperature in more detail, we examined the effects of four approximately equal intervals of temperature, 22.0–24.9, 25.0–26.9, 27.0–29.0, and over 29°C, all with dissolved oxygen concentrations above 6.0 mg/L. At temperatures from 22 to 29°C (and with adequate oxygen available), small striped bass were relatively abundant, but above 29°C, the catch of fish per net dropped markedly. Mean catches per unit effort for small striped bass for the four temperature ranges were 7.0, 6.1, 6.5, and 1.9, respectively; these differences were significant at $P = 0.05$ ($H = 7.69$, df = 3).

Discussion

From 1981 to 1986, there was strong seasonality in the catch of striped bass in gill nets 40 km uplake from the dam in the Red River arm of Lake Texoma. Large fish were completely absent from all collections from June through September, and catch per net of medium-sized fish was significantly lower during those months. Seasonal patterns of abundance were strongly linked to a threshold temperature: large fish were never collected when uplake surface temperatures exceeded 22°C, and medium-sized fish showed a highly significant decline in abundance under those conditions. Catch of small striped bass decreased in the uplake area in June–September and when water

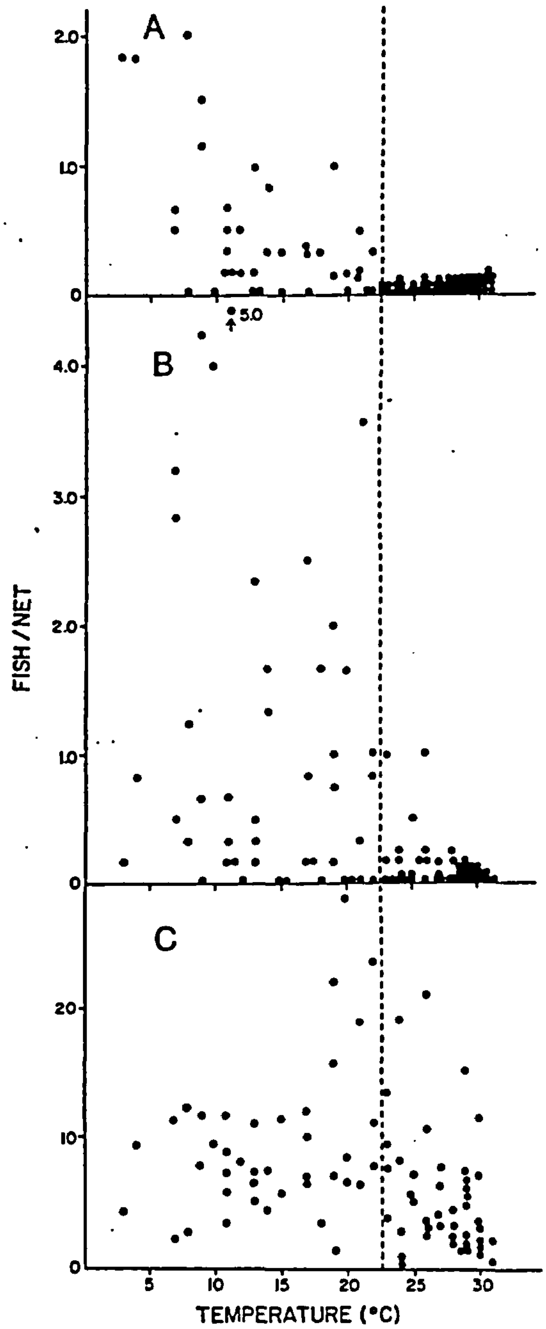

FIGURE 3.—Catch per unit effort for large (A), medium (B), and small (C) striped bass at temperatures indicated for all years 1981–1986 in the uplake study area on Lake Texoma. The vertical dashed line is at 22°C. No large striped bass were taken at temperatures above 22°C; points to the right of the dashed line in A represent the number of collections (nets) in which catch of large striped bass was zero.

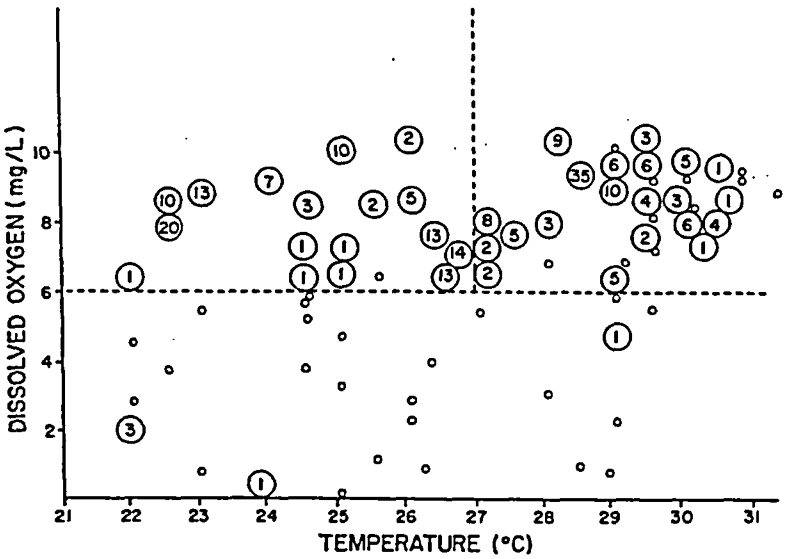

FIGURE 4.—Catch of small striped bass per gill net set in summer 1981 and 1982 in the uplake study area on Lake Texoma. Each collection is plotted on horizontal and vertical coordinates that represent temperature and dissolved oxygen concentration, respectively, which were measured at the location and depth of the net. The number of small striped bass caught in each net is indicated by the number within the circle. Small open circles represent nets in which no striped bass were caught.

temperature exceeded 22°C, but substantial numbers of these individuals remained active in the uplake area all summer. Only at temperatures above 29°C was there a marked reduction in catch of small fish relative to catch at other summer temperatures.

Absence from collections cannot prove unequivocally that a species of size-class is absent from an area. However, our data, combined with that of Summers (1982), strongly suggest that, in hot summer months, large striped bass vacate the uplake area and move downlake to the coolest oxygenated water available. This conclusion is consistent with Coutant's (1985) temperature–oxygen hypothesis for striped bass behavior and supports the generalization of Cheek et al. (1985) that, in a wide variety of reservoir types, large striped bass move to cool refugia in summer, whether these refugia are uplake (due to cool inflows) or downlake (in deep water). In concert with Coutant's (1985) suggestion that 25°C is about the upper thermal limit for large striped bass, our water quality data for summer 1982 and 1983 suggested that large individuals migrated from uplake waters to occupy downlake habitats just above the anoxic hypolimnion, as inferred by Matthews et al. (1985). For example, on 16 August 1982, when we found large numbers of fish concentrated downlake just above the anoxic hypolimnion (Matthews et al. 1985), none of the water downlake was as cool as 25°C. However, in that part of the reservoir at a depth of about 12 m, water was 27.8°C with 4 mg/L dissolved oxygen. On the same date, oxygen and temperature profiles in the uplake gillnetting area showed that all of the water column with more than 3 mg/L dissolved oxygen had temperatures ranging from 29 to 31.5°C. On all of our late-summer water quality profile and collecting dates in 1982 and 1983, a similar pattern prevailed: large striped bass would have found adequately oxygenated water closer to 25°C in the downlake than in the uplake areas.

Although we cannot rigorously describe all migration patterns of adult striped bass in Lake Texoma based on our uplake netting data, our physicochemical measurements throughout the lake, and Summers' (1982) data, all available evidence suggests that seasonal locations of large striped bass in Lake Texoma are consistent with predictions of Coutant's (1985) temperature–oxygen squeeze hypothesis. Our only point of departure from this hypothesis is that, as we have indicated previously (Matthews et al. 1985), the population of adults in Lake Texoma seems able to tolerate temperatures somewhat warmer than 25°C without high mortality (Matthews 1985). Similarly, Zale et al. (1988) found that adult striped bass in Keystone Reservoir (Oklahoma) tolerate temperatures as high as 29°C. This is no way implies, however, that adults in Lake Texoma somehow defy temperature as a factor that influences habitat use seasonally—adults seem instead to be sharply influenced by intolerably high temperatures throughout the water column in uplake areas, which they abandon in summer.

The finding that a few medium-sized and many small striped bass remain active in the uplake area in the summer is also consistent with Coutant's (1985) hypothesis that smaller striped bass have greater tolerance of high temperatures than adults. Our results correspond closely to predictions about habitat use by small striped bass that can be made from Coutant's thermal niche hypothesis. Figure 2 of Cox and Coutant (1981) shows growth rates of juvenile striped bass over a wide range of constant temperatures. In their study, when fish were fed to satiation, maximum growth occurred at about 26°C. The percent of maximum growth was high (about 93 and 81% of maximum) at 23.5 and 28°C but dropped sharply to 50% of maximum at about 30°C. In the field, juvenile striped bass occupied temperatures warmer than those selected by adults. For the many small fish collected in our study at 22°C and above, our results and the findings of Cox and Coutant (1981) are highly complementary: at the same temperatures (about 29–30°C) at which growth declined in the laboratory, we found a marked reduction in the catch of similar-sized fish in the field.

All size-classes of striped bass in our study demonstrated seasonal patterns of habitat use and responses to physicochemical conditions that were predictable from the temperature–oxygen hypothesis advanced by Coutant and his coworkers. Both temperature and oxygen seem to be important variables that influence the distribution of essentially all sizes of striped bass in Lake Texoma, and the reduced catch of small striped bass at temperatures above 29°C is evidence of an underlying physiological casualty, as suggested by Cox and Coutant (1981). Fishery managers should take into account reservoir-wide profiles of physicochemical conditions and the responses of different size-classes of striped bass to those conditions when estimating the total habitat available to striped bass populations. Seasonality in habitat use by striped bass may also have a profound influence on their potential interactions with other species.

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References

Axon, J. R., and D. K. Whitehurst. 1985. Striped bass management in lakes with emphasis on management problems. Transactions of the American Fisheries Society 114:8–11.

Chadwick, H. K. 1967. Recent migrations of the Sacramento–San Joaquin River striped bass populations. Transactions of the American Fisheries Society 96:327–342.

Cheek, T. E., J. M. Van Den Avyle, and C. C. Coutant. 1985. Influences of water quality on distribution of striped bass in a Tennessee River impoundment. Transactions of the American Fisheries Society 114: 67–76.

Clark, J. R. 1968. Seasonal movements of striped bass contingents of Long Island Sound and the New York Bight. Transactions of the American Fisheries Society 97:320–343.

Combs, D. L., and L. R. Peltz. 1982. Seasonal distribution of striped bass in Keystone Reservoir, Oklahoma. North American Journal of Fisheries Management 2:66–73.

Coutant, C. C. 1985. Striped bass, temperature, and dissolved oxygen: a speculative hypothesis for environmental risks. Transactions of the American Fisheries Society 114:31–61.

Coutant, C. C., and D. S. Carroll. 1980. Temperatures occupied by ten ultrasonic-tagged striped bass in freshwater lakes. Transactions of the American Fisheries Society 109:195–202.

Cox, D. K., and C. C. Coutant. 1981. Growth dynamics of juvenile striped bass as functions of temperature and ration. Transactions of the American Fisheries Society 110:226–238.

Dudley, R. G., A. W. Mullis, and J. W. Terrell. 1977. Movements of adult striped bass (*Morone saxatilis*) in the Savannah River, Georgia. Transactions of the American Fisheries Society 106:314–322.

Harper, J. L., and H. E. Namminga. 1986. Fish population trends in Texoma Reservoir following establishment of striped bass. Pages 122–136 *in* G. E. Hall and M. J. Van Den Avyle, editors. Reservoir fisheries management: strategies for the 80's. American Fisheries Society, Southern Division, Reservoir Committee, Bethesda, Maryland.

Hubert, W. A. 1983. Passive capture techniques. Pages 95–111 *in* L. A. Nielsen and D. L. Johnson, editors. Fisheries techniques. American Fisheries Society, Bethesda, Maryland.

Matthews, W. J. 1984. Influence of turbid inflows on vertical distribution of larval shad and freshwater drum. Transactions of the American Fisheries Society 113:192–198.

Matthews, W. J. 1985. Summer mortality of striped bass in reservoirs of the United States. Transactions of the American Fisheries Society 114:62–66.

Matthews, W. J., and L. G. Hill. 1988. Physical and chemical profiles in Lake Texoma (Oklahoma–Texas) in summer 1982 and 1983. Proceedings of the Oklahoma Academy of Science 68:33–38.

Matthews, W. J., L. G. Hill, and S. M. Schellhaass. 1985. Depth distribution of striped bass and other fish in Lake Texoma (Oklahoma–Texas) during summer stratification. Transactions of the American Fisheries Society 114:84–91.

Moore, C. J., and D. T. Burton. 1975. Movements of striped bass, *Morone saxatilis*, tagged in Maryland waters of Chesapeake Bay. Transactions of the American Fisheries Society 104:703–709.

Moss, J. L. 1985. Summer selection of thermal refuges by striped bass in Alabama reservoirs and tailwaters. Transactions of the American Fisheries Society 114:77–83.

Patten, B. C. 1975. A reservoir cove ecosystem model. Transactions of the American Fisheries Society 104: 596–619.

Siegel, S. 1956. Nonparametric statistics for the behavioral sciences. McGraw-Hill, New York.

Siler, J. R., W. J. Foris, and M. C. McInerny. 1986. Spatial heterogeneity in fish paramenters within a reservoir. Pages 122–136 *in* G. E. Hall and M. J. Van Den Avyle, editors. Reservoir fisheries management: strategies for the 80's. American Fisheries Society, Southern Division, Reservoir Committee, Bethesda, Maryland.

Summers, G. L. 1982. Texoma striped bass biotelemetry. Oklahoma Department of Wildlife Conservation, Federal Aid in Fish Restoration Project F-29-R, Final Report, Oklahoma City.

Trent, L., and W. W. Hassler. 1968. Gill net selection, migration, size and age composition, sex ratio, harvest efficiency, and management of striped bass in the Roanoke River, North Carolina. Chesapeake Science 9:217–232.

Zale, A. V., R. L. Lochmiller, and J. D. Wiechman. 1988. Analysis of the suitability of Keystone Reservoir, Oklahoma, for habitation by adult striped bass. Oklahoma Department of Wildlife Conservation, Federal Aid in Fish Restoration Project F-41-R, Final Report, Oklahoma City.

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Summer Selection of Thermal Refuges by Striped Bass in Alabama Reservoirs and Tailwaters

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Abstract

Adult and subadult striped bass *Morone saxatilis* began concentrating in two small spring-fed tributaries of the Alabama River in early June as ambient river temperatures approached 27 C. Fish collected from summer refuges had lower condition factors than those collected during April through May. Six striped bass (2.7–5.9 kg) equipped with ultrasonic and radiotelemetry transmitters tended to seek cool-water refuges (22–26 C) in reservoirs during summer, but they tolerated temperatures 5–6 C higher during excursions of several hours from or between refuges.

Recent studies have indicated that striped bass *Morone saxatilis* may react to the summer temperatures found in many southern reservoirs with changes in behavior, movement, and habitat preference (Dudley et al. 1977; Coutant and Carroll 1980). Summer die-offs of adult striped bass in reservoirs have been reported informally by managers in Kentucky, Tennessee, South Carolina, Mississippi, and Louisiana (see also Matthews 1985, this issue). It is suspected that these mortalities may result from combinations of high water temperatures and low dissolved-oxygen concentrations in stratified reservoirs that greatly constrict the amount of habitat suitable for striped bass. Although conspicuous die-offs of striped bass have not been documented in Alabama, their occurrence elsewhere has generated concern about the survival of this species in eutrophic, shallow Alabama reservoirs where they have been stocked. Low harvest rates of larger fish by anglers, sampling difficulties by agency personnel, and relatively poor condition of adults in summer indicates that striped bass may be under stress in these reservoirs. This prompted a study of the importance of thermal refuges to striped bass in Alabama impoundments, the subject of this paper.

Striped bass populations existed in Alabama rivers before dam construction began. They consisted of anadromous stocks that made upstream spawning runs from March through May. The reservoirs created fisheries for striped bass; however, populations declined because stocks were overfished and upstream spawning migrations were blocked by dams. Striped bass no longer reproduce in mainstream reservoirs. Because fishing demand for this species remains high and because striped bass help to control gizzard shad *Dorosoma cepedianum* in reservoirs, the Alabama Game and Fish Division stock 6–8-week-old striped bass into the state's public waters each year.

The objectives of this study were (1) to determine if striped bass in Alabama use thermal refuges; (2) to document changes in condition of striped bass found in refuges; (3) to determine the location and movement patterns of striped bass equipped with transmitters during summer; and (4) to determine water quality of thermal refuges with striped bass concentrations.

Study Sites

Lake Jordan is a narrow, 2,792 hectare reservoir on the Coosa River in central Alabama (Fig. 1). It reaches depths of 28 m near Jordan Dam and is highly eutrophic. Its summer stratification pattern is somewhat atypical because of upstream hydroelectric generation. During warm summer periods, water temperature may vary only 1–3 C from surface to bottom, but dissolved-oxygen concentrations drop rapidly from near saturation in the upper 4 m to less than 3 mg/liter at a depth of 6–8 m. Striped bass were first introduced into this reservoir in 1969 and age-0 juveniles have been stocked annually since then at the rate of 18 fish/hectare.

Millers Ferry Reservoir is a narrow, eutrophic 8,903 hectare impoundment between Claiborne and Jones Bluff reservoirs in south-central Alabama (Fig. 1). Discharges from hydroelectric op-

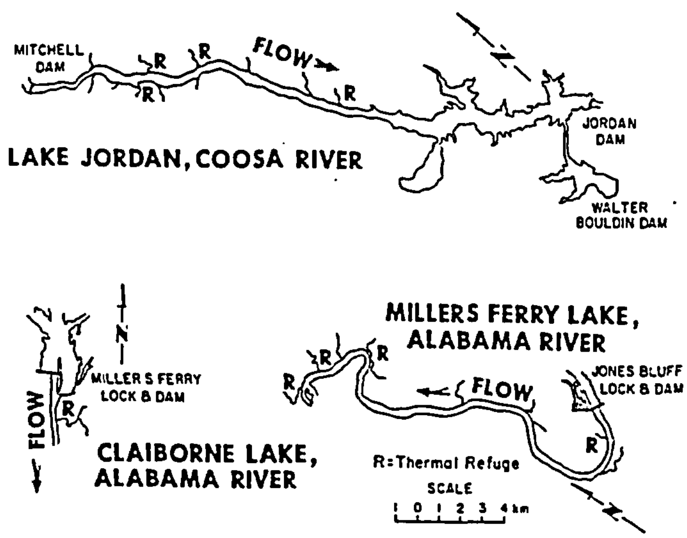

FIGURE 1.—*Study areas on three Alabama reservoirs showing known thermal refuge sites (R). Millers Ferry Lock and Dam separates Millers Ferry Lake (upstream) from Claiborne Lake.*

erations keep summer temperatures essentially isothermal downstream of Jones Bluff Dam. The reservoir has been stocked annually with age-0 striped bass at an average rate of 7.3 fish/hectare since 1973. Several thermal refuges used by adult and subadult striped bass have been identified within and below this reservoir.

Thermal refuges are typically regions of cool (21–25 C), oxygenated (≥5 mg/liter) waters created by underwater springs or spring-fed creeks, or that occur in deep oligotrophic impoundments (Coutant and Carroll 1980; Schaich and Coutant 1980). The thermal refuges described in this study were spring-fed tributaries flowing into each reservoir.

Methods

Routine sampling for striped bass in reservoirs during summer months by agency personnel was unsuccessful until June 1979 when adult striped bass were discovered concentrating in two spring-fed tributaries along the Alabama River. One area was 0.6 km below Millers Ferry Dam and the other was 0.6 km below Jones Bluff Dam. Further investigation revealed that these two sites had water temperatures 5–8 C lower and dissolved oxygen concentrations 1–6 mg/liter higher than comparable readings taken in midreservoir. These areas had similar characteristics to thermal refuges described in other studies (Coutant and Carroll 1980; Schaich and Coutant 1980; Cheek et al. 1985, this issue). A project was begun to study this phenomenon and to make some observations on striped bass using these refuges.

Striped bass were collected from June 1979 to September 1981 with electrofishing gear from two thermal refuges on the Alabama River. Fish were tagged with numbered Floy spaghetti tags inserted into the intramuscular region below the soft dorsal fin with a Dennison tagging gun. Refuges were sampled biweekly to determine the frequency of recapture.

During the summers of 1981 and 1982 striped bass from these two refuges were sampled with electrofishing equipment and measured for condition factors ($K = 10^5 \cdot \text{weight/length}^3$). Condition factors also were calculated for striped bass collected on the Alabama River during 1982 spring brood collections.

Data were subjected to analysis of covariance (Snedecor and Cochran 1967) and linear regression analysis (Steel and Torrie 1960). Probabilities were determined with an F-test at the 0.05 level of significance.

Telemetry Studies

Striped bass collected during the 2-year telemetry study were captured from the tailwaters below Jones Bluff and Millers Ferry Dam on the Alabama River. Fish were collected between June and September with electrofishing gear consisting of a 5.2 m fiberglass boat with boom mounted electrodes. A Smith-Root electrofisher (VI-A) delivering 1,000 volts in pulsed direct current from a 5,000 watt generator was the most effective way of collecting adult striped bass in good condition. Captured striped bass were immediately netted and placed in a holding tank on board the boat where they were anesthetized with a mild quinaldine solution. Total length in millimeters and weight in grams were recorded from most fish. Large fish were preferred because Winter et al. (1978) suggested transmitter weight should not exceed 1.25% of the fish's weight. Fish were allowed to recover and regain equilibrium before release.

Striped bass movements were monitored daily for the first few days following transmitter attachment. As movement patterns became established positions were monitored on a biweekly basis. Search procedures began when a tagged fish was not relocated at its last recorded position and continued until the specimen was found or until the entire study area was checked.

The first phase of the telemetry study began on Millers Ferry Reservoir in 1980 with two types of ultrasonic transmitters. The Smith-Root SR-69-A had an advertised transmitting time of 8 weeks, a range of 2 to 5 km and different pulse rates to permit individual fish identification. The transmitter weighed approximately 49 g. Bayshore Systems T-3T series tags incorporated a thermistor whose pulse rate varies with water temperature. They had an advertised transmission time of 6–8 weeks, a range of about 825 m, and a weight of approximately 24 g. Various transmitting frequencies were used to identify individuals. A Smith-Root TA-60 Receiver and SR-70-H Hydrophone were used to track striped bass equipped with ultrasonic transmitters.

After fish were collected and anesthetized, ultrasonic transmitters were attached externally as described by Waddle et al. (1980). The transmitter first was equipped with a section of 1 mm diameter stainless steel wire about 20 cm long secured in place by rubber castrator bands. Two 14-gauge hypodermic needles then were inserted through the dorsal musculature of the fish about 5 cm apart, one just below the anterior bass of the spiny dorsal fin and the other below the posterior portion. Small sections of plastic tubing were secured on the sides of each needle to prevent the steel wire from cutting the tissue at entry and exit sites. The ends of the wire on the transmitter body were pushed through each needle, the needles were removed, the transmitter was pulled snug to the fish's body, and the leads were twisted together and trimmed. The procedure took 5–7 minutes to complete.

The second and final phase of the telemetry study was completed on Lake Jordan in June of 1981. Because we were unable to collect resident striped bass from Lake Jordan, transmitter-equipped fish from the Alabama River were transported to the study site and released. We felt justified in using nonresident fish in Lake Jordan because movement of the tagged fish was desirable, and the study was not designed to monitor home range or homing characteristics. All the striped bass used in the Lake Jordan study were equipped with radiotelemetry transmitters to take advantage of aerial tracking capabilities and longer range. Radiotelemetry transmitters were manufactured by Wildlife Materials, Incorporated. The HMPI-2100 and HMPTT-1000 transmitters had an advertised transmission range of 880 m and a life of approximately 1 year. The HMPTT-1000 series tags had an external thermistor that indicated water temperature via pulse rate. The transmitter frequencies differed, allowing individual identification. A Smith-Root RF-40 tracking receiver was used to track fish movement.

All radio transmitters except one were attached by surgical procedures similar to those described by Summerfelt and Mosier (1976) and Dudley et al. (1977). The fish were anesthetized and a 3-cm medial incision was made along the abdomen parallel to the ventral midline and anterior to the vent. The tag was inserted in a lateral position and the incision was closed with Deknatel II Green Ploydek General Closure (U.S.P.) tied in 5 to 8 interrupted surgeons' stitches. The procedure required about 8 minutes to complete.

Results

Of 438 striped bass tagged in two thermal refuges along the Alabama River from 1979 through 1981, 21 were recaptured in the same two sites in 1980 and 6 in 1981. The average number of striped bass collected in refuge sites per sample trip was 18.3.

Summer habitat selection of transmitter-equipped striped bass in Millers Ferry Reservoir (1980) and Lake Jordan (1981) indicated that they tended to seek cool, spring-fed tributaries

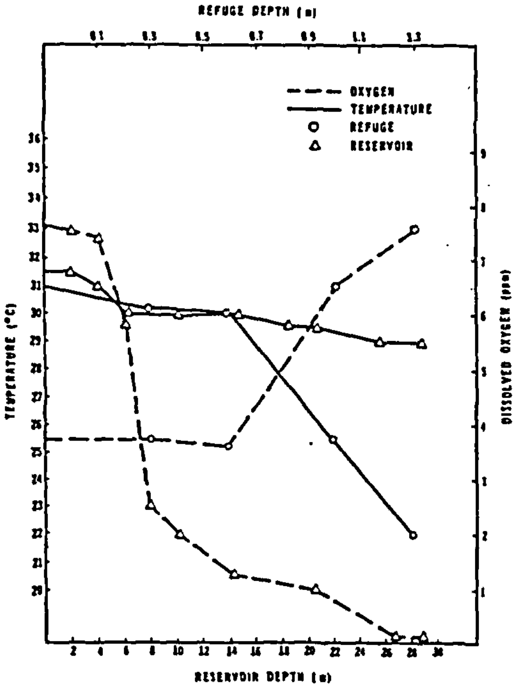

FIGURE 2.—*Midsummer oxygen and temperature profiles typical of study reservoirs and thermal refuges.*

previously described as thermal refuges. The existence and nature of thermal refuges has been discussed in other studies conducted in the southeast (Schaich and Coutant 1980; Waddle et al. 1980; Cheek et al. 1985). These areas typically have cool oxygenated inflows that are preferred by adult striped bass during summer months from June through September when reservoir temperatures are highest. Midsummer oxygen and temperature profiles typical of study reservoirs and thermal refuges are presented in Fig. 2 for comparison.

Condition Factors

Condition factors of striped bass collected from thermal refuges in midsummer were lower than those of fish collected in early spring. Average condition of refuge fish ranged from 1.03 to 1.25, while striped bass collected during April–May 1982 ranged from 1.37 to 1.63 (Table 1). The seasonal differences were significant (*F*-test; $P \leq 0.05$) for each size category. Within each refuge, striped bass in the smallest size group had higher average condition factors than the fish in larger size categories, suggesting that the larger fish may be subject to greater stress. Among fish larger than 450 mm, condition was lower below Jones Bluff Dam than below Millers Ferry Dam but not significantly so. No trends in condition could be detected during the June through September sampling at either refuge, which suggests the fish continued to feed during this period.

Telemetry

Tagged striped bass used in this study ranged from 610 to 826 mm in total length and weighed 2.7 to 7.1 kg. Twenty-one striped bass were equipped with transmitters; however, 10 died within 48 hours or were never relocated following their release. Five fish were tracked in Millers Ferry Reservoir during the summer of 1980 and 6 fish in Lake Jordan during 1981. Two fish from Millers Ferry Reservoir and three from Lake Jordan showed little movement and are omitted from this discussion.

Millers Ferry Reservoir

The three striped bass tracked in Millers Ferry Reservoir bore external ultrasonic transmitters with thermistors. All three were collected and released in a small thermal refuge 0.6 km below Jones Bluff Dam. Fish 1 (4.9 kg) was released on July 14, when the refuge was 26 C and reservoir temperatures outside the refuge were 30–31 C. About 3 hours after release this fish began an overnight downstream movement that brought it, by 0530 hours, to the mouth of another small thermal refuge 21 km below the first. Water temperature was 25–26 C in this refuge, but the fish had spent 12 hours in 30–32 C river water during its transit. Fish 1 was not relocated subsequently.

Fish 2 (weight unmeasured) was released on July 15. About 1 hour after its release it began a downstream movement of approximately 2 km before returning to the release site 4 hours later. During the next week, its use of this refuge varied with the cycle of hydroelectric generation at Jones Bluff Dam; when power generation stopped at midnight, the reservoir dropped, the refuge became too shallow, and Fish 2 moved into the river. It returned to the refuge around midmorning when dam releases reflooded the refuge. When the fish was in the refuge, its thermistor indicated temperature of 25–29 C; when the fish was forced into the reservoir, water temperatures averaged about 30 C. On July 24, 9 days after its release Fish 2 was located approximately 20 km downstream in a second thermal refuge with

TABLE 1.—*Condition (K = 10^5·weight/length^3) of striped bass collected from two summer refuges in 1981–1982 compared with that of striped bass collected below Jones Bluff and Millers Ferry dams during April–May 1982 on the Alabama River.*

Collection			Striped bass total length (mm)			
Location	Temperature (C)	Measure	301–450	451–600	601–750	751–914
April–May, collections of striped bass below Jones Bluff and Millers Ferry dams	17–21	Mean of *K*		1.43	1.37	1.63
		Range of *K*		1.21–1.60	1.27–1.89	1.23–1.94
		N		4	27	24
June–September, thermal refuge below Millers Ferry Dam	21–26	Mean of *K*	1.20	1.14	1.13	1.10
		Range of *K*	1.00–1.43	0.96–1.47	0.95–1.31	0.87–1.37
		N	18	36	47	13
June–September, thermal refuge below Jones Bluff Dam	22–26	Mean of *K*	1.25	1.08	1.08	1.03
		Range of *K*	1.04–1.40	0.84–1.25	0.88–1.29	0.87–1.28
		N	8	50	41	31

temperatures near 26 C. Five days later, it was relocated in the same position, but then moved 0.5 km downstream to a third refuge (25–26 C), where it remained until it was last located the next day. Of 19 position plots for this fish over 15 days, 11 were in thermal refuges, but it tolerated warmer temperatures at other times.

Fish 5 (5.2 kg) was released on August 5 and followed movement patterns very similar to those of Fish 2: movement in and out of the refuge was regulated by hydroelectric releases. During excursions outside the refuge Fish 5 was plotted in positions only 10–25 m from the refuge mouth. River temperatures during this time were about 32 C while corresponding refuge temperatures were 6–10 C lower.

Thirty days after its release, Fish 5 was recaptured with electrofishing gear to check condition and observe the transmitter mount region. Tissue erosion was severe, necrosis was evident, and the fish was lethargic. When Fish 5 was released it subsequently died, probably resulting from stress and shock. Fifteen other striped bass collected at the same time and handled similarly were not affected; they recovered and swam away. Long term external transmitter mounts may stress fish, possibly altering normal movement or behavior. Therefore we considered procedures for internal tag placement in future studies.

Lake Jordan

The three striped bass tracked in Lake Jordan were collected in thermal refuges along the Alabama River. They were equipped with radiotelemetry transmitters and released at various locations around the reservoir. Transmitters were attached internally on all but one fish.

Fish 7 (2.7 kg) was released on June 25 in a backwater area along the central portion of Lake Jordan. Surface water temperature was 33 C. On June 26 the fish was located in Town Creek, a small thermal refuge 4 km upstream having temperatures 25–26 C. Subsequent position plots, 10 days later, indicated that Fish 7 was actively roaming around the lower portion of the reservoir; movement was rapid and continuous. On July 9, its last known location was adjacent to Jordan Dam approximately 10 km downstream from Town Creek. In the 5 position plots recorded over a 15-day period only one plot located this fish in a known thermal refuge. However the movement pattern of Fish 7 may have been atypical as it was a nonresident.

Fish 8 (5.9 kg) was released on July 1 in the headwaters of Lake Jordan, about 0.5 km below Mitchell Dam. Temperatures at midreservoir were 31–33 C. Over the next 15-day period this fish remained within 0.5 km of the release site and showed no major movement. However, on July 21, Fish 8 was located in Chestnut Creek, a thermal refuge 3.5 km downstream from Mitchell Dam. Three days later (July 21) this fish was located in Proctor Creek, another refuge site located directly across the reservoir from Chestnut Creek. Water temperatures in refuge sites were 25–26 C while midreservoir water temperatures were 31–33 C. During the next 2 months Fish 8 continued to shuttle between these two refuges. Its last recorded position was in Chestnut Creek on September 25. This fish was located in 2 thermal refuges on 14 different tracking days over an 87-day period demonstrating a apparent selection of cool-water habitat over warmer open water habitat.

Fish 11 (3.6 kg) was released 0.5 km below Mitchell Dam on September 9. Thermistor readings indicated the fish was in 28 C water while surface reservoir temperature was 29 C. The next day Fish 11 moved 0.5 km upstream to a position immediately below the turbine discharges. On September 16 and 18, the fish was located in Chestnut Creek, 3.5 km downstream of the dam, where water temperature was 24 C. A week later (September 25) Fish 11 was again below Mitchell Dam near the turbine discharge. Contact was lost until October 15 when it was relocated 21 km downstream above the turbine intake structure of Walter Bouldin Dam. Thermistor readings indicated the fish was in 19 C water while surface temperature was 23 C. This was the last known position. Although released late in the summer when temperatures were dropping Fish 11 continued to show a preference for cooler refuge water on two occasions while in Chestnut Creek.

Discussion

All six transmitter-equipped striped bass released in Millers Ferry Reservoir and Lake Jordan during the summers of 1980 and 1981 were located in known thermal refuge areas at least once during the monitoring period. Fishes 2, 5, and 8 spent considerable time within these refuge regions; fishes 1, 7, and 11 were located in thermal refuges less frequently. However, because these striped bass sought out cool-water refuges during the warm summer months, a definite preference for these regions is indicated. The movement pattern of Fish 11 may indicate less preference for thermal refuges as water temperatures cool in autumn.

The question of whether or not thermal refuges are necessary for the survival of this species in southern reservoirs remains a speculative matter. If thermal refuges are important to the success of striped bass in southern reservoirs, they may control the carrying capacity of the system. Managers may be overstocking if they exceed the carrying capacity of the refuges. We found that striped bass moved into refuge areas when reservoir temperatures approached 27 C in late May or early June. During the remaining summer months, movement patterns were associated with the availability of thermal refuges. Similar behavior has been observed in studies by Dudley et al. (1977); Schaich and Coutant (1980); Waddle et al. (1980); and Crateau et al. (1982).

Length–weight data collected from striped bass in summer refuges during this study show fish to be in relatively poor condition when compared to fish collected in spring samples. Poor condition and mortalities of adult striped bass during summer months have also been reported by Axon (1979) and Heuer and Tomljanovich (1980).

The future of striped bass in eutrophic southern reservoirs is still undecided. Questions about summer-long occupation of striped bass in waters ≥30 C without access to thermal refuges remain unanswered. Many state agencies, including the Alabama Game and Fish Division, have decided to stock hybrid striped bass (white bass *Morone chrysops*) × striped bass) in lieu of striped bass in many reservoirs where summer habitat is marginal and harvest of large striped bass (6.0 kg or greater) has been poor. Although hybrid striped bass were occasionally seen in thermal refuges during our 4-year study, only 15 or 3.4% of the total number of fish sampled were hybrids. We believe that hybrids are more tolerant of high water temperatures than striped bass.

On a positive note, striped bass that successfully over-summer in Alabama thermal refuges appear to regain their body weight during fall and spring feeding periods, and growth appears adequate.

Acknowledgments

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References

AXON, J. R. 1979. An evaluation of striped bass introductions in Herrington Lake. Kentucky Department of Fish and Wildlife Resources Fisheries Bulletin 63.

CHEEK, T. E., M. J. VAN DEN AVYLE, AND C. C. COUTANT. 1985. Influences of water quality on distribution of striped bass in a Tennessee River impoundment. Transactions of the American Fisheries Society 114:67–76.

COUTANT, C. C., AND D. S. CARROLL. 1980. Temperature selection by ten ultrasonic-tagged striped bass in freshwater lakes. Transactions of the American Fisheries Society 109:195–202.

CRATEAU, E. J., P. MOON, AND C. M. WOOLEY. 1982. Biology, population dynamics, and management of *Morone* sp., with emphasis on native Gulf of Mexico race and introduced Atlantic race striped bass, Apalachicola River, Florida. United States

Fish and Wildlife Service, Apalachicola River striped bass project—Annual Progress Report FY 1981, Panama City, Florida, USA.

DUDLEY, R. G., A. W. MULLIS, AND J. W. TERREL. 1977. Movement of adult striped bass in the Savannah River, Georgia. Transactions of the American Fisheries Society 106:314–322.

HEUER, J. H., AND D. A. TOMLJANOVICH. 1980. A synopsis of fisheries investigations on Cherokee Reservoir: 1941–1979. Tennessee Valley Authority Division of Water Resources Technical Report WR-40-80-1, Knoxville, Tennessee, USA.

MATTHEWS, W. J. 1985. Summer mortality of striped bass in reservoirs of the United States. Transactions of the American Fisheries Society 114:62–66.

SCHAICH, B. A., AND C. C. COUTANT. 1980. A biotelemetry study of spring and summer habitat selection by striped bass in Cherokee Reservoir, Tennessee, 1978. Oak Ridge National Laboratory, ORNL/TM-7127, Oak Ridge, Tennessee, USA.

SNEDECOR, G. W., AND W. G. COCHRAN. 1967. Statistical methods, 6th edition. Iowa State University Press, Ames, Iowa, USA.

STEEL, R. G., AND J. H. TORRIE. 1960. Principles and procedures of statistics. McGraw-Hill, New York, New York, USA.

SUMMERFELT, R. C., AND D. MOSIER. 1976. Evaluation of ultrasonic telemetry to track striped bass to their spawning grounds. Oklahoma Department of Wildlife Conservation, Federal Aid in Fish Restoration Project F-29-R, Final Report, Oklahoma City, Oklahoma, USA.

WADDLE, H. R., C. C. COUTANT, AND J. L. WILSON. 1980. Summer habitat selection by striped bass, *Morone saxatilis*, in Cherokee Reservoir, Tennessee, 1977. Oak Ridge National Laboratory, ORNL/TM-6927, Oak Ridge, Tennessee, USA.

WINTER, J. D., V. B. KUECHLE, D. B. SINIFF, AND J. R. TESTER. 1978. Equipment and methods for radio tracking freshwater fish. University of Minnesota Report 152, St. Paul, Minnesota, USA.

Movements of Adult Striped Bass (*Morone saxatilis*) in the Savannah River, Georgia

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ABSTRACT

During 1973, 1974, and 1975 movements of 33 striped bass [*Morone saxatilis* (Walbaum)] in the Savannah River, Georgia were followed through the use of ultrasonic and radio transmitters. During March through May striped bass congregate and spawn in a tidally influenced, relatively shallow, small branch of the river (Little Back River) near Savannah, Georgia, about 30 km upstream from the river mouth. During the spawning season striped bass do not exhibit any specific movement pattern, but remain in this particular sector of the river. Immediately after spawning, all tracked fish moved upstream, some as far as 301 km from the spawning area. Fish remained in the upstream areas at least 4 months. We detected no fish moving downstream during this period. Our data and those from previous work strongly suggest that individuals in this population of striped bass spend the majority, if not all, of their lives in the Savannah River.

The striped bass [*Morone saxatilis* (Walbaum), family Percichthyidae] is native to the Atlantic coast of North America from the St. Lawrence River in Canada to the St. Johns River, Florida and in the Gulf of Mexico from western Florida to Lake Pontchartrain, Louisiana. Introduced to the Pacific coast in 1879, it now ranges from San Diego, California to the Columbia River, and possibly as far north as Alaska (Nichols 1966; Raney 1952).

Noted for their value to both sport and commercial fisheries, Atlantic coast striped bass populations contribute more than 9 million fish to sport fishermen (U.S. Department of the Interior 1970) and about 4,000 metric tons to commercial fishermen (Koo 1970) each year. The striped bass' habit of feeding on schools of pelagic clupeids has made it a valuable predator and popular sport fish in freshwater lakes and reservoirs as well.

Within its range on the Atlantic and Gulf coasts biologists have differentiated several races of striped bass based on clinal and other differences in meristic, morphometric, and biochemical characteristics (Raney and Woolcott 1955; Barkaloo 1967, 1970; Lewis 1957; Lund 1957; Morgan et al. 1973).

Most striped bass are anadromous, and ascend rivers to spawn in fresh or brackish water in March to June when water temperatures reach 15 C to 19 C (Raney 1952; Stevens 1964; Barkaloo 1967). After spawning, followed perhaps by a short stay in fresh waters, most adult striped bass return to marine waters. A portion of those populations from Chesapeake Bay northward participate in a general northerly migration during the early and midsummer following spawning. These fish then return to wintering areas prior to entering home streams to spawn.

Striped bass populations from southern North Carolina southward do not contribute to this northward migration (Raney 1954). A 3 year fishery survey of coastal Georgia found striped bass only in tidal creeks and rivers (Mahood et al. 1974). Smith (1970), after tagging striped bass in the Savannah River, received no tag returns from coastal waters. However, local fishermen catch adult striped bass more than 300 km upstream in the Savannah River from May to September and catch fish in the extreme downstream tidal reaches of the river during the winter. The major known spawning area for striped bass in the Savannah River is in the tidally influenced area 30 to 40 km upstream from the river mouth (Smith 1970; McBay 1968; Robert Rees, Richmond Hill Hatchery, Richmond Hill, Georgia, personal communication).

The growing sportfishery and increasing

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industrial development on the Savannah River increase our need for a better understanding of this population, which may be typical of other southern striped bass populations. Although previous work has helped delineate the spawning area in the Savannah River, these studies have not determined the extent to which this population is riverine, nor have they allowed a detailed description of the movements of these fish while in the river.

STUDY AREA

The headwaters of the Savannah River arise in the southern Appalachian Mountains of North Carolina, South Carolina, and Georgia at an elevation of about 1,600 m. They flow southeastwardly and at the confluence of the Seneca and Tugaloo rivers form the Savannah River which then flows 505 km to the Atlantic Ocean and forms the border between South Carolina and Georgia. Several dams blocking fish passage have been built on the Savannah River, but all these are more than 333 km upstream from its mouth. The New Savannah Bluff Lock and Dam, 301 km upstream, probably creates a partial barrier to fish movement. Striped bass are found above it, however, and the dam's gate type construction allows fish to pass under it. Fish probably go through the lock as well. Striped bass in this area may also originate from those stocked in upstream reservoirs. A navigation channel is maintained by the U.S. Army Corps of Engineers from the coast to Augusta (322 km).

The tidally-influenced sector of the Savannah River is divided into three branches (Fig. 1). The Front Savannah River (the most southwestern branch) is the widest branch and is the main channel for navigation. It receives effluent from a number of industries. The Little Back River (the most northeastern branch of the river) is more narrow and shallower than the Front River, and it is bordered on both sides by marshy vegetation and cypress forest of the Savannah Wildlife Refuge. Smith (1970) and McBay (1968) found that the Little Back River upstream from the U.S. Route 17 bridge and downstream from the mouth of Union Creek, is the primary striped bass spawning area, although some spawning occurs in upstream areas (Smith 1970). The Middle River lies between the Front and Little Back rivers, and it is similar to the Little Back River in depth, width, and vegetation types. In general, salinity is less than one part per 1,000 upstream from U.S. Highway 17A and at or near zero upstream from U.S. Highway 17.

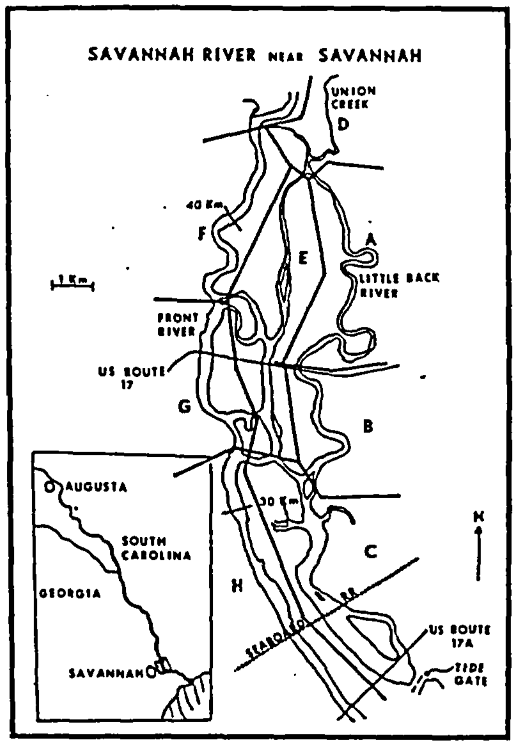

FIGURE 1.—*The Savannah River near Savannah showing the various branches of the river. Capital letters indicate the sections of the river used in the analysis of fish movements. The inset shows the relation of the enlarged portion, near Savannah, to the lower Savannah River.*

The river sector between the New Savannah Bluff Lock and Dam and the tidal area near the coast is fairly uniform and smooth flowing with a meandering pattern. In the Augusta area the Savannah River is characterized by a 25-km stretch of river above the New Savannah Bluff Lock and Dam that is similar to downstream segments. From about 5 km upstream from Augusta to 11 km upstream at the City of Augusta Dam, the river is rocky and shallow. Striped bass cannot go beyond the City of Augusta Dam.

Just upstream from Augusta four dis-

TABLE 1.—*Fish tagged and tracked during 1973 through 1975. Two other fish were tagged: one was never relocated; the other had a faulty transmitter. (Method—S = Surgical, O = Oral; Cause of termination—R = Regurgitated, L = Signal lost, P = Lack of personnel; Tag type—U = Ultrasonic, R = Radio.)*

Fish	Fork length cm	Weight kg	Sex	Start	End	Duration	Tag type	Tagging method	Cause of termination
				Spring 1973—Savannah					
SF	91.4	13.6	F	12 Apr.	20 Apr.	7.9	U	S	L
SX	83.8	10.2	M Ripe	19 Apr.	24 Apr.	4.7	U	S	L
SY	73.7	7.7	M Ripe	19 Apr.	8 May	18.9	U	S	P
SZ	52.1	2.1	M Ripe	19 Apr.	19 Apr.	0.1	U	S	L
				Spring 1974—Savannah					
SA	88.9	17.3	F	24 Mar.	1 Apr.	7.4	U	O	R
SB	71.1	6.4	F	27 Mar.	15 Apr.	18.9	U	O	R
SC	73.7	4.8	M Ripe	1 Apr.	20 Apr.	18.7	U	O	R
SD	83.8	10.2	M Ripe	4 Apr.	3 May	29.1	U	O	L
SE	83.8	8.6	M Ripe	4 Apr.	10 Apr.	5.8	U	O	R
SG	83.8	6.6	M Ripe	4 Apr.	21 Apr.	16.8	U	O	L
SH	88.9	11.4	M Ripe	4 Apr.	1 May	26.7	U	O	L
SI	99.1	13.6	F	10 Apr.	15 Apr.	4.9	U	O	R
SJ	81.3	9.1	M Ripe	17 Apr.	19 Apr.	1.9	U	O	L
SK	78.7	6.8	M Ripe	26 Apr.	7 May	10.8	U	S	L
SL	83.8	5.5	M Ripe	26 Apr.	22 May	26.1	U	S	L
SM	93.9	10.0	F Spent	28 Apr.	29 Apr.	1.1	U	O	L
SN	91.4	8.2	M Ripe	30 Apr.	2 May	1.9	U	S	L
				Fall and Winter 1974–1975—Augusta (upstream from lock and dam)					
RA	76.0	5.4		23 Oct.	22 Nov.	30	R	O	R
RB	86.5	7.5		7 Nov.	22 Feb.	107	R	O	R
RE	85.0	9.5		29 Jan.	28 May	120	R	S	L
				Fall and Winter 1974–1975—Augusta (downstream from lock and dam)					
RD	92.6	10.0		18 Dec.	29 Jan.	42	R	O	R
				Spring 1975—Savannah					
RG	84.0	10.0		4 Mar.	18 June	107	R	S	L
RI	93.7	14.1	M	12 Mar.	28 May	78	R	S	L
RJ	93.2	14.3	M	25 Mar.	31 July	129	R	S	L
RK	84.7	9.5	F	25 Mar.	28 Apr.	35	R	S	L
RL	97.5	13.6	F	1 Apr.	19 Apr.	19	R	S	L
RM	86.5	11.3	F	8 Apr.	13 June	67	R	S	L
RN	101.0	18.1	F	19 Apr.	11 June	54	R	S	L
RO	82.4	9.3	M	19 Apr.	31 July	104	R	S	L
RP	78.0	7.7	F	19 Apr.	25 Apr.	7	R	S	L
RQ	100.0	18.8	F	23 Apr.	25 Aug.	125	R	S	P
RS	76.0	7.2	M	28 Apr.	25 Aug.	120	R	S	P
RT	94.5	13.6	F	28 Apr.	29 May	32	R	S	L

charge canals enter the Savannah River from the Augusta Canal which originates at the City of Augusta Dam. These discharge canals harbored striped bass during much of the year.

Most sectors of the Savannah River suffer from some form of pollution (Georgia Water Quality Control Board 1972a, 1972b; U.S. Environmental Protection Agency 1972).

METHODS

We captured striped bass with electrofishing gear or with a pound net. After capture, we weighed and measured each fish and tagged it with an external dart tag. If the fish was large enough a radio or ultrasonic transmitter was inserted.

Initially, in 1973, we tagged fish surgically. We quieted the fish with quinaldine or by electronarcosis and made a slit about 3 cm long near the ventral midline, anterior of the anus. A transmitter was inserted and the opening closed with sutures. Since some fish died during surgery, we tagged 11 fish in early 1974 by placing transmitters into the fish's stomach via the mouth. With some fish we placed a transmitter in the stomach after attaching a short piece of monofilament line and a small trebel hook. We had hoped that the hook would prevent regurgitation of the tag, but regurgitation occurred anyway, perhaps because the hook was corroded by digestive juices. Due to this difficulty, we returned to the surgical implantation procedure for most of the remaining fish tagged during 1974 and all fish tagged during 1975.

We used both ultrasonic and radio tracking equipment to study movements of striped bass in the Savannah River. The ultrasonic transmitters, type SR69A from Smith-Root Electronics (Vancouver, Washington),[3] which emit an ultrasonic signal at 74 kHz, measured 14 mm and 19 mm in diameter at the two ends and 90 mm in length. They weighed about 40 g in air, 20 g in water, and had a volume of about 20 ml. The radio transmitters, obtained from AVM Instrument Co. (Champaign, Illinois), had an irregular shape and measured 60 by 21 by 10 mm. They weighed about 20 g in air and 10 g in water, had a volume of about 10 ml, and emitted a pulsed radio signal at 50 mHz. Receiving equipment used was manufactured by the maker of the respective transmitter type. Since a 15-kg fish tagged with an ultrasonic transmitter would have to increase its air bladder volume by only 1.8% to maintain neutral buoyancy, we assumed the transmitters did not drastically alter fish behavior (Marshall 1966).

Fish tagged during 1973 and 1974 (ultrasonic transmitters) were located as often as possible, and at times virtually continuously for 24 h to study movements of these fish in the spawning areas. Fish tagged in 1975 (radio transmitters) were monitored less often, especially when they migrated upstream from the spawning areas. Attempts were made to find these fish at least once a week after they left the spawning grounds but some fish were more readily found than others. Fish tagged in the fall of 1974 (radio transmitters) in the Augusta area were located every one to two weeks. Except for the four fish tagged in the Augusta area, all fish fitted with transmitters were captured in the spawning area.

Although our primary interest was to determine the movements of striped bass in the Savannah River, we had the opportunity, especially during 1974, to attempt to correlate short term movements of the fish with environmental variables. To do this we measured surface water temperature, salinity, and dissolved oxygen in the immediate vicinity each time a fish was located. We also recorded lunar stage, tidal stage, time and date. To facilitate analysis, we divided the tidal cycle into 12 stages and divided the lunar cycle into eight stages. The location of each fish was marked on a nautical chart of the area and numbered. This number and the corresponding data was then recorded on data sheets maintained for each fish.

Minimum rates of fish movement were estimated by dividing the distance between successive locations by elapsed time. The data used for this type of analysis did not include observations separated by more than 1.5 h. We used multiple regression analysis to find what variables would best predict movement.

RESULTS

From 1973 through 1975, 33 striped bass were successfully tagged and tracked (Table 1).

Movements of Striped Bass During the Spawning Season

Striped bass electronically tagged and tracked during March and April utilized the Little Back River and its tributaries more than any other part of the lower Savannah River. By examining data from fish tracked in this part of the river for more than 4 days, we found that striped bass spent about 75% of their time in the Little Back River (Table 2, Section A and B, Fig. 1). Forty-three percent of their time was spent in the Little Back River between the Route 17 bridge and the mouth of Union Creek (Section A on Fig. 1). The proportion of time fish spent in Section A differed significantly among the 3 yr (χ^2 = 87.16, df = 2). Some of the differences in use of different sections of the river among years may be due to differences in data collection. Environmental factors may have contributed to the differences between 1974 and 1975. For example, in 1974 water temperature reached a high of 21 C in late March, dropped to 14 C, and then rose again. In 1975 water temperatures did not reach 21 C until early May. The temperature regime of 1974 may have caused the fish to meander more.

[3] Mention of products in this paper does not imply endorsement of those products.

TABLE 2.—*Utilization of various sections of the lower Savannah River by striped bass during the spawning season. Each number represents the number of days on which each fish was found in a particular section. If a fish was observed more than once per day in a given section this was counted as one observation. If this fish was found in more than one section on a given day this was counted as one observation in each section. Only fish observed on more than 4 days on the spawning grounds are presented here. See Fig. 1 for location of river sections.*

		River section								
Year	Fish	A	B	C	D	E	F	G	H	Total
1973	SF	5	2	1						
	SY	2	2							
	Total days	7	4	1						12
	% of total	58%	33%	8%						
1974	SB	5	3	8					1	
	SC	6	5	5	3	1				
	SD	2	1	1	6	3	1			
	SE	5			2					
	SG	8	4		5	1				
	SH	14	13							
	SI	3	3		2					
	Total days	43	29	14	18	5	1		1	111
	% of total	39%	26%	13%	16%	5%	1%		1%	
1975	RG	2	1		1					
	RI	6	17	2	2					
	RJ	6	3							
	RK	10		1	2					
	RL	5	7	1						
	RM	5	5		1					
	RO	6	1							
	Total days	40	34	4	6					84
	% of total	48%	40%	5%	7%					
1973–1975	Total days	90	67	19	24	5	1		1	207
	% of total	43%	32%	9%	12%	2%	0.5%		0.5%	

Striped bass tended to move more when the water was cooler (Fig. 2) but we obtained very little continuous data at water temperatures below 14 C. However, regression tests indicated that movement was significantly ($P < 0.1$) higher at lower temperatures.

Although movement patterns of individual striped bass differed greatly, as a group they tended to move primarily during the afternoon and early evening (Fig. 2) while in the spawning area. The few fish which were tracked continuously to about 32 km upstream in 1974 tended to move at night while in upstream areas, but there are too few data to draw any definite conclusions.

Fish tended to move less at flood tide than at any other tide and seemed to move more when the tide was dropping than when it was rising (Fig. 2). Due to the large confidence intervals no statistical significance can be attached to the data although cyclic (cubic and fourth power) regressions were tested.

Fish tended to move least during the period surrounding the new moon (Fig. 2). A cyclic relationship seems to be present in the data (Fig. 2) but again large variances prevent the assigning of statistically significant cyclic (cubic or fourth power) relationships.

Using multiple regression we found significant relationships between movement on the spawning grounds and the following combinations of variables: (1) water temperature and change in water temperature ($R^2 = 0.07$); (2) lunar stage and tidal stage ($R^2 = 0.05$); and (3) lunar stage, tidal stage, and season ($R^2 = 0.07$). Since none of these combinations accounted for more than 7% of the variability in the movement data and were significant only at the $P \leq 0.1$ level, the regressions have no predictive value.

Movement of Striped Bass after the Spawning Season

The movement patterns of striped bass changed markedly at the end of the spawn-

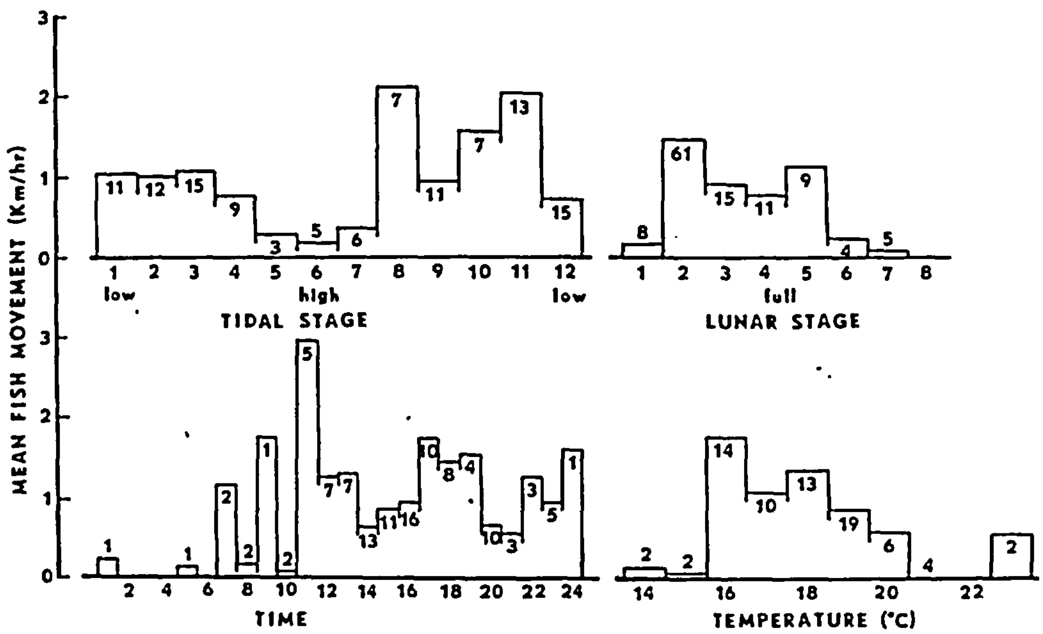

FIGURE 2.—*Relationship between some variables and movement of striped bass on the spawning grounds in the spring of 1974. In most cases small sample sizes within each category and large variances precluded the assignment of statistically significant relationships. Numbers of observations are given at the tops of columns.*

ing season. After remaining in a relatively confined area of the Little Back River all fish left this area. Of 20 fish which contained working tags when they left the spawning grounds, 14 were subsequently found upstream; six were never found. Only three of 12 radio-tagged fish were not found after spawning.

Most fish observed left the spawning area between 16 April and 1 May. Fish RG may have left the spawning area quite a bit earlier (18 March) than the other fish, but this fish was not relocated for almost 2 months. Excluding fish RG the mean date of last observation on the spawning grounds was April 25 (± about 5 days). Male fish did not leave on a significantly different date from females. Fish tagged in 1974 did not leave the spawning area earlier in spite of the warmer water temperatures which occurred that year. Fish which were not later located did not leave at a different date than those which were located.

Striped bass tagged with ultrasonic transmitters provided little information on post-spawning movement. Striped bass tagged with radio tags were easier to locate in upstream areas than ultrasonic tagged fish and were found for several months. Some striped bass moved upstream quite rapidly after spawning. Two radio-tagged fish (RI and RN) moved 240 km upstream from the spawning grounds in less than 3 weeks. Another (RJ) remained 136 km upstream for several weeks before moving further. Eight of the nine radio-tagged fish found after spawning moved at least 160 km upstream from the spawning grounds. The other fish (RT) was last located at the mouth of a tributary impassable to our boat. Most fish remained in a relatively short section of the river after the post-spawning migration (Table 3). We detected no significant downstream movement. The fish remained in upstream portions at least until we lost the transmitter signal.

Movement of Striped Bass in the Augusta Area

We tagged and tracked four striped bass captured near Augusta in the autumn and winter of 1974–75 (Table 1). None of these fish moved great distances and none exhibited movement patterns related to any obvi-

TABLE 3.—*Distances from the mouth of the Savannah River where individual striped bass remained for more than 5 days. Data are from fish tagged with radio transmitters in 1975. Of nine fish tagged and subsequently found upstream, these seven remained in specific areas more than 5 days. (Fish RI and RT moved steadily upstream until the signal was lost.) The last date shown is the last date on which a signal was found for that fish.*

Fish	Location (km from river mouth)	First found at this location	Last found at this location
RG	195	14 May	30 May
RJ	127–137	29 May	17 June
	257–280	15 July	31 July
RM	225–228	14 May	13 June
RN	283–291	10 May	11 June
RO	253–272	5 June	31 July
RQ	232–238	15 May	11 June
	249–252	19 June	25 Aug.
RS	293–301	19 June	25 Aug.

ous influence. Three fish (RA, RB, RE) tagged in or near the discharge canals were most often found either in the canals or within a few kilometers of them. They were never found more than 10 km from the tagging site. A fish (RD) tagged a few hundred meters downstream from the New Savannah Bluff Lock and Dam remained within 7 km of the dam.

Other Tagging Methods and Collections

Of 126 striped bass marked with external anchor tags only two were recaptured. One fish tagged at Augusta just downstream from the lock and dam in early November was found at the Savannah spawning grounds in March. One fish tagged (7 November 1974) in the Augusta area in canal 2 was captured by a fisherman about a month later in the rapids upstream from Augusta.

Striped bass were found (with electrofishing equipment) in the Augusta area both upstream and downstream from the lock and dam during the summer, fall and winter months. Fish were most likely to be found in the discharge canals, in the vicinity of a power plant downstream from Augusta and in a 1 km section of river downstream from the lock and dam. No fish were found in the spring when these sections were sampled on 16 April 1975. However, the water levels on this date were too high for efficient shocking.

DISCUSSION

In general the striped bass is an anadromous fish, but in the Savannah River the degree of anadromy is greatly reduced. This tendency in southern populations has been reported by previous workers (Barkaloo 1967; Raney 1952; Raney and Woolcott 1955).

Although our study strongly supports earlier studies (Smith 1970; McBay 1968) in establishing the Little Back River as the major spawning area, we did not discover what environmental characteristics attract striped bass to this area.

Our data indicate that most Savannah River striped bass migrate upstream after spawning and remain in the river. These fish must then return to the spawning grounds the following spring, although little direct evidence for downstream migration is provided by this study. This theory is supported by virtually all our data although some factors still remain unclear.

Although Mahood et al. (1974) found very few striped bass in a coastal survey of Georgia marine waters, fishermen do catch striped bass in the lower estuaries especially from 15 November through January 31. On the other hand we captured an adult striped bass (fish RD) just downstream from the lock and dam in December of 1974, and in January of 1974 we saw numerous striped bass in the rapids upstream from Augusta. The meaning of this latter observation is clouded by the existence of the lock and dam which may hinder free movement of fishes. Striped bass may remain in all parts of the river in winter, and then perhaps move toward the spawning area in February or early March. Striped bass were not captured in the Augusta area during the spawning season which might indicate that they did move downstream to spawn, but water conditions in Augusta hampered sampling during that period.

A possible reason as to why riverine populations of striped bass developed may be their temperature preferences. Excessively warm coastal waters may limit seaward migration of striped bass. Merriman (1941) felt that the maximum water temperatures at which striped bass would be found were 25 to 27 C. Maximum temperatures found in the downstream (warmest) part of the Savannah River were 26 C in July through September 1971 (Georgia Water Quality Control Board 1972b). Maximum temperatures of marine waters along the coast of Georgia in 1974 (Mahood et al. 1974) reached 27 to 30 C.

In years of warm ocean temperatures (up to 18.5 C) on the Pacific coast, seaward migrations of striped bass occurred, while during cooler years bass remained in inland reaches of the San Francisco Bay-Sacramento River system (Radovich 1963). Temperature preference could also be the constraint on the riverine population of striped bass in the St. Lawrence. River (Magnin and Beaulieu 1967; Beaulieu 1962). In general the larger rivers of the South are probably cooler than adjacent coastal waters and upstream portions are cooler than downstream waters. The construction of large reservoirs (e.g., Clark Hill and Hartwell on the Savannah River) lower the water temperatures of rivers further. Thus striped bass would be more likely to find acceptable temperatures by moving upstream after spawning.

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We are indebted to Messrs. R. Michaels, D. Stoeppelwerth, and F. Rosen for their many months of help in the field. We also thank Dr. M. Rawson, and Messrs. R. Boyer, D. Thompson and graduate students in fisheries at the School of Forest Resources, University of Georgia, who assisted us with the fieldwork. Drs. J. Clugston and A. Fox of the Georgia Cooperative Fishery Unit provided valuable support and suggestions.

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This project was initiated by Dr. M. Huish.

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LITERATURE CITED

BARKALOO, J. M. 1967. Florida striped bass. Fla. Game Fresh Water Fish Comm. Fish. Bull. 4. 24 pp.

———. 1970. Taxonomic status and reproduction of striped bass (*Morone saxatilis*) in Florida. Bur. Sport Fish. Wildl. (U.S.) Tech. Pap. 44. 16 pp.

BEAULIEU, G. 1962. Resultats d'etiquetage du bar d'amerique, dans le Pleuve Saint-Laurent de 1945 and 1960. Nat. Can. 89(8):217–236.

GEORGIA WATER QUALITY CONTROL BOARD. 1972a. Mercury pollution investigation in Georgia, 1970–1971. Rep. 117 pp.

———. 1972b. Water quality data, lower Savannah River, 1970–1971. Rep. 54 pp.

KOO, TED S. Y. 1970. The striped bass fishery in the Atlantic states. Chesapeake Sci. 11(2):73–93.

LEWIS, R. M. 1957. Comparative study of populations of the striped bass. U.S. Fish Wildl. Serv. Fish. Bull. 204. 54 pp.

LUND, W. A., JR. 1957. Morphometric study of the striped bass, *Roccus saxatilis*. U.S. Fish Wildl. Serv. Fish. Bull. 204. 54 pp.

MAGNIN, E., AND G. BEAULIEU. 1967. Le bar *Roccus saxatilis* (Walbaum), du fleuve Saint-Laurent. Nat. Can. 94:539–555.

MAHOOD, R. K., C. D. HARRIS, J. L. MUSIC, JR., AND B. A. PALMER. 1974. Survey of the fisheries resources in Georgia's estuarine and inshore ocean waters, part IV, coastal Georgia—southern, central, and northern section. Ga. Dep. Nat. Resour. Game Fish Div. Contrib. Ser. 25. 210 pp.

MARSHALL, N. B. 1966. The life of fishes. World Publishing Co., New York. 402 pp.

MCBAY, L. G. 1968. Location of sexually mature striped bass. Ga. Game Fish Comm. Coastal Reg. Fish Invest. Rep. Fiscal Yr. 1968. Job II-1:27–48.

MERRIMAN, D. J. 1941. Studies on the striped bass (*Roccus saxatilis*) of the Atlantic coast. U.S. Fish Wildl. Serv. Fish. Bull. 50. 77 pp.

MORGAN, R. P., T. S. Y. KOO, AND G. E. KRANTZ. 1973. Electrophoretic determination of populations of the striped bass, *Morone saxatilis*, in the Upper Chesapeake Bay. Trans. Am. Fish. Soc. 102(1):21–33.

NICHOLS, P. R. 1966. The striped bass. U.S. Fish Wildl. Serv. Bur. Comm. Fish. Fish. Leaflet 592. 6 pp.

RADOVICH, J. 1963. Effect of ocean temperature on the seaward movements of striped bass, *Roccus saxatilis* on the Pacific coast. Cal. Fish Game 49(3):191–206.

RANEY, E. C. 1952. The life history of the striped bass *Roccus saxatilis* (Walbaum). Bull. Bingham Oceanogr. Collect. 14(1):5–97.

———. 1954. The striped bass in New York Waters. New York State Conservationist. February-March. Reprint 675. 1 p.

——, AND W. S. WOOLCOTT. 1955. Races of the striped bass, *Roccus saxatilis* (Walbaum), in the Southeastern United States. J. Wildl. Manage. 19(4):444–450.

SMITH, L. D. 1970. Life history studies of striped bass. Final Rep. Ga. Game Fish Div. 134 pp.

STEVENS, R. E. 1964. A final report on the use of hormones to ovulate striped bass, *Roccus saxatilis* (Walbaum). Proc. 18th Annu. Conf. Southeast. Assoc. Game Fish Comm. 525–538.

U.S. DEPARTMENT OF THE INTERIOR. 1970. Anadromous fish resources, their conservation, development, enhancement. Washington, D.C. 28 pp.

U.S. ENVIRONMENTAL PROTECTION AGENCY. 1972. A report on pollution in the middle reach of the Savannah River. Tech. Study Rep. TS 03-71-208-003. 30 pp. + 3a pp.

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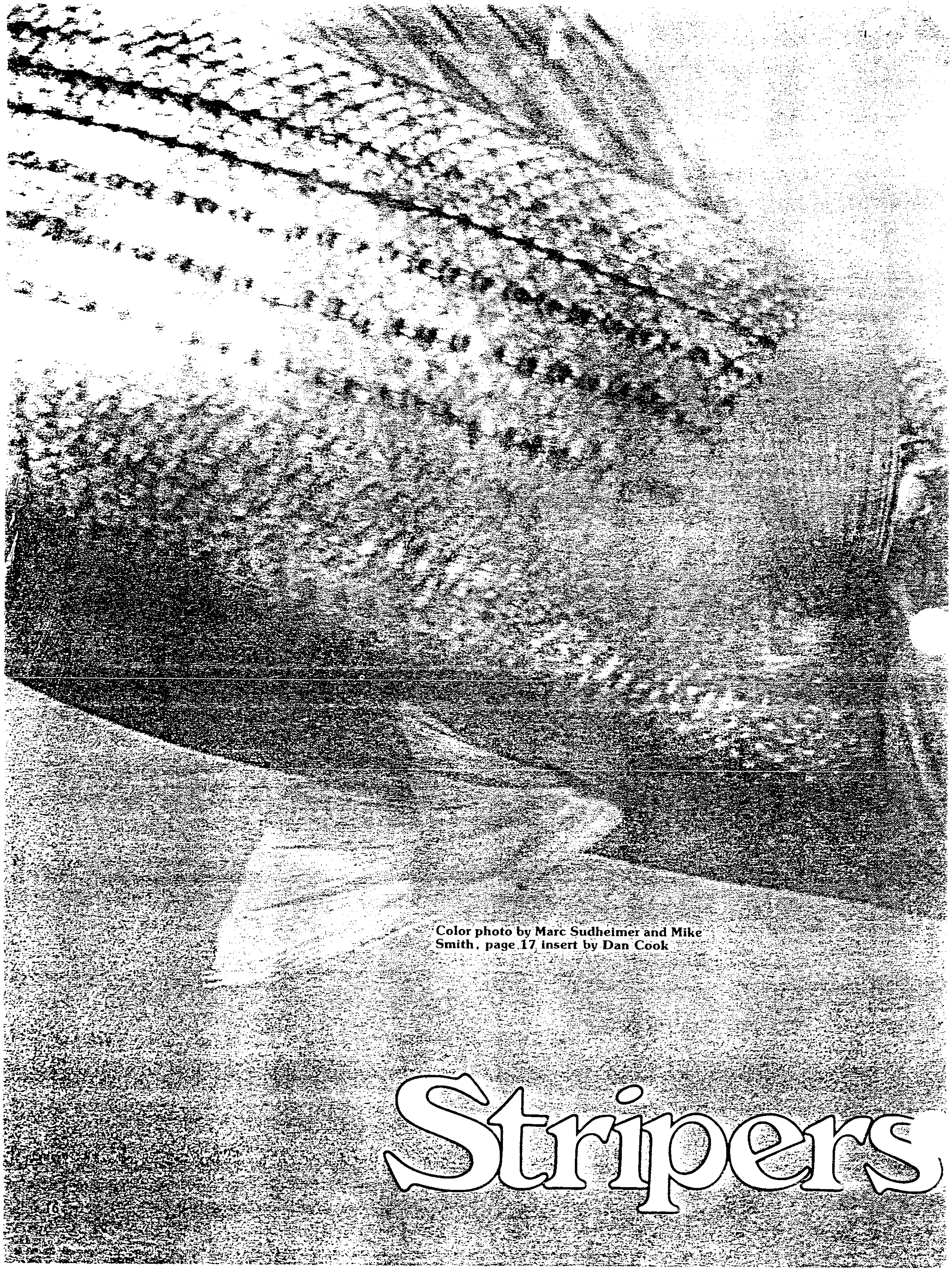
July / August 1982 Volume 6 Number 1

COVERS

Front—"Migisiwa" means "bald eagle" in the language of the Chippewas. Migisiwa belongs to the National Wildlife Federation and is on tour this year in celebration of the "Year of the Eagle." Hopefully, the bald eagle will soon be a year-round resident in Tennessee ....Sharon Coe, see article on page 4
Inside Front—White Bass Rewards ....Terry Madewell, see article on page 10
Inside Back—Snapper Trapper ....Dr. Roy Appleton, see article on page 21
Back—"Fish Eagle," or ospreys, are becoming more abundant in Tennessee ....Richard Simms, see article on page 4



Color photo by Marc Sudheimer and Mike Smith, page 17 insert by Dan Cook

Stripers

New information on the movements of striped bass indicates that "thermal refuges" in inland reservoirs such as Cherokee and Watts Bar are crucial to the summertime survival of this salt water native.

Terry Cheek

Under Stress

Since their introduction into Tennessee waters in 1948, striped bass have become a highly prized addition to the sportfisherman's catch. The thrill of landing one of these fighters, or watching helplessly as line screams off your reel until the last sickening "pop," was once reserved for saltwater anglers. But now the spectacular sport of striper fishing can be experienced here in our home state.

As saltwater stocks of striped bass dwindle on the east coast, research has intensified on the striper to determine its requirements for survival in the freshwater reservoir environment as well as the marine system. Recent research in Tennessee has focused on the thermal nature, or "temperature tolerance," of striped bass in selected reservoirs. The results of this research will impact on striped bass stocking programs across the country ultimately resulting in healthier striper populations and increased angler success.

It is ironic, yet appropriate, that this story begins with Cherokee Reservoir in upper east Tennessee. It is here where some of the first striped bass were introduced, that problems with their reservoir environment first came to light. In late summer 1971, dead adult striped bass were discovered in areas of heavy fishing pressure. This observation was initially attributed to hook and release mortality. However, another kill occurred at the same time in 1972, but this one was too widespread to be hook mortality alone.

Nearly every year thereafter die-offs of adult striped bass occurred in varying degrees. Many hypotheses explaining the deaths of the stripers were explored; parasites, disease, pesticide pollution, low dissolved oxygen and high water temperatures were the front runners. The latter two turned out to be the most important.

Initial research on the problem was conducted by University of Tennessee graduate students Harold Waddle and Barbara Schaich, under the guidance of Dr. Charles C. Coutant of the Department of Energy's Oak Ridge National Laboratory. During the summers of 197[illegible] and 1978, striped bass were fitted with transmitters, allowing the researchers to follow their movements and record the temperature of the water they occupied.

What the researchers found was an astonishing sensitivity displayed by striped bass to water temperature. During spring, Cherokee stripers were detected throughout the reservoir. However, as the sun warmed the waters to their summertime highs, the fish were located exclusively in isolated and limited areas having an influx of cool (approximately [illegible]) oxygenated (at least [illegible] ppm) water. These places were termed "thermal refuge" areas. Most of the striped bass in the 30,000 acre Cherokee Reservoir were being forced into known thermal refuges representing [illegible] of the total reservoir area.

Water temperatures and dissolved oxygen concentrations in the major portion of the reservoir during the summer forced the striped bass into an environmental squeeze play between too high temperatures but adequate dissolved oxygen near the surface; and cool temperatures but inadequate dissolved oxygen levels at deeper levels.

Crowding in these thermal refuges brought on a stressful situation for the stripers, lowering their resistance to parasites and diseases. Fishermen soon discovered these areas and angling success was fantastic. However, hook and release mortality was commonplace. But as water temperatures cooled, reflecting the approach of winter, the surviving striped bass again utilized the entire reservoir.

Needless to say, the potential impact these findings could have on striped bass management programs throughout the country has caused great interest among fisheries biologists. Many were skeptical about the striped bass' degree of sensitivity to water temperature, and attributed the striper's behavior in Cherokee Reservoir to the polluted conditions found there. In addition, up to this point, only Cherokee Reservoir had had problems with striper die-offs. Norris, Watts Bar, and Chickamauga Reservoirs, all located near Cherokee Reservoir, boasted healthy populations of striped bass, and were apparently free of the problems Cherokee stripers faced. Indeed, more research was needed to determine if striped bass in other reservoirs exhibited behavior similar to those in Cherokee Reservoir.

Through the efforts of Dr. Coutant, Dr. Mike Van Den Avyle of the U. S. Fish and Wildlife's Cooperative Fishery Research Unit at Tennessee Technological University (presently Unit Leader, Cooperative Fishery Research Unit, University of Georgia), and Anders I. Myhr of the Tennessee Wildlife Resources Agency, a research project was implemented to determine the distribution and habitat selection of adult striped bass in the 38,000 acre Watts Bar Lake. Biotelemetry techniques (attachment of transmitters) were used to monitor as many stripers as possible, and extensive water quality samples were taken over an 18 month period to shed more light on the relationship between the striper and water temperature. Primary funding for the project was secured from the TWRA, with additional assistance from O.R.N.L., to support a Tennessee Technological graduate student researcher. The author was fortunate enough to be chosen as that graduate student.

From July 1979 to December 1980, 71 adult striped bass, ranging in size from 5 to 30 lbs. and averaging 14 lbs., were fitted with transmitters and their movements monitored. Each time a tagged fish was found, water temperature and dissolved oxygen measurements were made as near as possible to the fish's location.

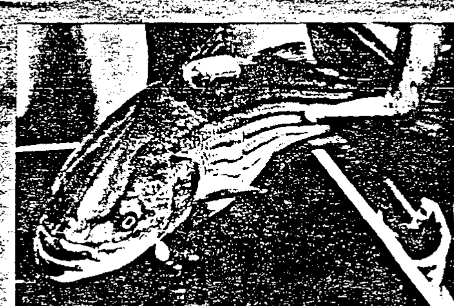
Some very interesting aspects of striped bass behavior in Watts Bar Reservoir were learned as a result of this study, but the most intriguing behavior observed was a migratory pattern of movement dictated by seasonal changes in water temperatures. During spring months, Watts Bar stripers exhibited a preference for the headwater areas of the reservoir, specifically the Clinch River below Melton Hill Dam and the Tennessee River between Fort Loudoun Dam and Kingston, Tennessee. Stripers would travel the entire length of the reservoir (70 miles) to get to these areas; some would move as much as 50 miles in one week. Two fish tagged below Melton Hill Dam were located 6 days later below Fort Loudoun Dam.

This migration was no doubt associated with the urge to spawn. Water temperatures in the headwaters ranged from 59°—66°F, the required spawning temperatures. However, while spawning attempts were made, successful reproduction by striped bass has not been documented as it has in some other reservoirs. (Successful spawning has occurred in Barkley, Kentucky and possibly Cherokee Reservoirs, but not to a significant degree).

After their spawning urges were quelled, most stripers returned to the main body of the reservoir, from Kingston to Watts Bar Dam; but some chose to spend the entire summer in the headwaters. For those stripers that returned to the main portion of the lake, their stay was to be a brief one as water temperatures slowly but surely crept upward as the summer sun intensified.

By late summer-early fall the striped bass had again moved into the headwater areas and not a single tagged fish could be located in the main body of the reservoir where water temperatures had exceeded the preferred 72° F. Initially, there was a similar environmental squeeze as observed in the Cherokee Reservoir study; warm undesirable temperatures and plentiful dissolved oxygen near the surface, with cool desirable water temperatures but inadequa' dissolved oxygen at greater depths. Hov ever, as conditions worsened, there was no squeeze, and the stripers had no choice. Water temperatures top to bottom exceeded 77° F in the main body of the reservoir, thus movement to the headwaters was imperative.

Striped bass during those critical summer months (August and September) preferred the Clinch River, which offered water below 72° F, with sufficient dissolved oxygen. That portion of the Tennessee River extending below Fort Loudoun Dam to the City of Loudon also provided refuge for striped bass by offering cooler, more oxygenated water

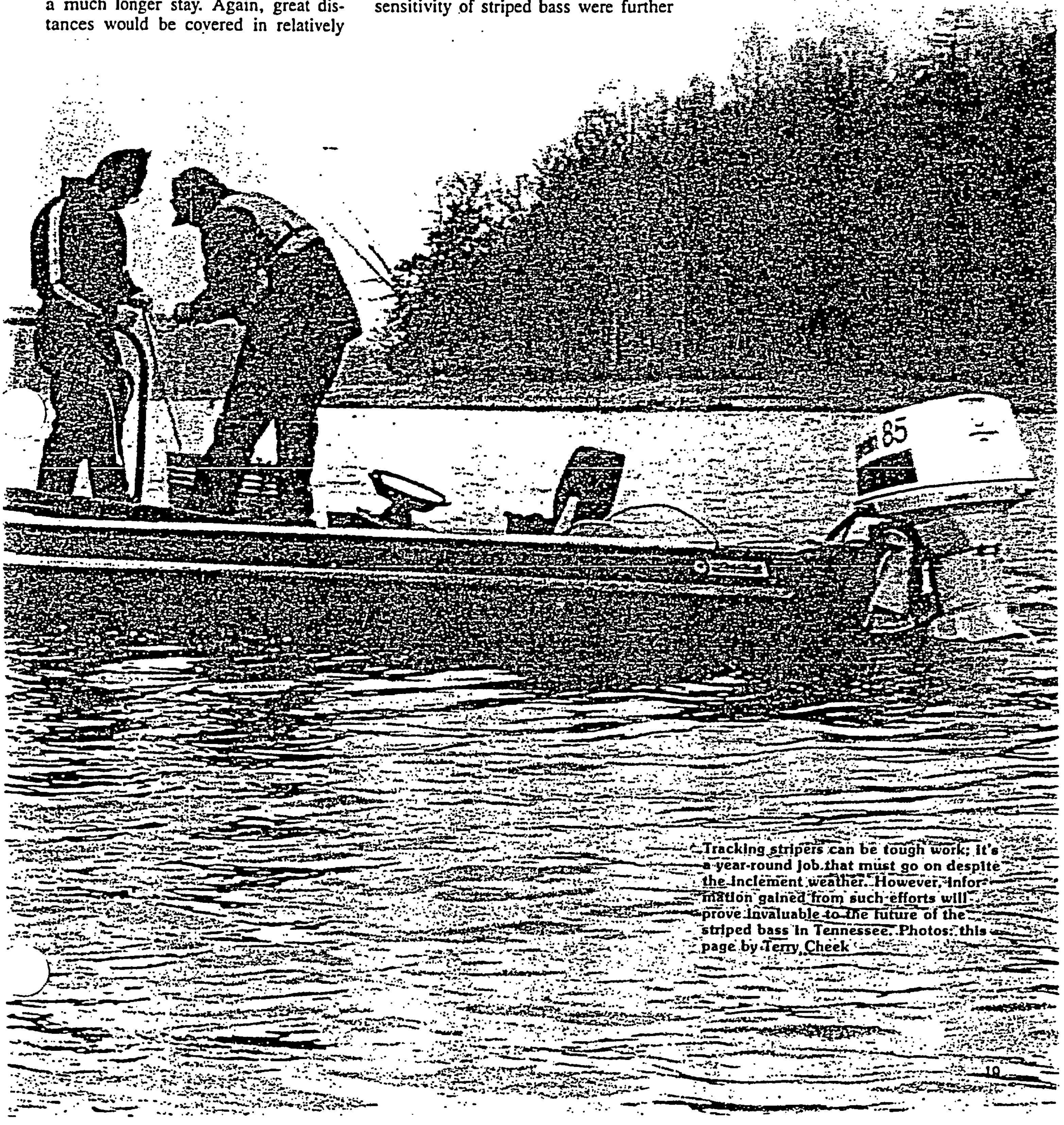


*Dissolved oxygen concentrations lower than 3.0 parts per million are lethal to most fish.

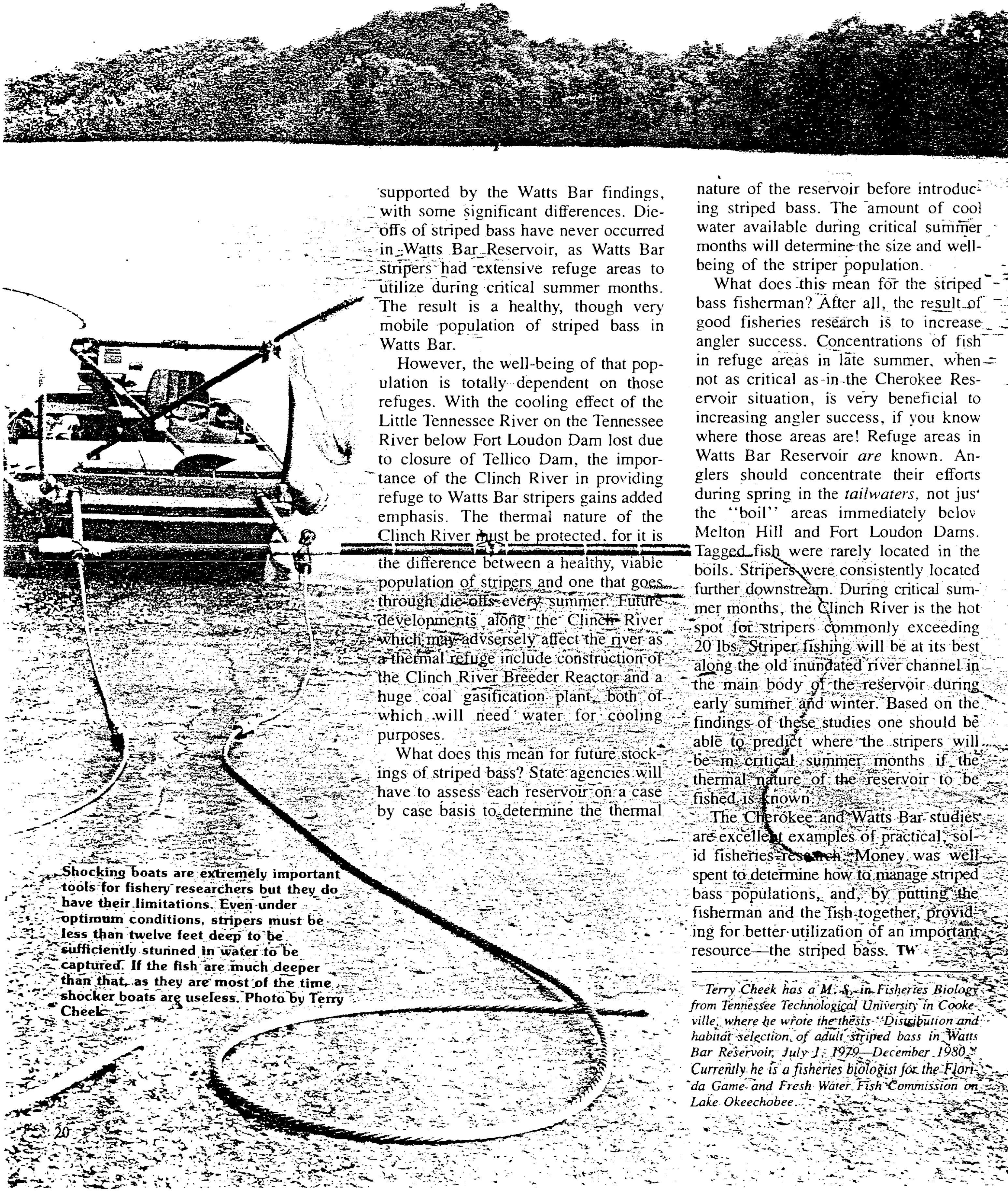
than could be found in the main body of the reservoir. The Watts Bar Reservoir record striped bass of 42 lbs. was caught in the mouth of the Little Tennessee River below Tellico Dam prior to its closure in September 1979.

As water temperatures cooled with the approach of winter, the importance of the refuge areas diminished and the stripers once again returned to the main body of the reservoir; but this time for a much longer stay. Again, great distances would be covered in relatively short periods of time. One tagged fish moved from Fort Loudoun Dam to Watts Bar Dam (70 miles) in 4 weeks; another negotiated Watts Bar Dam itself and moved 30 miles into the next reservoir downstream (Chickamauga); still another moved 18 miles overnight. To these saltwater natives, Watts Bar Reservoir must surely feel like a farm pond.

Conclusions drawn from the Cherokee Reservoir study about the thermal sensitivity of striped bass were further



Tracking stripers can be tough work; it's a year-round job that must go on despite the inclement weather. However, information gained from such efforts will prove invaluable to the future of the striped bass in Tennessee. Photos: this page by Terry Cheek



supported by the Watts Bar findings, with some significant differences. Die-offs of striped bass have never occurred in Watts Bar Reservoir, as Watts Bar stripers had extensive refuge areas to utilize during critical summer months. The result is a healthy, though very mobile population of striped bass in Watts Bar.

However, the well-being of that population is totally dependent on those refuges. With the cooling effect of the Little Tennessee River on the Tennessee River below Fort Loudon Dam lost due to closure of Tellico Dam, the importance of the Clinch River in providing refuge to Watts Bar stripers gains added emphasis. The thermal nature of the Clinch River must be protected, for it is the difference between a healthy, viable population of stripers and one that goes through die-offs every summer. Future developments along the Clinch River which may adversely affect the river as a thermal refuge include construction of the Clinch River Breeder Reactor and a huge coal gasification plant, both of which will need water for cooling purposes.

What does this mean for future stockings of striped bass? State agencies will have to assess each reservoir on a case by case basis to determine the thermal nature of the reservoir before introducing striped bass. The amount of cool water available during critical summer months will determine the size and well-being of the striper population.

What does this mean for the striped bass fisherman? After all, the result of good fisheries research is to increase angler success. Concentrations of fish in refuge areas in late summer, when not as critical as in the Cherokee Reservoir situation, is very beneficial to increasing angler success, if you know where those areas are! Refuge areas in Watts Bar Reservoir *are* known. Anglers should concentrate their efforts during spring in the *tailwaters,* not jus' the "boil" areas immediately belov Melton Hill and Fort Loudon Dams. Tagged fish were rarely located in the boils. Stripers were consistently located further downstream. During critical summer months, the Clinch River is the hot spot for stripers commonly exceeding 20 lbs. Striper fishing will be at its best along the old inundated river channel in the main body of the reservoir during early summer and winter. Based on the findings of these studies one should be able to predict where the stripers will be in critical summer months if the thermal nature of the reservoir to be fished is known.

The Cherokee and Watts Bar studies are excellent examples of practical, solid fisheries research. Money was well spent to determine how to manage striped bass populations, and, by putting the fisherman and the fish together, providing for better utilization of an important resource—the striped bass. **TW**

Shocking boats are extremely important tools for fishery researchers but they do have their limitations. Even under optimum conditions, stripers must be less than twelve feet deep to be sufficiently stunned in water to be captured. If the fish are much deeper than that, as they are most of the time shocker boats are useless. Photo by Terry Cheek

Terry Cheek has a M. S. in Fisheries Biology from Tennessee Technological University in Cookeville, where he wrote the thesis "Distribution and habitat selection of adult striped bass in Watts Bar Reservoir, July 1, 1979—December 1980." Currently he is a fisheries biologist for the Florida Game and Fresh Water Fish Commission on Lake Okeechobee.

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Temperature-Oxygen Habitat for Freshwater and Coastal Striped Bass in a Changing Climate

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Abstract.—Habitat space for a fish species is normally constrained by extreme temperatures and low dissolved oxygen concentrations that the fish avoid. Both latitudinal limits to a species' geographic distribution and availability of suitable habitat on the local level may be altered by climate change. During the next century, average temperatures are expected to rise globally, and rainfall is expected to decrease in mid latitudes and increase in high latitudes. I have predicted some possible effects of climate change on distribution of anadromous and landlocked stocks of striped bass *Morone saxatilis*. The tenuous existence of striped bass along the northern coast of the Gulf of Mexico and in Florida will likely be jeopardized by regional warming and reduced streamflow. In many freshwater lakes, reservoirs, and estuaries, the existing summer constriction of suitable habitat by high temperatures and low oxygen concentrations may be aggravated by warming, altered streamflow, and increased hypoxia. A major loss of habitat is predicted to occur in the Chesapeake Bay, where the species has had its greatest abundance historically. An expansion of the species' range around Nova Scotia and farther into the Gulf of St. Lawrence may occur, although the cold Labrador Current may increase in volume and cancel any potential water temperature increases in the northernmost range of the species. Our understanding of the habitat requirements of many commercially and recreationally important fish species exceeds our confidence in climate models, but will allow forecasts of changes in regional and local habitat suitability as our understanding of climate and our ability to forecast it improve.

The linkage between physiological performance of fishes under different environmental regimes and the volume of water that provides suitable conditions over time for sustained high performance is crystalizing as an important definition of a fish population's "habitat." This habitat is expected to be modified in local environments as climate changes in the next century. Such modification could result in changes in large-scale distribution patterns for fish species.

Thermal Niche Space

From the seminal papers of Fry (1947) on the effects of environment on animal activity and of Hutchinson (1957b) on niche space has evolved the concept of a fish's thermal niche, summarized by Magnuson et al. (1979). An "optimum" temperature for a species (or sometimes for a life stage; Coutant 1985, 1986) is exemplified by the temperature of maximum growth rate and the preferred temperature. Optimum growth rate is that attained under regimes of unlimited food supply, and the preferred temperature is the median temperature occupied in a thermal gradient that is experienced over a period of days in the absence of competing demands of food limitation, predators, or competitors; the growth optimum and preferred temperature closely coincide (Jobling 1981; McCauley and Casselman 1981), although there may be some seasonal acclimatization to lower preferred temperatures in cool seasons. Given a choice, fish in laboratory and many field situations in summer seem to occupy a thermal band within ±2.0°C of the preferred temperature. This band has been suggested by Magnuson et al. (1979) as a quantitative definition of the noninteractive "fundamental niche" of Hutchinson (1957b). Temperatures above or below this range are often actively avoided when possible. When the fundamental niche is not available, fish occupy the best conditions available (the interactive "realized niche"), which involves some sacrifice of metabolic efficiency on their part.

With the above concept of a thermal niche in mind, the thermal structure of a water body (i.e., the spatial and temporal distribution of water temperatures) can be analyzed over an annual cycle to determine quantitatively the amount of available water—the thermal niche space—that promotes high performance for a fish species (Coutant 1987b; Magnuson et al. 1990, this issue). The amount of water that is within the 4°C fundamental thermal niche has been shown to be positively related to fishing yield for three fish species in a set of 21 large North American lakes (Christie and Regier 1988).

Hypoxia

The clear linking of thermal niche space and fish production, however, is confounded when the habitat is made unsuitable by a low dissolved oxygen concentration. Anoxic or hypoxic water is common in the depths of biologically productive lakes, reservoirs, and estuaries during warm months (Hutchinson 1957a). Dissolved oxygen concentrations lower than about 6 mg/L can lower fish production; concentrations that are below 2–3 mg/L are physiologically critical for the metabolism of most fish species (Chapman 1986). Often, water volumes that are cool enough in summer to lie within the thermal niche of coldwater or coolwater fishes (as defined by Hokanson 1977) become depleted of oxygen before fall mixing occurs. In response, resident fish move to relatively small thermal refuges where temperature and oxygen remain favorable. If such refuges are nonexistent, fish are obliged to occupy waters of progressively increasing temperature as the oxycline, the layer with dissolved oxygen concentration rapidly decreasing to below 2–3 mg/L, rises in the water column (Rudstam and Magnuson 1985; Coutant 1987b). Whether thermal refuges are available or not, spatial squeeze and metabolic inefficiency can lead to lowered performance and, in extreme cases, to mortality and reduced population success (Coutant 1987a).

Climate Change

Global climate may change (or is changing now) because of increased atmospheric concentrations of carbon dioxide, chlorofluorocarbons, methane, and other radiatively active gases (Ramanathan 1988; also see other papers in this issue). Several aspects of this climate change can affect fish habitat: a global increase in surface air and water temperatures, especially in winter and at high latitudes; altered precipitation patterns across continents; increased runoff at high latitudes; changed wind direction and intensity that affect mixing of water bodies and modify oceanic and coastal currents; and an altered freeze–thaw cycle, that includes both earlier seasonal snowmelt and ice breakup and later freeze-up. Surface warming of a few degrees Celcius has been forecast after a doubling of atmospheric carbon dioxide, whereas estimates of associated changes in regional hydrological balances and wind forcing are expected to be of the order of 5 to 10% relative to present-day values (Wright et al. 1986).

Quantitative estimates of several facets of climate change are available from two general circulation models. One is the product of the U.S. National Aeronautics and Space Administration's Goddard Institute for Space Studies (GISS); the other is from Princeton University's Geophysical Fluid Dynamics Laboratory (GFDL). Both are dynamic models that simulate the physical processes of the atmosphere in order to estimate global climate. The models operate on short time steps, and the output is saved as estimates of average monthly values for weather variables in segments of the globe (grid boxes, 8° latitude × 10° longitude in the case of GISS and 4.4° latitude × 7.5° longitude for GFDL). They are calibrated by mimicking present climate and have been used to simulate climates associated with various alternative compositions of greenhouse gases. Grotch (1988) provided information on these and other general circulation models used for North America and compared their predictive abilities.

I discuss in this paper how an altered climate can affect two simultaneous determinants of fish distribution and performance, namely thermal niche space and suitable dissolved oxygen concentration, so that fish population success is altered. I suggest general principles regarding the effects of climate change on fish by forecasting some results for a sample species, the well-studied striped bass *Morone saxatilis*, which has both landlocked freshwater and anadromous coastal stocks.

Striped Bass

Striped bass are distributed in eastern North America from the St. Johns River, Florida, to the St. Lawrence River estuary, Quebec; a relict population occurs in lower reaches of rivers draining to the northern Gulf of Mexico (Setzler et al. 1980; Figure 1). Population strength since the mid-1800s, when records began to be kept, has been greatest roughly from Cape Hatteras, North Carolina, to Cape Cod, Massachusetts. The St. Lawrence estuary and the Gulf of St. Lawrence are sparsely populated by striped bass (Y. Mailhot, Québec Ministère du Loisir, de la Chasse et de la Pêche, personal communication). Northern stocks have mixed success and some uncharacteristic life history attributes, such as upstream migration in fall to overwinter in lakes (Rulifson et al. 1987). The species also is largely riverine south of Albemarle Sound, North Carolina (McIlwain 1980). Extensive north–south migrations occur seasonally along the eastern seaboard between Cape Hatteras and the Gulf of Maine (Boreman and Lewis 1987). The

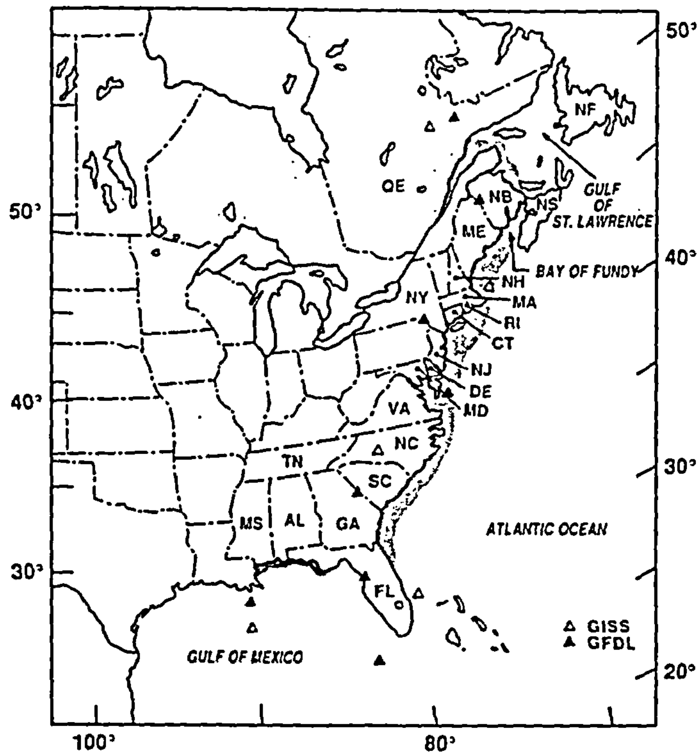

FIGURE 1.—Coastal distribution of striped bass in eastern North America (shaded) and centers of grid polygons of the GISS and GFDL climate models used to estimate future temperature changes (triangles). Striped bass distribution is based on Setzler et al. (1980); climate model data are from the U.S. Environmental Protection Agency, Office of Policy, Planning, and Evaluation, Washington, D.C.

species has been introduced to many freshwater lakes and reservoirs, particularly in the southeastern USA, and to the Pacific coast. The adult striped bass's fundamental thermal niche appears to be 19–23°C. Adults have a strong tendency to avoid temperatures in excess of about 25°C; juveniles have a higher fundamental thermal niche of about 24–28°C (Coutant 1985; Matthews et al. 1989). Available evidence suggests that the different niches for juveniles and adults are relatively consistent for each throughout the species' range.

Environmental Change Scenarios

I use predictions of climate resulting from a doubling of carbon dioxide levels from the GISS and GFDL models as a basis for constructing aquatic habitat scenarios to be used in evaluating effects on fish. The model results were obtained from the U.S. Environmental Protection Agency (EPA), Office of Policy, Planning and Evaluation, which has coordinated formulation of a consistent set of model outputs for use by numerous investigators (Smith 1989). The centers of each model's grid squares for eastern North America are shown in Figure 1. It is important to consider more than one of these general circulation models to convey a sense of the uncertainty that pervades their forecasts. Conversely, when the two models tend to agree, we may feel more confident in the nature, if not the precise extent, of the change that is forecast. However, the several models available are not necessarily independent in their origin and assumptions. General circulation models are relatively new tools for estimating global climate, and the results should be used with caution. Nevertheless, it is useful for the fisheries profession to keep pace with the level of sophistication developed by climatologists.

The general circulation model results used here are incremental changes from current conditions. The model output provided to investigators consisted of estimated average monthly values of weather conditions (1) at the time when the global climate has come to equilibrium with double the present amount of CO_2 ($2\times CO_2$), and (2) under "current" conditions ($1\times CO_2$) that are defined as an average for the period 1951–1980. The EPA has calculated ratios of these two estimates for each grid square and month and provided them to investigators. To obtain a $2 \times CO_2$ scenario for a particular aquatic habitat, I have multiplied the models' monthly and grid-box-specific ratios of $2 \times CO_2 : 1 \times CO_2$ for various weather attributes by historic conditions at selected sites in a grid box. This approach was used by Parry (1987) to analyze the effects of climate change on agriculture. For example, if a grid box is estimated to average 2°C warmer in May in the $2 \times CO_2$ model calculations, then all locations in that grid box are assumed to be 2°C warmer than the present data in May. Year-to-year and daily variabilities are assumed to be the same, even though some investigators have said that changes in these variabilities may be the most striking feature of climate change (Healey 1990, this issue). Historical data for my paper have been obtained from several sources, including the U.S. Department of Commerce (NOAA 1973), for U.S. coastal waters; Cheek et al. 1982) and the Tennessee Valley Authority (unpublished data), for Tennessee reservoirs.

When applied to aquatic environments, my approach encounters problems that do not arise when altered weather patterns are estimated for agriculture. Aquatic systems have annual heat budgets and internal circulation patterns that cause water temperatures to diverge from direct parity with air temperatures (Wright et al. 1986; Schertzer and Sawchuk 1990, this issue). These influences on thermal structure can be modeled if the system is well understood (Blumberg and Di Toro 1990, this issue; McCormick 1990, this issue) or empirical correlations between air and water temperatures can be made if historical records are available (Hill and Magnuson 1990, this issue); both conditions are often not met for waters of interest. In coastal waters, a changed hydrological cycle will alter salinity, and relatively small changes in salinity may affect both the static stability of the water column and the biosphere directly (Wright et al. 1986). Sea-level rise, predicted as a result of global warming (NRC 1985), would alter shoreline contours and thus current patterns. Any attempt to speculate upon changes in aquatic systems caused by predicted changes in atmospheric forcing is thus bound to be uncertain.

Nonetheless, I generally take the simplistic view that water temperatures characteristic of a site can be adjusted upward directly by the models' predicted change in air temperatures to provide estimates of new water temperature conditions.

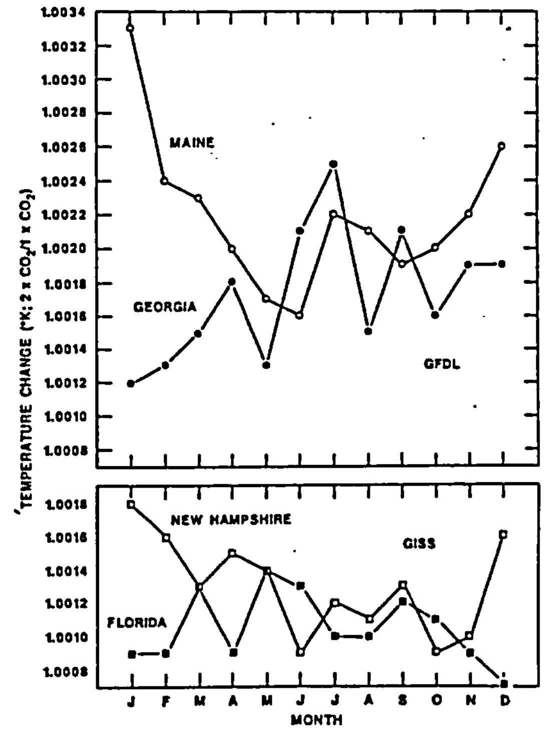

FIGURE 2.—Latitudinal and seasonal differences in temperature rise predicted by the GISS (lower panel) and GFDL (upper panel) climate models for northern and southern areas in the eastern range of striped bass. Temperatures under conditions of double the present CO_2 concentrations in the atmosphere and of current levels ($2 \times CO_2 : 1 \times CO_2$) are expressed as the ratios of absolute temperatures (°K). (Plotted from data supplied by the U.S. Environmental Protection Agency.)

Water current patterns are assumed to remain constant for these temperature adjustments. Transient effects—any climatic or aquatic effects characteristic of the period of transition to a $2 \times CO_2$ equilibrium—are also ignored.

Latitudinal and seasonal differences in temperature rise are characteristic of the model results along eastern North America (Figure 2). In northern latitudes, typified by grid square centers off the coast of New Hampshire and in northern Maine in the GISS and GFDL models, respectively (Figure 1), the estimated future temperature rise is greatest in winter. These winter increases are greater than any seen in the southern latitudes typified by Florida and Georgia. Southern latitudes will have their greatest temperature increases in the warm months, and the magnitudes of increase generally will be similar at southern and northern latitudes during summer. The GFDL model tends to predict greater temperature rises than does the GISS model for the same times and places, even when allowances are made for the models' somewhat different size and placement of grid squares.

Results

Latitudinal Distribution

Fish distribution on a continental scale can be expected to shift northward as global temperatures rise. For coastal stocks of striped bass, the historical pattern of seasonal coastal temperatures (Figure 3, left panel) is accompanied by seasonal north–south migrations (Boreman and Lewis 1987). The linkage is thought to be causal (Coutant 1985), although the causality is controversial. Winter aggregations are common along the coasts of the Carolinas. The fish appear attracted to the warmer southern waters; large numbers leave the north when temperatures cool to below about 5°C. Some fish find overwintering sites in the north, often in deep holes in estuaries, although striped bass in the Canadian Maritimes tend to move into freshwater lakes in winter (Rulifson et al. 1987), perhaps finding warmer water there. With spring warming, ocean fish move northward. Spawning, generally in or close to natal rivers, occurs somewhat below the cooler end of the adult fundamental thermal niche (Setzler et al. 1980). Spawning is treated separately in the following discussion. Optimal temperatures for adults have historically prevailed in midsummer in the mid-Atlantic to southern New England area during the times adult striped bass are present (NOAA 1973), whereas the southern region that is avoided from May through September is above 25°C. With autumn cooling, many adults appear to follow optimal temperatures southward.

A pronounced upward shifting of estimated annual coastal temperatures characterizes both climate models (Figure 3). The South Carolina coast could be above 25°C, and avoided by striped bass, from April to early November, during which time temperatures may peak well above 30°C. It seems unreasonable to expect water temperatures to rise to 37°C as suggested by air temperature differentials in the GFDL model, however. Stocks along the Gulf of Mexico and Florida east coast may be reduced or extirpated. Summer water temperatures there could be much in excess of those that the fish can tolerate, except where cool river waters are maintained by summer hypolimnetic discharges from reservoirs or artesian water from large springs—which seem to be major factors in survival now (Wooley and Crateau 1983; Coutant 1985). The Roanoke River–Albemarle Sound striped bass, which lie at the boundary between the coastal migratory habits of the more northern fish and the riverine habits of the more southern stocks, could become clearly riverine and congregate in summer in the cool dam tailwaters upriver.

The continued availability of cool springs and hypolimnetic discharges as riverine thermal refuges may be in jeopardy, however. Increased temperatures in the past have resulted in increased aridity in the southeastern USA (Coleman 1988). Aridity could reduce the volume of groundwater and the storage of cold winter water in reservoirs. The GISS and GFDL models are inconsistent in their predictions of precipitation. The GISS model predicts increased precititation in the southeastern USA for all months other than September–December; the GFDL model predicts increased precipitation in February–April and November–December but decreased precipitation in all other months.

The zone of optimal coastal temperatures for striped bass in summer could shift to mid-New England, north of Cape Cod. The latitude of Chesapeake Bay, where males and perhaps half of the females are resident throughout the year (Kohlenstein 1981), would probably become too warm (as discussed in more detail later in this paper).

Stocks in the Bay of Fundy (Figure 3; station ME_2 in northern Maine), in the Saint John estuary (New Brunswick), and in the Northumberland Strait and estuaries entering the Gulf of St. Lawrence (described by Rulifson et al. 1987) now live under suboptimal thermal conditions and have sporadic year classes; warming could produce conditions closer to optimal and thus may increase population size and range. Particularly important in these northern regions would be warmer conditions for juvenile rearing, because the juvenile thermal niche of 24–28°C would be more likely to occur in the shallow estuaries.

A projected expansion of the striped bass range, or at least an increase in population abundance, in the Gulf of St. Lawrence region would depend greatly on the configuration of coastal currents there. Wright et al. (1986) speculated upon changes in ocean and coastal currents and temperatures in eastern Canada, based on an understanding of the present current regime and tendencies for change under a climate change scenario (Figure 4). In general, they expect that coastal water temperature will increase less than surface air temperature.

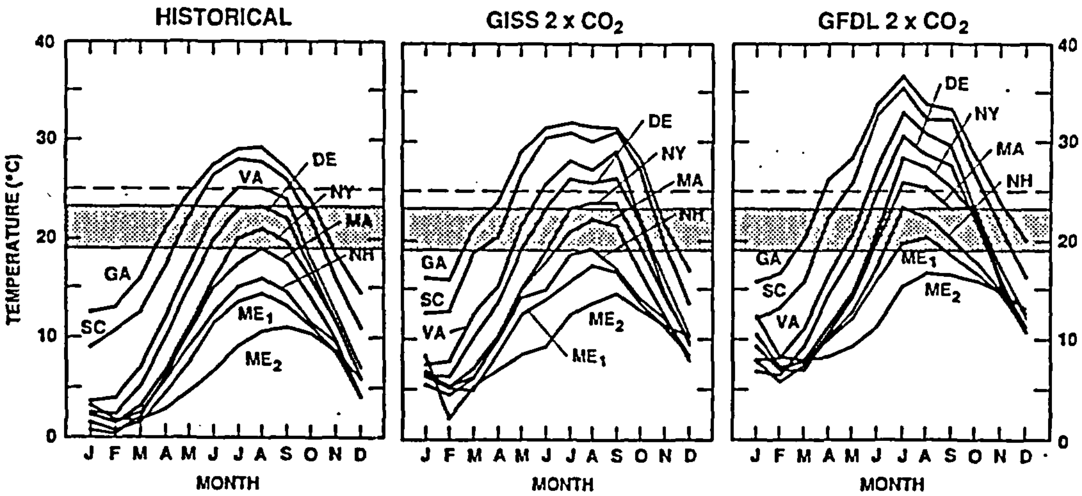

FIGURE 3.—Atlantic coastal water temperatures: historical and after adjustment according to two global climate models (GISS, GFDL) that simulate a climate under equilibrium with a doubled concentration of atmospheric carbon dioxide (monthly historical averages: NOAA 1973). Stations are Brunswick, Georgia (GA), Myrtle Beach, South Carolina (SC), Kiptopeke, Virginia (VA), Breakwater Harbor, Delaware (DE), Montauk, New York (NY), Cape Cod Canal, Massachusetts (MA), Portsmouth, New Hampshire (NH), Bar Harbor, Maine (ME_1), and Eastport, Maine (ME_2); ME_2 is presumed representative of the Bay of Fundy. Dashed line indicates the upper avoidance temperature for adult striped bass (25°C); shaded area is the striped bass thermal niche (19–23°C).

Both oceanic and coastal circulation would be involved in altering nearshore temperatures in the Canadian Maritimes. On a large scale, the warm Gulf Stream is expected by Wright et al. (1986) to weaken somewhat, and the cold Laborador Current may strengthen. These changes in the northwest Atlantic are caused by weakened wind-driven gyres, the consequences of reduced wind stress magnitudes and stronger buoyancy-driven currents caused by an intensification of the hydrologic cycle. Continental shelf waters could, therefore, be cooler than at present. Nearer shore, higher continental runoff via the St. Lawrence and other rivers is expected to increase the strength, and further reduce the salinity, of the relatively cold and fresh buoyancy-driven currents that account

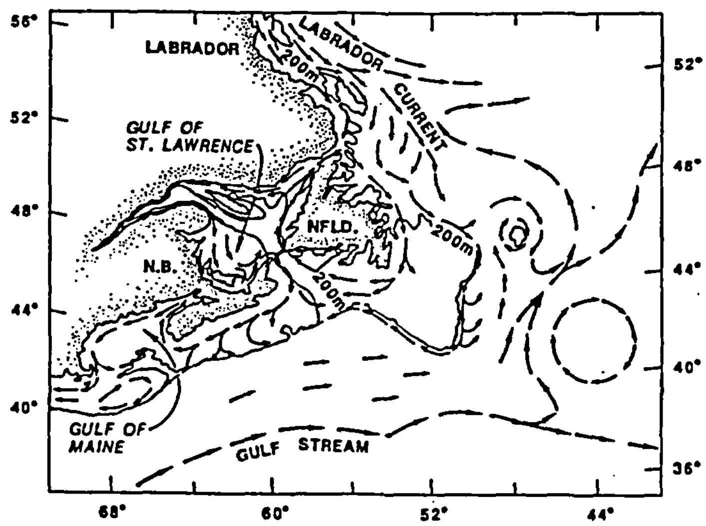

FIGURE 4.—Present major surface currents along the east coast of Canada that influence water temperatures in the Gulf of St. Lawrence, the Gulf of Maine, and adjacent coasts. (Adapted from Wright et al. 1986).

for the general southward flow over the continental shelves from Labrador through the Gulf of Maine. Cohen (1986) and Marchand et al. (1988), however, suggested that there will be a net reduction in outflow from the Great Lakes under a $2\times CO_2$ scenario, which would minimize any strengthening of the southward currents; the St. Lawrence River accounts for about 30% of the total freshwater flow to the Gulf of St. Lawrence. How much the general warming of high-latitude source waters would offset the cooling of coastal zones by any increase in southward coastal flows is unknown.

Many peculiarities in the existing stocks of striped bass of the Canadian Maritimes, such as wintering in lakes (with downstream migrations to spawn), fall spawning, spawning just after ice disappears, and sporadic year classes (Rulifson et al. 1987), may be adjustments to life in a particularly cold region. These deviations from typical individual and population behavior may be analogous to the appropriation of cooler rivers by the southern stocks. These peculiarities of the northern stocks may disappear as climate warms. If the specific overwintering and spawning behavior patterns of these stocks are not in themselves genetically determined, but rather local expressions of the general temperature preference genotype of the species, these northern fish may be able to assume life history patterns more characteristic of the zone where the species population is strongest.

Timing of Spawning

With temperatures predicted to be higher under a $2\times CO_2$ scenario, annual events that seem related to the water temperature cycle may have their timing advanced. An important example is spawning. After day length sets the annual maturation cycle of temperate-zone fishes, temperature plays a dominant role in keying the actual spawning events. Striped bass are reported to spawn in the wild over a range of about 10 to 25°C in spring (Westin and Rogers 1978). Rulifson et al. (1987) reported one incidence of fall spawning near the northern end of the range. The average temperature at maximum striped bass spawning across the species' east coast range is 16°C, and first spawning occurs at an average 14.8°C, based on data in Westin and Rogers (1978). Whether either of these temperatures represents index of successful recruitment is debatable, however, for multiple spawning times are common in many rivers and survival of eggs and larvae appears to depend on the relative timing of egg deposition and environmental vagaries within the spawning period (Polgar 1982). Nonetheless, it is instructive to see how much the timing of these spawning indices might change under a climate-change scenario.

The estimated change in timing of spawning depends on both location and climate change model (Figure 5). In northern latitudes, exemplified by coastal water temperatures at Bar Harbor, Maine, the two models differ by nearly 1 month in the estimated time at which spawning temperatures will be reached. Because striped bass in Canada are reported to spawn over a wide range of temperatures, it is difficult to estimate a timing change. Also, river temperatures may influence spawning more than coastal temperatures. At other sites, exemplified by the Hudson River, the Chesapeake Bay, and the Savannah River, the estimated differences in spawning times are more clear, ranging from 3 to 4 weeks.

Concurrent with temperature change can be a flooding of the spawning estuaries and wetland nursery areas by rising sea levels (Orson et al. 1985). Predictions of how the coastal environment necessary for striped bass spawning and juvenile rearing will respond to a rising sea level require consideration of many coastal processes (Mehta et al. 1987) including tidal ranges, storm surges, intrusion of groundwater and surface water, and sedimentary processes, as well as the responses by the plant communities of coastal ecosystems to changes in these processes. The results are likely to be highly site specific and to include changes both in temperature and dissolved oxygen structure and in physiographic features.

Suitability of Coastal Estuaries

As climate warms, estuaries now highly important for fish species such as the striped bass may no longer provide suitable thermal niche space, especially in summer. A longitudinal profile of Chesapeake Bay illustrates potential changes in thermal habitat suitability during the warm months of May through October (Figure 6). In a representative year such as 1968 (left column), spring warming of the Susquehanna River and solar insolation cause upper bay and surface temperatures to exceed striped bass's upper avoidance temperature of 25°C in early July (Seitz 1971). By early August, two zones have water warmer than 25°C extending from surface to bottom: the shallower part of the upper bay north of Annapolis and a roughly 75-km reach extending between the

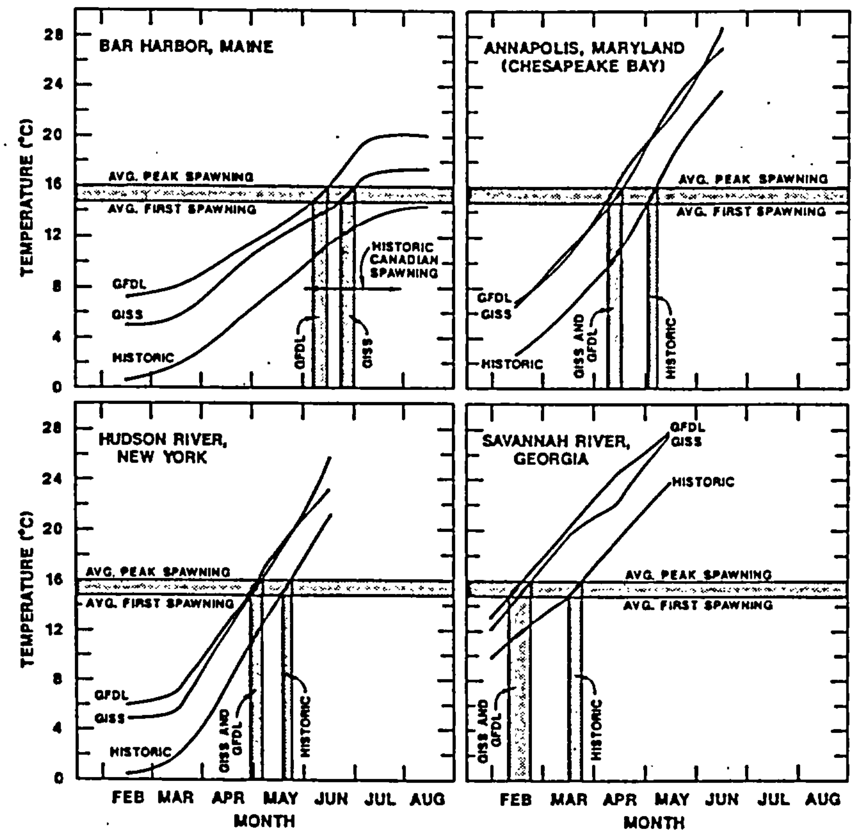

FIGURE 5.—Spawning times of striped bass, historical and as estimated by two climate models (GFDL, GISS) at four locations in the species' latitudinal range. Horizontal shaded area indicates the thermal range between average first and peak spawnings (Westin and Rogers 1978). Curves are rising spring temperatures (NOAA 1973), as modified by the temperature differences estimated by the GISS and GFDL climate models. Intersections of spawning temperatures with the temperature curves are projected downward (vertical shading) to dates on the horizontal axis.

mouths of the Rappahannock and Patuxent rivers. The latter reach is suspected of being the site of a thermal blockage that could have historically separated the bay populations into a largely resident upper bay stock and a more coast-oriented lower bay stock (Coutant and Benson 1988). In any case, many of the adult striped bass that were in the bay in spring leave for the coast (Kohlenstein 1981), a move that is believed related to temperature (Coutant 1985). The volume of water above the upper avoidance temperature cools and dissipates by mid-September. The year 1968 was somewhat warmer than the average year, based on a 12-year (1949–1961) summary by Stroup and Lynn (1963), although intersection of the 25°C isotherm with the shallow sill at the mouth of the Rappahannock River is typical of the average year (Coutant and Benson 1988). An alternative exit from the upper bay through the Chesapeake and Delaware Canal, known to be used in spring (Koo and Wilson 1972), is also warmer than 25°C in summer and is probably avoided.

The annual timing and volume of water above 25°C may expand under a warmer climate (Figure 6, second and third columns). The 1968 pattern of early July is nearly replicated in early June by the GISS model estimates; the intersection of 25°C with the bottom in the lower bay has already occurred by this time in the GFDL estimates. Essentially the entire bay is predicted to be above 25°C from early July through mid-September in both 2 × CO_2 scenarios. The deeper portion of the bay (which is saline and the last to be mixed by winds) remains above 25°C even in late October in the GFDL forecasts. Thus, the month-long periods of unsuitably high temperatures for adult striped bass that have occurred in a large portion of the bay in recent years may increase to about

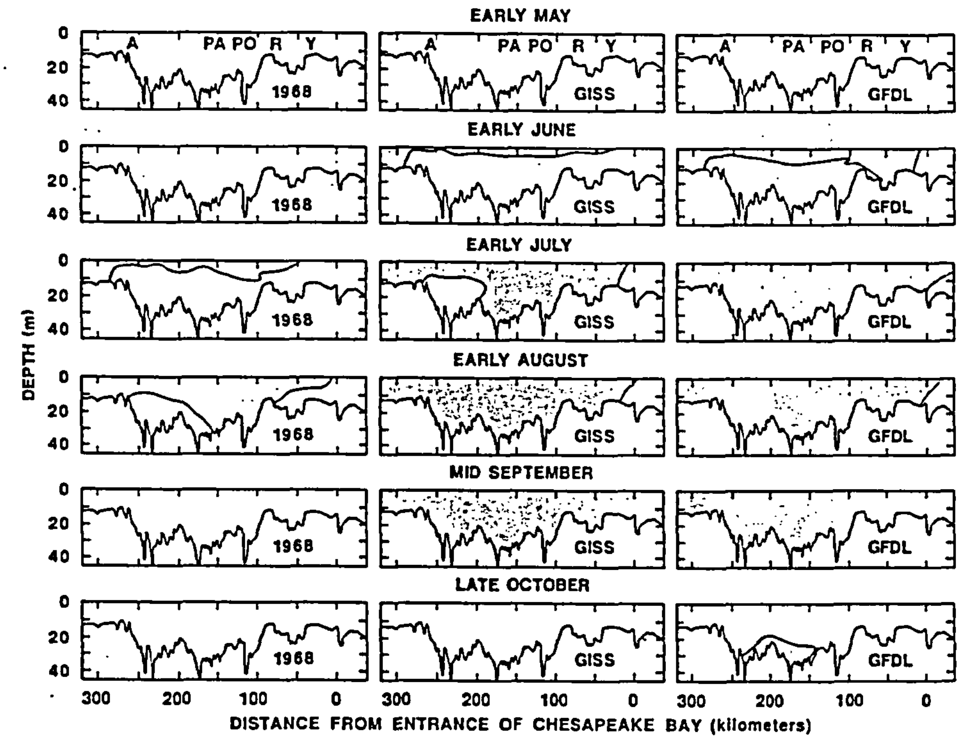

FIGURE 6.—Depths along the longitudinal axis of the Chesapeake Bay where temperatures exceeded the upper avoidance temperature of striped bass (>25°C, shaded) during May–October 1968 (left panels) and where they exceed that threshold when the 1968 data are adjusted upward according to projections of the GISS and GFDL global climate models for a doubling of atmospheric carbon dioxide concentration (middle and right panels). In each panel, the Susquehanna River is at left, the coast at right, and the lower curve is the bottom contour. Landmarks (top left panel) include Annapolis, Maryland (A), and the Patuxent (PA), Potomac (PO), Rappahannock (R), and York (Y) river mouths. (Adapted from Seitz 1971.)

3 months of equally or more unsuitable thermal conditions in the future.

A current problem for striped bass in Chesapeake Bay—expanded anoxia in the deeper waters over the past two decades (Officer et al. 1984; Price et al. 1985)—may be intensified by climate warming. Earlier temperature rise and protracted fall cooling may mean both earlier and more prolonged hypoxia. Thus, the deeper layers with cooler temperatures closer to those preferred are likely to be unavailable to striped bass; only waters much warmer than 25°C may remain oxygenated in the middle and upper bay. Anoxia is related to the strength of water column stratification, which, in turn, is influenced by freshwater runoff from the Susquehanna River (Schubel and Pritchard 1986). Projected changes in rainfall and runoff with development of a warmer climate will affect the Chesapeake Bay stratification regime in ways beyond those considered here. Both climate models estimate precipitation changes, but they are highly variable in the late winter and spring. Hydrodynamic models of the Chesapeake Bay that are under development (HydroQual, Inc., Mahwah, New Jersey, unpublished) should be able to estimate these temperature–oxygen habitat changes quantitatively.

Despite the loss of suitable temperature–oxygen habitats in summer, conditions in the bay during the remainder of the year might be more suitable for striped bass—closer to the thermal niche—than they are now, and thus might promote higher annual striped bass production. Magnuson et al. (1990) projected a longer growing season for cool- and coldwater fishes in some of the Great Lakes after a simulated climate warming. For juvenile striped bass, with their higher fundamental thermal niche, the suitable habitat in Chesapeake Bay could very well expand. However, this scenario would require alternative summer habitat for the large striped bass in the open coastal waters and larger-than-present annual thermoregulatory migrations into and out of the bay similar to the migrations seen in some freshwater reservoirs (Cheek et al. 1985). Such movement occurs now among the larger females (Kohlenstein 1981), although thermoregulatory mechanisms are not the universally accepted explanation of them (Coutant 1985). It could be of most benefit to those fish occupying the lower bay and not trapped in the upper reaches by high temperature at the sill near the Rappahannock River mouth.

Habitat Space in Southeastern Reservoirs

Introduction of striped bass into purely freshwater environments since the late 1950s (Stevens 1975) has opened a vast array of new habitats to the species. Many introductions have been highly successful, and important recreational fisheries have developed. In some instances, however, the populations that were established have experienced physiological difficulties leading to summer mortalities (Matthews 1985), high temperature and low dissolved oxygen concentration being implicated in many of these cases (Coutant 1985). It was investigation of these cases of environmental stress in fresh water that led to better understanding of the species' thermal niches, which change with age (Coutant 1986). If freshwater populations are now being restricted by summer conditions of temperature and dissolved oxygen in many lakes and reservoirs, climate change that may both raise temperatures and reduce dissolved oxygen concentration could be detrimental to summer survival. There might be the benefit of an extended period of optimal temperatures in the cooler months, however, as projected for the Great Lakes (Magnuson et al. 1990).

I examined the annual temperature cycle in Tennessee reservoirs with different geographies and hydrodynamics. One, Watts Bar Reservoir, is a mainstem Tennessee River impoundment that is highly riverine (largely confined to the river channel, with low volume in relationship to flow). The other, Cherokee Reservoir, is a tributary storage reservoir, characterized by high volume in relation to flow. Each is believed typical of many mainstem and storage reservoirs in river systems throughout the southeastern USA. Temperature and dissolved oxygen profiles from the lower two-thirds of each reservoir were used, even though each has thermal refuges that are used by larger striped bass in the warm months (Schaich and Coutant 1980; Waddle et al. 1980; Cheek et al. 1985).

Climate warming appears to exert its effect on these reservoirs primarily by lengthening the summer period of supra-optimal temperatures (Figure 7). If one assumes that deoxygenation proceeds in step with water temperature (see Blumberg and Di Toro 1990 for Lake Erie), a lengthened period of hypoxia must be projected. In Watts Bar Reservoir, the summer period of unsuitable temperature–oxygen conditions that presently lasts about 1 month would be lengthened to 3–4 months according to the climate model projections. In Cherokee Reservoir, the current 3-month duration of unsuitable habitat could be lengthened to about 4 months.

The length of time when water temperatures lie in the thermal niche of 19–23°C, or a broader acceptable range of 17–25°C, changes little. In Watts Bar Reservoir, this duration could be reduced, primarily because a prolonged current period of 19–25°C would be eliminated; there could be a slight increase in duration of these temperatures in Cherokee Reservoir. Each type of reservoir warms and cools rapidly, passing through the preferred thermal range for striped bass rather quickly. Behavioral thermal regulation could, however, allow a fish to extend the time it experiences the optimum temperature range, if the fish moved, for example, from warm shorelines to deeper and cooler reaches.

Watts Bar Reservoir maintains a healthy population of striped bass in part because it has a large thermal refuge in the form of a tributary, the Clinch River, which is fed by hypolimnetic discharge from upstream Norris Reservoir (Cheek et al. 1985). There is an annual migration of striped bass into and out of this tributary that is believed to represent thermoregulation. Under the simplistic climate change scenario of simply raising water temperatures, the summer thermal conditions in the Clinch River would merely rise from the low end of the thermal niche to the upper end. The seasonal pattern of hypolimnetic discharges could be affected by the heat budget of Norris Reservoir, however, and by the operating agency's water management in the face of altered runoff and demand for electricity. Alterations of thermal patterns in a stairstep of reservoirs could be complex.

Discussion

As we speculate upon the possible changes in fish species' distributions and population successes in a changing climate, we recognize inadequacies in our knowledge of both fish biology and ecology and the dynamics of temperature and dissolved oxygen in natural waters, as well as in the

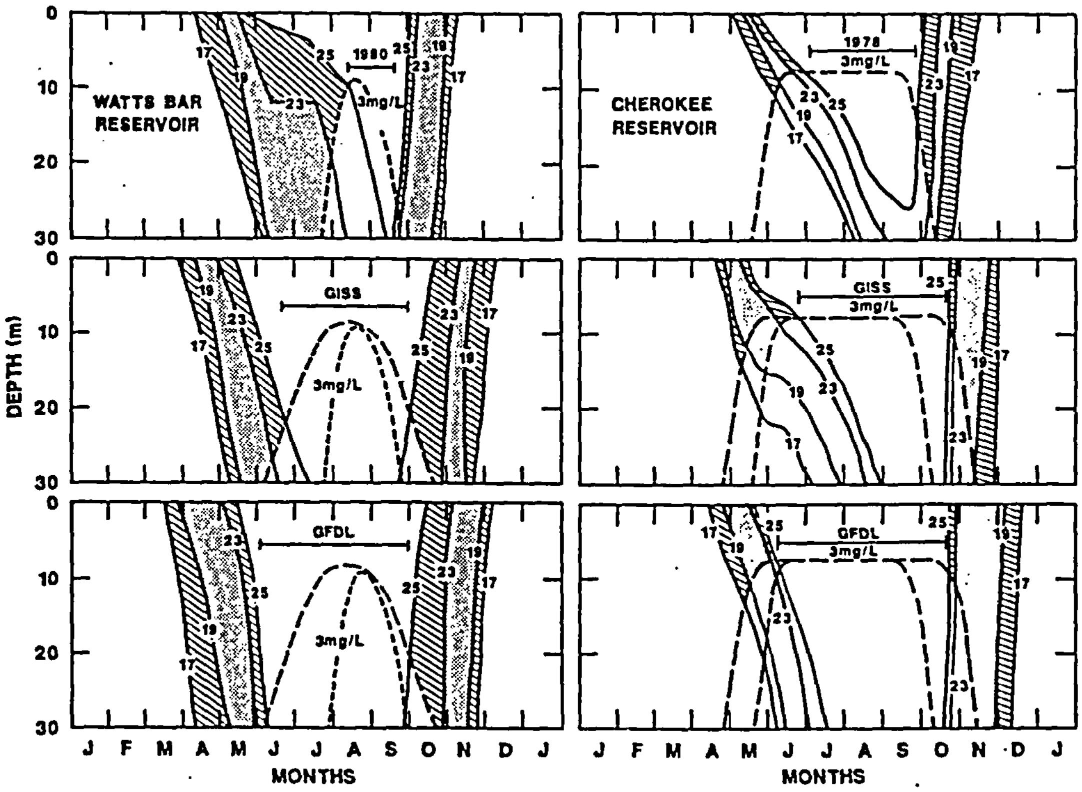

FIGURE 7.—Annual thermal niche space for adult striped bass in the downstream portions of two Tennessee reservoirs, Watts Bar (main stem) and Cherokee (tributary storage), historically and after adjustment of temperatures upward according to projections of the GISS and GFDL global climate models for a doubling of atmospheric carbon dioxide concentration. The fundamental thermal niche for adult striped bass is the preferred temperature, 21 ± 2°C (stippled areas); a band of ±4°C (cross-hatched) includes the upper avoidance temperature of 25°C (Coutant 1985). Dashed lines indicate habitat unsuitable because of low dissolved oxygen (DO < 3 mg/L); short dashes are historial data, and long dashes are an estimated curve based on the assumption that oxygen depletion is a function of temperature. Times when no habitat is suitable for striped bass (>25°C and <3mg/L DO) are bracketed.

climate models themselves. The genetic diversity of striped bass and its relationship to the species' adaptability to climate change is largely unknown. Whether small differences in "preferred" temperatures seen in various field studies indicate rapid adaptation by local populations with high original genetic diversity or simply errors and variability of observations remains uncertain. However, when we try to estimate climate change effects on a well-studied species such as striped bass, we find that the understanding of fish habitat requirements exceeds confidence in the climate models and in predictions of future water temperatures and dissolved oxygen concentrations. Our understanding of habitat requirements, although still somewhat controversial in its own right, allows tentative forecasts of population trends to be made. The present exercise should be fruitful more for its identification of direction of change and of uncertainties than for reliable predictions.

Climate models with more predictive power would be welcomed, but development of such models is in its infancy. Reliance on scenarios that predict equilibrium conditions with a $2\times CO_2$ condition are clearly unrealistic, for the world's climate will lag behind a dynamically rising concentration of gases in the atmosphere that affect global heat balance, and there is unlikely to be a halt in warming at the $2\times CO_2$ level. Much more severe conditions may prevail in situations of greater CO_2 increase. Prudence for those interested in protecting or enhancing fisheries seems to lie in making incremental gains in forecast realism as confidence in the evolving climate models improves.

Clearly, forecasting effects on fisheries will depend on much better resolution of the linkage between atmospheric changes and the thermal and oxygen structures of water bodies. There has been notable success with research-scale models of the heat and chemical budgets and hydrodynamics of lakes and reservoirs (Brown 1986; Blumberg and Di Toro 1990; McCormick 1990; Schertzer and Sawchuk 1990) and estuaries (HydroQual, Inc., unpublished), but most estuarine and coastal waters remain less well understood and modeled. Only qualitative generalizations about altered current patterns and future thermal and chemical regimes seem possible for the coasts (Wright et al. 1986). Close coordination of physical and chemical modeling with intended fisheries applications seems desirable, the goal being to estimate the quantitative aspects of thermal and chemical structure so essential to fish habitat.

The detailed responses of striped bass to constriction and elimination of their most suitable (fundamental) temperature–oxygen habitat should be quantified. Severe temperature–oxygen squeezes are likely in many fresh waters and estuaries from the middle of the species' range to its southern end, based on present experience and the trend of climate changes. Behavioral responses and the responses of individuals and the aggregate population to various degrees of physiological stress in the "realized niches" should be quantified in areas where these habitat limitations now occur. Effects of changes in behavior and physiology on population success should be determined, in particular, in the linkage between bioenergetic deficits in summer and reproductive competence the following spring (Coutant 1987a).

The plasticity of northern populations as climate changes bring their habitat closer to optimal needs to be explored for its implications for fisheries management. On the positive side, fisheries management agencies may wish to capitalize on a future expansion of range and increased abundances of striped bass in the St. Lawrence estuary and in the Gulf of St. Lawrence. On the negative side, they may be concerned that stocks in Nova Scotia that now travel upstream in fresh water to overwinter in lakes may move northward and inland to colonize the Great Lakes. Striped bass might thrive in the lower Great Lakes, based on experiences in reservoirs, and present a threat to prized salmonids.

The focus here on one species raises more questions than answers about the fish community in general across North America. There is already high thermal stress on several freshwater fish species such as stream minnows and darters in the southwestern USA and the plains (W. J. Matthews, University of Oklahoma, personal communication). Wherever drainage patterns or artificial stocking allow population migration, species may adapt; other species may suffer extinction or major population declines.

A decision regarding how much global warming is too much depends on the relative costs of future worldwide economic losses and any measures that would be taken to halt the warming (P. Crosson, Resources for the Future, personal communication). How does one measure the cost–benefit aspects of the changes in striped bass distribution and abundance that I have explored? The Canadian Maritimes are likely to gain economic value from expansion of the species' range, while the southeastern coast and inland reservoirs of the United States will suffer losses of valuable striped bass populations. There is, therefore, an international as well as a purely economic trade-off. As the climatic, hydrographic, and biological questions regarding climate change and fish are explored, the economic aspects need attention as well.

These simplistic extrapolations of climate change scenarios to effects on an important fish species will certainly be supplanted by better estimates. They are presented to illustrate types of analyses and directions of effects in hopes that additional progress can be made in evaluating the impacts of what Ramanathan (1988) has called our "inadvertent global experiment."

Acknowledgments

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Note added in proof.—We recently used the model of Brown (1986) to simulate reservoir temperatures and dissolved oxygen concentrations and the resulting striped bass habitat using baseline data on meteorology, hydrology, and inflow water quality and changes in these characteristics as predicted by the GISS and GFDL climate models (L. H. Chang, S. F. Railsback, and R. T. Brown, Oak Ridge National Laboratory, unpublished). Climate change scenarios based on both climate models predicted overall declines in amount of summer striped bass habitat, mostly as a result of elevated reservoir water temperatures.

References

Blumberg, A. F., and D. M. Di Toro. 1990. Effects of climate warming on dissolved oxygen concentrations in Lake Erie. Transactions of the American Fisheries Society 119:210–233.

Boreman, J., and R. R. Lewis. 1987. Atlantic coastal migration of striped bass. American Fisheries Society Symposium 1:331–339.

Brown, R. T. 1986. Modeled influence of point and non-point source nutrients on Boone Reservoir water quality. Tennessee Valley Authority Report WR28-2-31-105, Norris, Tennessee.

Chapman, G. 1986. Ambient water quality criteria for dissolved oxygen. U.S. Environmental Protection Agency, Office of Water Regulations and Standards, EPA 440/5-86-003, Washington, D.C.

Cheek, T. E., M. J. Van Den Avyle, and C. C. Coutant. 1982. Distribution and habitat selection of adult striped bass, *Morone saxatilis* (Walbaum), in Watts Bar Reservoir, Tennessee. Oak Ridge National Laboratory, ORNL/TM-8447, Oak Ridge, Tennessee.

Cheek, T. E., M. J. Van Den Avyle, and C. C. Coutant. 1985. Influences of water quality on distribution of striped bass in a Tennessee River impoundment. Transactions of the American Fisheries Society 114: 67–76.

Christie, G. C., and H. A. Regier. 1988. Measures of optimal thermal habitat and their relationship to yields for four commercial fish species. Canadian Journal of Fisheries and Aquatic Sciences 45:301–314.

Cohen, S. J. 1986. Impacts of CO_2-induced climatic change on water resources in the Great Lakes basin. Climatic Change 8:135–153.

Coleman, J. M. 1988. Climate warming and increased aridity in Florida, USA. Climatic Change 12:165–178.

Coutant, C. C. 1985. Striped bass, temperature, and dissolved oxygen: a speculative hypothesis for environmental risk. Transactions of the American Fisheries Society 114:31–61.

Coutant, C. C. 1986. Thermal niches of striped bass. Scientific American 255(2):98–104.

Coutant, C. C. 1987a. Poor reproductive success of striped bass from a reservoir with reduced summer habitat. Transactions of the American Fisheries Society 116:154–160.

Coutant, C. C. 1987b. Thermal preference: when does an asset become a liability? Environmental Biology of Fishes 18:161–172.

Coutant, C. C., and D. L. Benson. 1988. Linking estuarine water quality and impacts on living resources: shrinking striped bass habitat in Chesapeake Bay and Albemarle Sound. U.S. Environmental Protection Agency, EPA 503/3–88-001, Washington, D.C.

Fry, F. E. J. 1947. Effects of the environment on animal activity. University of Toronto Studies, Biological Series 55. (Publication of the Ontario Fisheries Research Laboratory 68:1–62.)

Grotch, S. L. 1988. Regional intercomparisons of general circulation model predictions and historical climate data. U.S. Department of Energy, DOE/NBB-0084, Washington, D.C.

Healey, M. C. 1990. Implications of climate change for fisheries management policy. Transactions of the American Fisheries Society 119:366–373.

Hill, D. K., and J. J. Magnuson. 1990. Potential effects of global climate warming on the growth and prey consumption of Great Lakes fish. Transactions of the American Fisheries Society 119:265–275.

Hokanson, K. E. F. 1977. Temperature requirements of some percids and adaptations to the seasonal cycle. Journal of the Fisheries Research Board of Canada 34:1524–1550.

Hutchinson, G. E. 1957a. A treatise on limnology, volume 1. Geography, physics and chemistry. Wiley, New York.

Hutchinson, G. E. 1957b. Concluding remarks. Cold Spring Harbor Symposia on Quantititive Biology 22:415–427.

Jobling, M. 1981. Temperature tolerance and the final preferendum—rapid methods for the assessment of optimum growth temperatures. Journal of Fish Biology 19:439–455.

Kohlenstein, L. C. 1981. On the proportion of the Chesapeake Bay stock of striped bass that migrates into the coastal fishery. Transactions of the American Fisheries Society 110:168–179.

Koo, T. S. Y., and J. S. Wilson. 1972. Sonic tracking striped bass in the Chesapeake and Delaware Canal. Transactions of the American Fisheries Society 101: 453–462.

Magnuson, J. J., L. B. Crowder, and P. A. Medvick. 1979. Temperature as an ecological resource. American Zoologist 19:331–343.

Magnuson, J. J., J. D. Meisner, and D. K. Hill. 1990. Potential changes in the thermal habitat of Great Lakes fish after global climate warming. Transactions of the American Fisheries Society 119:254–264.

Marchand, D., M. Sanderson, D. Howe, and C. Alpaugh. 1988. Climatic change and Great Lakes levels—the impact on shipping. Climatic Change 12:107–133.

Matthews, W. J. 1985. Summer mortality of striped bass in reservoirs of the United States. Transactions of the American Fisheries Society 114:62–66.

Matthews, W. J., L. G. Hill, D. R. Edds, and F. P. Gelwick. 1989. Influence of water quality and season on habitat use by striped bass in a large southwestern reservoir. Transactions of the American Fisheries Society 118:243–250.

McCauley, R. W., and J. M. Casselman. 1981. The final preferendum as an index of the temperature for optimum growth in fish. Pages 81–93 *in* K. Tiews, Aquaculture in heated effluents and recirculation systems, volume 2. Heenemann Verlagsgesellschaft, Berlin.

McCormick, M. J. 1990. Potential changes in thermal structure and cycle of Lake Michigan due to global

warming. Transactions of the American Fisheries Society 119:183–194.
McIlwain, T. D. 1980. Striped bass in coastal waters, South Atlantic and Gulf. Pages 37–43 *in* H. Clepper, editor. Marine recreational fisheries 5. Sport Fishing Institute, Washington, D.C.
Mehta, A. J., R. G. Dean, W. R. Dally, and C. L. Montague. 1987. Some considerations on coastal processes relevant to sea level rise. University of Florida, UFL/COEL-87/012, Gainesville.
NOAA (National Oceanic and Atmospheric Administration). 1973. Surface water temperature and density. Atlantic coast, North and South America. NOAA, National Ocean Survey Publication 31-1, 4th edition, Rockville, Maryland.
NRC (National Research Council). 1985. Glaciers, ice sheets, and sea level: effect of a CO_2-induced climatic change. U.S. Department of Energy, DOE/ER/60235-1, Washington, D.C.
Officer, C. B., R. B. Biggs, J. L. Taft, L. E. Cronin, M. A. Taylor, and W. R. Boynton. 1984. Chesapeake Bay anoxia: origin, development, and significance. Science (Washington, D.C.) 223:22–27.
Orson, R., W. Panageotou, and S. P. Leatherman. 1985. Response of tidal salt marshes of the U.S. Atlantic and Gulf coasts to rising sea levels. Journal of Coastal Research 1:29–37.
Parry, M. 1987. The impact of climatic variations on agriculture: introduction to the IIASA/UNEP case studies in semi-arid regions. International Institute for Applied Systems Analysis, Vienna.
Polgar, T. T. 1982. Factors affecting recruitment of Potomac River striped bass and resulting implications for management. Pages 427–442 *in* V. S. Kennedy, editor. Estuarine comparisons. Academic Press, New York.
Price, K. S., and seven coauthors. 1985. Nutrient enrichment of Chesapeake Bay and its impact on the habitat of striped bass: a speculative hypothesis. Transactions of the American Fisheries Society 114: 97–106.
Ramanathan, V. 1988. The greenhouse theory of climate change: a test by an inadvertent global experiment. Science (Washington, D.C.) 240:293–299.
Rudstam, L. E., and J. J. Magnuson. 1985. Predicting the vertical distribution of fish populations: analysis of cisco, *Coregonus artedii*, and yellow perch, *Perca flavescens*. Canadian Journal of Fisheries and Aquatic Sciences 42:1178–1188.
Rulifson, R. A., S. A. McKenna, and M. L. Gallagher. 1987. Tagging studies of striped bass and river herring in upper Bay of Fundy, Nova Scotia. East Carolina University, Institute for Coastal and Marine Resources, Technical Report 87-02, Greenville, North Carolina.
Schaich, B. A., and C. C. Coutant. 1980. A biotelemetry study of spring and summer habitat selection by striped bass in Cherokee Reservoir, Tennessee, 1978. Oak Ridge National Laboratory, ORNL/TM-7127, Oak Ridge, Tennessee.
Schertzer, W. M., and A. M. Sawchuk. 1990. Thermal structure of the lower Great Lakes in a warm year: implications for the occurrence of hypolimnion anoxia. Transactions of the American Fisheries Society 119:195–209.
Schubel, J. R., and D. W. Pritchard. 1986. Responses of upper Chesapeake Bay to variations in discharge of the Susquehanna River. Estuaries 9:236–249.
Seitz, R. C. 1971. Temperature and salinity distributions in vertical sections along the longitudinal axis and across the entrance of the Chesapeake Bay (April 1968–March 1969). Johns Hopkins University, Chesapeake Bay Institute, Graphical Summary Report 5, Reference 71-7, Baltimore, Maryland.
Setzler, E. M., and eight coauthors. 1980. Synopsis of biological data on striped bass, *Morone saxatilis* (Walbaum). NOAA (National Oceanic and Atmospheric Administration) Technical Report NMFS (National Marine Fisheries Service) Circular 433.
Smith, J. B. 1989. Methodology. Pages 57–69 *in* J. B. Smith and D. Tirpak, editors. The potential effects of global climate change on the United States. U.S. Environmental Protection Agency, EPA 230-05-89-050, Washington, D. C. (U.S. Government Printing Office, GPO 055-000-00358-1, Washington, D.C.).
Stevens, R. E. 1975. Current and future considerations concerning striped bass culture and management. Proceedings of the Annual Conference Southeastern Association of Game and Fish Commissioners 28: 69–73.
Stroup, E. D., and R. J. Lynn. 1963. Atlas of salinity and temperature distributions in Chesapeake Bay 1952–1961 and seasonal averages 1949–1961. Johns Hopkins University, Chesapeake Bay Institute, Graphical Summary Report 2, Reference 63-3, Baltimore, Maryland.
Waddle, H. R., C. C. Coutant, and J. L. Wilson. 1980. Summer habitat selection by striped bass, *Morone saxatilis*, in Cherokee Reservoir, Tennessee, 1977. Oak Ridge National Laboratory, ORNL/TM-6927, Oak Ridge, Tennessee.
Westin, D. T., and B. A. Rogers. 1978. Synopsis of biological data on the striped bass, *Morone saxatilis* (Walbaum) 1792. University of Rhode Island, Marine Technical Report 67, Narragansett.
Wooley, C. M., and E. J. Crateau. 1983. Biology, population estimates, and movement of native and introduced striped bass, Apalachicola River, Florida. North American Journal of Fisheries Management 3:383–394.
Wright, D. G., R. M. Hendry, J. W. Loder, and F. W. Dobson. 1986. Oceanic changes associated with global increases in atmospheric carbon dioxide: a preliminary report for the Atlantic coast of Canada. Canadian Technical Report of Fisheries and Aquatic Sciences 1426.

Transactions of the American Fisheries Society 119:757–778, 1990

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Summer Habitat Suitability for Striped Bass in Chesapeake Bay: Reflections on a Population Decline

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Abstract.—We evaluated summer water temperatures, dissolved oxygen concentrations, distribution of striped bass *Morone saxatilis* subadults and adults, and juvenile abundance indexes in Chesapeake Bay to discern any influences of summer habitat suitability on historical changes in populations. Criteria for habitat suitability were those identified in freshwater reservoirs (temperature below 25°C and dissolved oxygen above 2–3 mg/L), which we confirmed for the York–Pamunkey estuary in the lower bay. Habitat suitability in the upper central basin in July declined significantly from 1962 to 1987, as did juvenile abundance indexes (mean catches per standard seine haul). Thickness of suitable temperature–oxygen habitat correlated significantly with Maryland juvenile indexes the following year. Relative reproductive performance of upper (Maryland) and lower (Virginia) bay stocks changed between 1967–1973 and 1980–1988 in parallel with reduction in upper bay summer habitat. The annual temperature–oxygen cycle in the bay revealed two key areas for striped bass subadults and adults: (1) a zone of cool water in north-central Chesapeake Bay near Annapolis, Maryland, where fish of these ages congregate in summer, and (2) a shallow sill across the lower bay near the mouth of the Rappahannock River, Virginia, where warm surface waters (>25°C) in summer impinge on the bottom and may block egress from the bay. The importance of year-round bay residents for reproduction in the upper bay may have been underestimated previously, at least for the recent low population levels. Reduced juvenile production at the head of the bay and population decline would be consistent with limitation of historically important habitat in summer and resultant physiological stresses of high temperature and low dissolved oxygen that affect reproductive competence the following year.

There is a need to evaluate systematically the effects of water quality degradation on the biota of estuaries and to develop stategies and priorities for arresting habitat deterioration and restoration of lost habitats. Estuaries throughout the USA are experiencing the pressures of increasing human population, including discharge of domestic wastes (or the nutrients resulting from wastewater treatment); toxic discharges; power plant cooling water use; and nonpoint runoff of pesticides, acid deposition, and fertilizers. Notable improvements have been made in the quality of some systems such as the Hudson River (Smith 1988). Other systems such as Chesapeake Bay are exhibiting alarming trends toward progressive degradation of both water quality and living resources (Officer et al. 1984; Boreman and Austin 1985; Seliger et al. 1985) that have garnered political attention (interagency Chesapeake Bay Agreement, signed in 1987). The striped bass *Morone saxatilis* along the east coast of North America, which historically has depended on Chesapeake Bay for a major part of its reproduction (Setzler et al. 1980), has been in serious decline for much of the past 15 years, and a recent upturn in the population has occurred only after the imposition of highly restrictive harvest regulations (NMFS 1989).

This paper addresses two water quality variables in Chesapeake Bay—temperature and dissolved oxygen—found elsewhere to be especially important for both adult survival and reproductive success (i.e., the production of viable juveniles) of the striped bass. Chesapeake Bay, where water quality degradation and decline in populations of striped bass are concurrent concerns, offers a convenient prototype for analyzing water quality effects on estuaries by using a holistic view of the environment and animal activity fostered by F. E. J. Fry (1947). Our objective is to examine a hypothesis concerning striped bass habitat in Chesapeake Bay that embraces Fry's (1947) concepts of thermal tolerance, preferred temperatures, temperature optima, temperature effects on metabolism, and oxygen supply and consumption relationships. Those concepts and subsequent literature led to a general hypothesis regarding the importance of temperature and dissolved oxygen concentration for striped bass distribution, habitat suitability, and population success (Coutant 1985) and its application to Chesapeake Bay (Price et al.

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1985); we now deal in greater detail with conditions in Chesapeake Bay.

Ecological data on striped bass in both fresh- and saltwater environments suggest that the distribution and population success of this species can be related to habitat selection guided by thermal preferences alone or in concert with dissolved oxygen (Coutant 1985). The main points are as follows. The physiologically optimum temperature range shifts to lower temperatures as striped bass grow: for first-year juveniles it is near 26°C (Coutant et al. 1984), whereas it is near 20–24°C for subadults in their second year (Coutant and Carroll 1980) and 20–22°C for adults (Schaich and Coutant 1980). Older subadults and adults tend to avoid temperatures above about 25°C when cooler water is available. All ages avoid dissolved oxygen concentrations below 2–3 mg/L. The subadults and adults typically are limited to zones of a water body that are sufficiently cool and well oxygenated during summer. The size (volume) of these zones may be a small portion of the overall water body. In some systems, this restricted zone is a metalimnetic depth stratum (e.g., Matthews et al. 1985), whereas in other systems it is a cool tributary (Cheek et al. 1985) or spring (Schaich and Coutant 1980; Moss 1985). Fish unable to locate truly preferred temperatures at acceptable dissolved oxygen concentrations concentrate in suboptimal thermal habitat as close to optimal as possible above 2–3 mg/L dissolved oxygen for as long as they can survive. Temperatures up to 29°C have been occupied for short periods when there was no cool water available. The summer thermal and dissolved oxygen structure may thus restrict the annual carrying capacity of striped bass in the whole system. Similar summer habitat limitations have been observed by others for cisco *Coregonus artedii* in glacial lakes (Colby and Brooke 1969; Rudstam and Magnuson 1985), and confirmatory evidence has recently been obtained for striped bass in Lake Texoma, Oklahoma–Texas (Matthews et al. 1989), Keystone Reservoir, Oklahoma (A. Zale, University of Oklahoma, personal communication), and the Apalachicola River system in Florida and Georgia (Van Den Avyle and Evans 1990). Although much of the relevant information for striped bass has come from fresh water, habitat limitation by temperature and oxygen also occurs in the ocean (Barkley et al. 1978).

Direct and secondary detrimental effects have been seen in striped bass crowded into summer "thermal refuges" in freshwater reservoirs and river systems in which the species has been stocked and where local population responses are monitored carefully (Coutant 1985, 1987). The effects include direct mortality of fish that apparently cannot find the refuge (when ambient exceeds about 29°C), increased disease due to crowding within refuges, deteriorating body condition throughout the summer as food is exhausted, overfishing, catch-and-release mortality, and diminished reproductive competence of females the following year (presumably due to an energetic deficit during egg development). These effects do not occur where temperature and oxygen habitat conditions are favorable for most of the summer, and their occurrence and severity vary greatly among water bodies.

Although evidence is not fully conclusive that this type of habitat restriction is important for striped bass declines in estuaries such as Chesapeake Bay, the available information suggests that it may be a factor (Coutant 1985). We examined the following relevant questions: (1) whether the upper avoidance temperatures of subadult and adult striped bass in a saline estuary are similar to those in freshwater reservoirs, (2) whether there is significant correlation between suitable temperature–oxygen habitat in the bay and indexes of striped bass reproduction and survival, (3) whether there are different trends in reproductive success of upper and lower bay stocks over time that might indicate an influence of bay water quality on reproduction in the upper bay, and (4) whether there are patterns of seasonal temperatures and dissolved oxygen concentrations in the bay that could account for both the seasonal distribution of striped bass and their possible vulnerability to habitat constriction in summer.

Methods

Because there have been no detailed studies of temperature selection by striped bass in an estuary for comparison with responses in fresh water, we tested the upper avoidance temperature for estuarine striped bass by examining the York–Pamunkey estuary arm of Chesapeake Bay in Virginia. There, striped bass distribution was analyzed in a 1968–1969 tagging study by Grant et al. (1970) and in 1967–1971 catches by Grant (1974). Although detailed water temperature patterns were not determined at these times, monthly temperature–depth profiles were available along the length of the system and into the main bay for 1956–1959, which is considered representative (Massman 1962). Additional temperature data were also indicated by Grant (1974), and Brooks (1983a, 1983b) provided extensive data on temperature, dissolved oxygen, and salinity for 1970–1980.

We analyzed correlations between suitable summer habitat and striped bass reproductive success using historical temperature–oxygen depth distribtuions and juvenile index data. We used the computerized water quality data files compiled by the U.S. Environmental Protection Agency (EPA) Chesapeake Bay Program, which is a collection of files from such sources as the Johns Hopkins University Chesapeake Bay Institute. Data were available for most years between 1962 and 1987 for locations in the central basin (EPA area CB-4). The water column thickness containing suitable habitat for subadults and adults (temperature below 25°C and dissolved oxygen above 2 mg/L) was calculated for sampling dates in the latter half of July each year (Table 1). Annual indexes of juvenile abundance for specific locations in the bay were obtained from the Maryland Department of Natural Resources (unpublished, courtesy of H. Spier) and Colvocoresses and Austin (1987); updated Virginia data through 1988 were provided by J. A. Colvocoresses (Virginia Institute of Marine Science, personal communication; Table 1). The indexes were derived from beach seining surveys for approximately 100-d-old striped bass at standard locations from 1954–1988 (Maryland)

TABLE 1.—Thickness (m) of suitable habitat in the central basin of Chesapeake Bay in late July (temperature below 25°C; dissolved oxygen above 2 mg/L) for striped bass 2 years old and older[a] and juvenile indexes of abundance, 1954–1988. The Maryland juvenile index is listed for four areas surveyed and the average of collecting sites, 1954–1988[b]; the Virginia beach seine survey index is listed for the average of sites, 1967–1973 and 1980–1988.[c]

Year	Habitat thickness	Maryland juvenile index: Head of bay	Potomac River	Choptank River	Nanticoke River	Average	Virginia index average
1954		0.9	5.2	1.2	25.1	5.2	
1955		4.4	5.7	12.5	5.9	5.5	
1956		33.9	6.2	9.8	8.2	15.2	
1957		5.4	2.5	2.1	1.3	2.9	
1958		28.2	8.4	19.5	22.5	19.3	
1959		1.9	1.6	0.1	1.8	1.4	
1960		9.3	4.3	9.0	4.7	7.1	
1961		22.1	25.8	6.0	1.5	17.0	
1962	>18	11.4	19.7	6.1	6.6	12.2	
1963	>18	6.1	1.1	5.4	4.1	4.0	
1964	>18	31.0	29.1	10.6	13.3	23.5	
1965	>18	2.2	3.4	9.5	21.6	7.4	
1966	>18	32.3	10.5	13.6	3.3	16.7	
1967	>18	17.4	1.9	5.3	4.1	7.8	4.61
1968	>18	13.1	0.7	6.3	9.0	7.2	3.70
1969	8	26.6	0.2	4.8	6.2	10.5	2.91
1970	4	33.1	20.1	57.2	17.1	30.4	6.42
1971	>18	23.7	8.5	6.3	2.0	11.8	2.83
1972		12.1	1.9	11.0	25.0	11.0	1.19
1973		24.7	2.1	1.0	1.1	8.9	1.59
1974		19.9	1.5	15.3	3.9	10.1	
1975	4.6	7.6	7.8	4.7	5.2	6.7	
1976	3.0	9.8	3.2	2.4	1.7	4.9	
1977	3.0	12.1	1.9	1.2	1.0	4.8	
1978	4.5	12.5	7.9	6.0	4.8	8.5	
1979	2.7	8.3	2.2	2.8	0.9	4.0	
1980	0.9	2.3	2.2	1.0	1.8	2.0	2.54
1981		0.3	1.4	1.3	2.4	1.2	1.57
1982		5.5	10.0	13.0	6.2	8.4	2.71
1983		1.2	2.0	0.9	1.0	1.4	3.48
1984	0	6.1	4.7	2.8	1.5	4.2	4.36
1985	0	0.3	5.6	3.7	2.1	2.9	2.41
1986	0	1.6	9.9	0.5	2.2	4.1	4.92
1987	0	0.3	6.4	12.1	2.5	4.8	15.75
1988		7.3	0.4	0.7	0.4	2.7	7.80

[a] Calculated from data in the U.S. Environmental Protection Agency's Chesapeake Bay Program computerized data base.
[b] From the Maryland Department of Natural Resources (unpublished material).
[c] From Colvocoresses and Austin (1987) and J. Colvocoresses (personal communication).

and 1967–1973 and 1980–1988 (Virginia); sampling actually occurred over several months each year. Regression analysis, including analysis of variance (ANOVA), was conducted between juvenile index values for the several locations and suitable summer habitat depth for subadults and adults in the same year and the preceding year.

Differences in spawning success and larval–juvenile survival over time between locations in the bay were sought by a simplified "BACI analysis" (for *B*efore:*A*fter, *C*ontrol:*I*mpact) that was found useful by Stewart-Oaten et al. (1986) and Carpenter et al. (1989) for detecting changes in manipulated ecosystems relative to undisturbed (but randomly fluctuating) reference systems. The BACI analysis uses paired time series of data from "treatment" and reference systems. This type of analysis seemed appropriate to counteract two interacting difficulties with the juvenile index data that make direct correlations with environmental factors difficult: (1) large year-to-year variations and (2) major changes in overall stock size through the period. Ratios were calculated for temporally paired samples taken from juvenile index locations in the upper bay (Maryland) and lower bay (Virginia). The ratios were transformed to logarithms (to create a scale of positive and negative values) and plotted to give a visual interpretation of trends in magnitude and timing of differences. Unpaired, two-way *t*-tests were conducted between the pairs of ratios that include the early and late sets of Virginia dates.

We examined fisheries, hydrographic, and water quality reports and data sets for Chesapeake Bay that appeared relevant to identifying summer habitat limitations, including data and summaries on historical temperatures, dissolved oxygen concentrations, and striped bass distributions. We first summarized available information from the fisheries literature on seasonal changes in subadult and adult striped bass distribution. We then examined seasonally changing water temperature patterns in the main body and principal tributaries of Chesapeake Bay that could influence habitat selection by subadult and adult striped bass (age 2 and over), based on our temperature-preference results in reservoirs. Both the average condition and interannual variability were sought from data in reports dating from 1950–1980. We assumed that juveniles in their first year would occupy shallow, warm zones near the area in which they were spawned (Coutant 1985). We then sought to describe the spatial and temporal patterns of dissolved oxygen in the bay. We focused on quantitative changes in seasonal and interannual dissolved oxygen concentration in specific zones that we had estimated from temperature analyses to be important summer habitats for large striped bass. The seasonal cycle of density stratification of the bay that contributes to deoxygenation was explored in relation to striped bass distribution, for which we relied mainly on the published analyses of hydrographers (Seliger et al. 1985; Schubel and Pritchard 1986).

Striped Bass Upper Avoidance Temperature

We concluded that striped bass in the Chesapeake Bay system older than their first year have an upper avoidance temperature similar to that for comparable ages in fresh water because striped bass in the York–Pamunkey estuary showed movements in and out of the estuary when temperatures corresponded to those avoided in fresh water. The 1956–1959 data set for the York–Pamunkey system is a useful example of general water temperature conditions in this tributary estuary (Figure 1). Water temperatures at the surface and bottom were generally higher in the upper reaches in May through August and fairly isothermal or slightly cooler upriver in September and October. Headwater temperatures were in the striped bass's high occupancy range of 20–24°C (Coutant and Carroll 1980) in May, whereas lower reaches were cooler. As seasonal warming progressed, the upper reaches warmed above the preferred temperature range; by July, preferred temperatures occurred only in the lower reaches of the York estuary or in the main bay. The August pattern was variable: in a cool year (1957) the entire York system was in the upper portion of the preferred range, whereas in a warm year (1959) all temperatures were above those preferred. The entire system cooled to within or below the preferred range in September and October.

Brooks (1983a, 1983b) confirmed that summer temperatures are above 25°C most of the time in the York estuary. Dissolved oxygen values were almost always above 3–4 mg/L, even in summer, a range we would not consider to be a problem for fish distribution. Temperatures seemed to grade smoothly from the York River mouth to the headwaters with no special anomalies. If striped bass were to follow the preferred temperature range through the seasonally changing temperatures (e.g., crosshatched range in Figure 1), the fish would move up and down the York estuary. Movement would be to the upper reaches in May and would shift downstream in summer when the fish leave

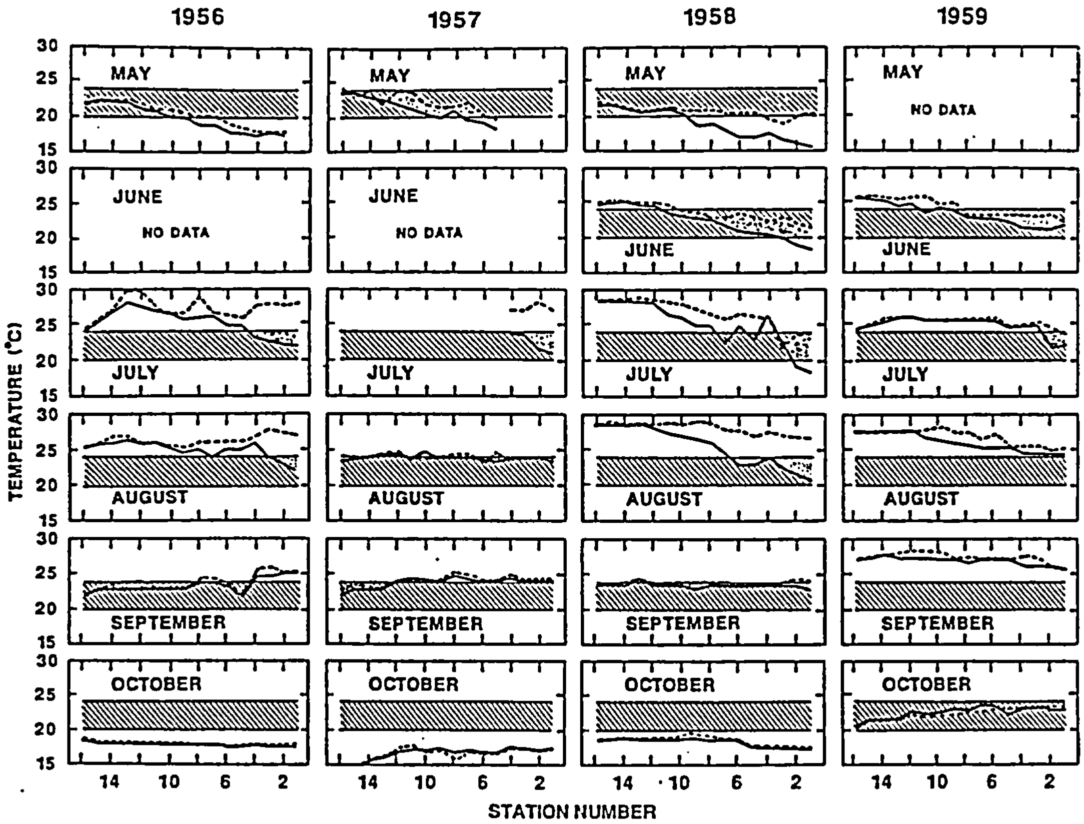

FIGURE 1.—May–October water temperatures at surface (broken line) and bottom (solid line) in the York River estuary and adjacent Chesapeake Bay sampled by Massman (1962) in relation to the temperatures occupied 75% of the time by subadult striped bass in fresh water (hatched range; Coutant and Carroll 1980). Station numbers increase from 1 near the bay mouth to 6 in the York River mouth, 12 at the Pamunkey River mouth, and 16 at a point 40 km up the Pamunkey River.

the upper reaches entirely. Striped bass would seek summer refuge in the deeper parts of the main bay or move out of the bay and then in September or October disperse into the upper estuary as the whole system returns to the preferred temperature range.

This scenario is supported by fish distribution data. Grant et al. (1970) observed that 2- and 3-year-old striped bass in his tagging study appeared to move from the York River into Chesapeake Bay in warmer months and return in the autumn. Grant (1974) found that mature striped bass caught in the fishery rarely appeared in the river in warmer months, although there were 2-year-olds present. There were anomalously more striped bass in the York River in the summer of 1969; this was a year, however, when there was rapid deoxygenation in the main bay (Taft et al. 1980) and the main bay had low dissolved oxygen concentrations in the deep channel (Price et al. 1985). Temperatures were relatively cool, however (EPA database). Habitat restriction by low oxygen concentrations in the bay in 1969 may have encouraged more fish to remain in the relatively cool, oxygenated York River estuary in summer.

To the extent that sketchy fish distribution data from the York estuary can be matched to more abundant temperature data, the general freshwater ranges of age- or size-dependent preferred and avoided temperatures for striped bass 2 years old and older seems confirmed. Further correlations among existing data sets in the Chesapeake Bay would be desirable, and more confidence in the conclusion would be gained through temperature telemetry or other direct studies of Chesapeake Bay fish. Additional confidence in the view that estuarine stocks follow the same temperature cues that we have identified for freshwater striped bass comes from the Connecticut River. There, Kynard and Warner (1987) found that the activity of subadults at fish lifts was related to temperature and that 72% of fish passage over a 7-year period occurred from 20°C to 24°C. These results seem sufficient to accept the published upper avoidance temperature near 25°C as the basis for a working hypothesis about habitat suitability for subadult and adult striped bass in the Chesapeake Bay system.

Comparison of Suitable Habitat and Juvenile Indexes

Progressive restriction of late-July habitat for subadult and adult striped bass in Chesapeake Bay (EPA area CB-4) by the combined effects of high temperature and low dissolved oxygen was evident for the 25-year time span (1962–1987) for which data were available in the computerized data set of the EPA Chesapeake Bay Program (Table 1). The declining trend is statistically significant (ANOVA, $P \leq 0.0001$). The major decline has been since the late 1960s. There were also declines in the juvenile index values over these years (plus 1988) for Maryland's head of the bay ($0.0001 < P \leq 0.005$), Nanticoke River ($0.005 < P \leq 0.01$), and overall average ($0.0001 < P \leq 0.005$) but not for the Choptank River, Potomac River, or Virginia sites.

There were signifciant correlations between thickness of suitable temperature–oxygen habitat for subadults and adults in the central basin in late July and Maryland juvenile indexes the following year. For the years without habitat restriction (suitable water column thickness greater than 18 m in Table 1), juvenile indexes the next year ranged widely. However, in years from 1969 to 1987 with less than 18 m of suitable late-July habitat, there was significant correlation between habitat thickness and next-year indexes for the head of the bay ($0.0001 < P \leq 0.005$), the bay average ($0.005 < P \leq 0.01$), the Choptank River ($0.01 < P \leq 0.025$), and the Nanticoke River ($0.025 < P \leq 0.05$), but not the Potomac River ($P > 0.25$). When habitat thickness was compared to the index for the same year, only the head-of-the-bay correlation was significant.

Although correlation does not prove causality, the statistical analyses suggest that the water column thickness having suitable temperatures and dissolved oxygen concentrations for subadult and adult striped bass in summer is linked to the species' reproductive success the following year. An alternative explanation, that both a general worsening of water quality and loss of reproduction parallel a reduction in overall stock size (due, perhaps, to fishing pressure), is made less plausible by the markedly poorer correlations between habitat and index data for the same years. The effects of overall stock size are germane, however, and were further addressed by comparing the relative reproductive performance (juvenile indexes) of upper bay (Maryland) and lower bay (Virginia) fish over time.

Juvenile Production in Upper and Lower Bay

We found relative production of striped bass juveniles to differ markedly between upper bay and lower bay sites over time (Table 1; Figure 2). Distinct patterns were evident that favor different mechanisms for control of juvenile production in zones that roughly match Maryland and Virginia waters. A comparison of the composite Maryland and Virginia indexes indicated a major shift in their relationship between the early (1967–1973) and more recent (1980–1988) Virginia sampling years (Figure 2a). Initially, Maryland indexes were always higher than the Virginia indexes, whereas they were nearly always lower in the later sampling years. The temporal differences in ratios were statistically significant ($0.0005 < P \leq 0.005$). The ratios may be due to systematic differences between the states' techniques, for the Maryland and Virginia data sets involve unique methods and chronologies (Colvocoresses and Austin 1987), but if so, the relationship should be relatively consistent over time. The main exception to lower Maryland indexes in later years was 1982, a year noted for its more normal production of striped bass juveniles (NMFS 1989). Exceptionally high production in Virginia waters in the last two years (1987 and 1988) was not matched by similar increases in Maryland, as one might expect if all sites respond primarily to the size and age structure of the coastal spawning stock. There is no obvious relationship between years of poor relative juvenile production in all of Maryland and conditions of high temperature and low dissolved oxygen in the bay, however.

The ratio of the head-of-the-bay (Maryland) indexes to the Virginia indexes also changed significantly between early and later sampling years ($P \leq 0.0005$). The head-of-the-bay location may show a correlation between years of poor juvenile production, relative to production in Virginia (as the surrogate for the general spawning stock size), and years of most severe habitat squeeze (Figure 2b).

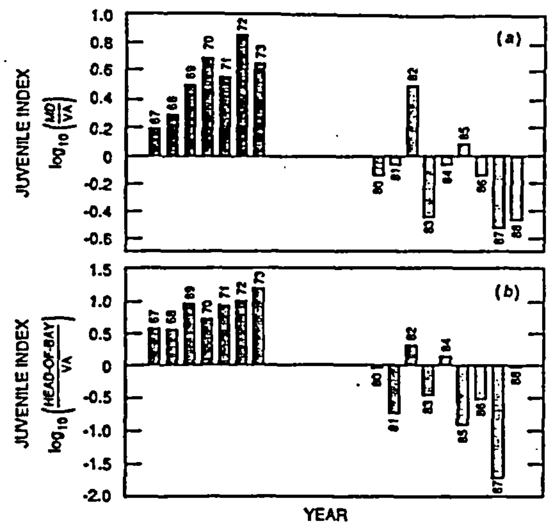

FIGURE 2.—Relationships of juvenile striped bass indexes for all Maryland stations combined (a) and the head-of-the-bay station (b) to all Virginia stations combined for years in which Virginia data were taken (1967–1973 and 1980–1988).

The three most prominent years of low relative production were 1981, 1985, and 1987. The first two years followed years for which the severity of anoxia has been reported in the literature (Officer et al. 1984; Seliger et al. 1985), although the EPA database does not show 1984 to be an especially bad year for temperature–oxygen habitat. The third year, 1987, was a year of especially high Virginia production that was not reflected at the head of the bay and a year that was preceded by severe temperature–oxygen habitat squeeze in the bay (EPA database, and unpublished analyses by R. Magnien, Office of Environmental Programs, Maryland Department of Health and Mental Hygiene). Thus, although juvenile striped bass production at all sites sampled in Maryland seems to have been controlled by factors different from those controlling production at Virginia sites, it is the head-of-the-bay site in Maryland that might be responding most strongly to summer water quality conditions in the central basin. It is also the site with the strongest correlation between thickness of suitable habitat in summer and the juvenile index the following year (above). How real the contrast is between upper bay and lower bay production and how biased it is by the selection of sampling sites by the two states and their different indexing techniques remains to be tested with additional data.

Summer Bay Residency by Subadult and Adult Striped Bass

We found historical evidence for summer residence of subadult and adult striped bass in upper Chesapeake Bay. Much less attention has been paid to the seasonal distribution of striped bass in Chesapeake Bay than to the contribution of bay striped bass to coastal waters where this stock has been dominant, at least before the recent population decline (e.g., Kohlenstein 1981), and to seasonal migratory movements in coastal waters. Summer records are particularly scarce because it is not the season of an intense commercial fishery. However, the literature does indicate a historical record of declining residency in the bay as striped bass grow older and also of summertime catches of large fish in certain areas, both of which may be correlated with water temperature and dissolved oxygen conditions.

From the early tagging and recovery studies by Vladykov and Wallace (1938) onward, it has been recognized that younger females (through about age 4) and most males tend to remain in the bay throughout the year, whereas larger females tend to leave. Substantial numbers (perhaps half) of bay females were estimated by Kohlenstein (1981) to have remained in the bay in the year before their first spawning at age 5. However, departure seems to depend on population density, according to Goodyear (1978) and Kriete et al. (1979), which suggests a limitation on the amount of suitable habitat for subadults and adults (food limitation also has been suggested). Goodyear (1978) based his conclusion on regressions between New York landings and young-of-the-year densities in the Maryland portion of Chesapeake Bay 3–6 years earlier. Kriete et al. (1979) found that when abundance is average, an insignificant proportion of 2-year-olds (<3%) joins the coastal migration; when population is high, more do so. Migration from the bay is often attributed to an innate migration behavior, although this behavior should not be affected by density. Mansueti and Hollis (1963) concluded that the principal contribution to natural reproduction is probably from the smaller females between 2.3 and 6.8 kg because these fish are more abundant than larger ones, even though larger fish produce more eggs per female (Jackson and Tiller 1952). Smaller fish are not necessarily younger (and thus more likely to be bay residents), but size could be a good indication of age.

Some sites of summer residence have been suggested for subadults and adults. Information from catch records and personal observations by authors is biased, however, by the preponderance of data on smaller fish and the failure of some studies to indicate clearly the sizes of fish. Vladykov and Wallace (1952) noted "summer feeding grounds" around Tilghman, Galesville, and Rock Hall (195, 213, and 245 km from the mouth of the Chesapeake Bay, respectively) and indicated that large fish of 2.7–6.8 kg had been taken by anglers in summer around Rock Hall and Tilghman. Mansueti and Hollis (1963) cited a June–September 1962 sportfishing survey near Annapolis (222 km from the mouth) showing that many large fish as well as smaller ones were being caught. About 1,300 fish (12%) were heavier than 6.8 kg. Recent personal communications from fisheries biologists in Maryland confirm the importance of this reach of the bay for summertime catches of large fish. Coker and Hollis (1950) noted the disappearance of large striped bass (33.5–106 cm) from midbay off the mouth of the Patuxent River (154 km from the mouth) in late June during Navy detonation testing conducted between early May and late August 1948.

Migrations within the bay have been identified in tagging and recapture studies since the 1930s, although most tagged fish have been small subadults. Excepting the high percentages of recaptures near the tagging sites, the most prominent feature has been a movement of fish southward along the western shore in autumn (Vladykov and Wallace 1952). This movement has also been recognized in the seasonal sequence of catches in pound nets. Dates of tag returns outside the bay indicated to Vladykov and Wallace (1952) that outward migration from the bay is partly a continuation of the down-bay migration in autumn.

These sketchy observations implicate a particular zone of the bay as especially important for larger striped bass in summer. The zone stretches from Tilghman Island near the mouth of the Choptank River and about 35 km south of Annapolis (latitude 38°40′N; 195 km from the mouth) to Rock Hall opposite the southern bank of the Patapsco River (Baltimore Harbor) (39°37′N; 245 km from the mouth), which is about 20 km north of Annapolis (Figure 3). The fish seem to disperse southward from this zone in autumn.

Temperatures in Chesapeake Bay

We found bay temperature patterns that would tend to concentrate larger striped bass in the upper middle bay in summer if fish selected preferred temperatures. Although the influence of temperature is likely altered by other factors (e.g., dissolved oxygen, which is discussed below, and food supply), the seasonal distribution of subadults and adults is consistent with water temperatures alone and with known temperature preferences. Tributary temperature surveys, such as those for the York–Pamunkey system detailed above, and surveys of the main channel of the bay provide records that are spotty but that include useful information from about 1950 to the present.

Tributary summer temperatures generally followed the pattern described for the York–Pamunkey system (Massman 1962). This generalization comes from examination of temperature-depth profiles for the summer season found in the EPA Chesapeake Bay Program's computerized data base (EPA, unpublished) and in original reports (James River: Brooks and Fang 1983; Mattaponi River: Brooks 1983c). Without recourse to consideration of other factors, it is quite likely that subadults and adults find tributary waters unsuitably warm in summer (>25°C) and at least the larger fish leave them, although subadults of age 2 may remain in substantial numbers.

Data from vertical temperature profiles along the longitudinal axis of the main bay through the year revealed temperature patterns that could guide larger striped bass. Seitz (1971) provided what appears in retrospect to be a reasonably typical pattern for changes in warm-season temperatures (Figure 4). The most prominent feature relative to striped bass distribution is a zone of cool water in summer centered about 220–240 km from the entrance to the bay, roughly between Annapolis and Rock Hall. This cool water is generally within the preferred temperature range of subadults and adults throughout the summer. The upstream boundary is sharply defined at an abrupt change in the bottom profile near Pooles Island, 259 km from the mouth (about 39°20′N). Upstream of this point, temperatures resemble those of other tributaries, exceeding preferred temperatures throughout the summer. Bathymetric charts show this most upstream end to be a narrow channel; the larger volume of water ends midway between Rock Hall and Annapolis. There is no definite downstream boundary of this zone of cooler water, for isotherms grade smoothly southward for many kilometers in a manner that is seasonally and annually variable. Midsummer temperatures that would be selected by large striped bass have persisted downstream past Tilghman in some years (Stroup and Lynn 1963).

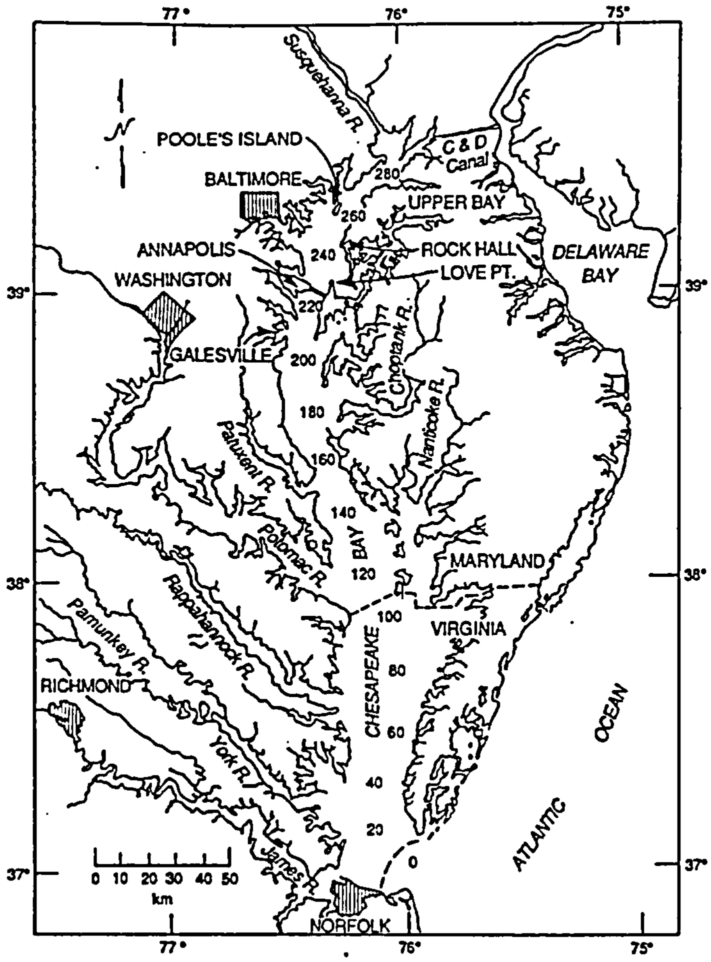

FIGURE 3.—Chesapeake Bay and its tributaries, showing features prominent for evaluating striped bass habitat (after Cronin 1971). Numbers in the bay are approximate kilometers from the mouth.

Of nearly equal importance for probable striped bass movements and seasonal distribution is a convergence of warm surface strata and a bottom sill across the bay near 37°42'N (about 84 km from the bay mouth), off the mouth of the Rappahannock River (Figure 4). Surface warming in many summers, coupled with striped bass avoidance of temperatures above about 25°C when cooler water is available, appears to provide an effective closure of the upper bay at this location for the seaward migration of large striped bass. Although there is a complex of similarly shallow sills southward toward the bay mouth, they occur in waters cooler than 25°C. Upstream of the northernmost sill, large striped bass would be expected to follow declining temperatures in an upstream (northward) direction as summer warming progresses; downstream, the fish would be directed toward the bay mouth and the open coast where cooler waters prevail.

A thermal barrier at this point during many summers is consistent with several facets of the ecology of striped bass in Chesapeake Bay. For example, the prominent southward migration observed in the bay in autumn by tag and recovery studies may reflect a dispersion of upper bay fish that repopulates the lower central basin and sill area vacated in summer because of its high temperatures. Stock separation at the sill between the Potomac and Rappahannock rivers could account for differences between the population dynamics of striped bass from the Virginia tributaries (especially the York and James rivers) and those of the Potomac River and upper bay stocks noted

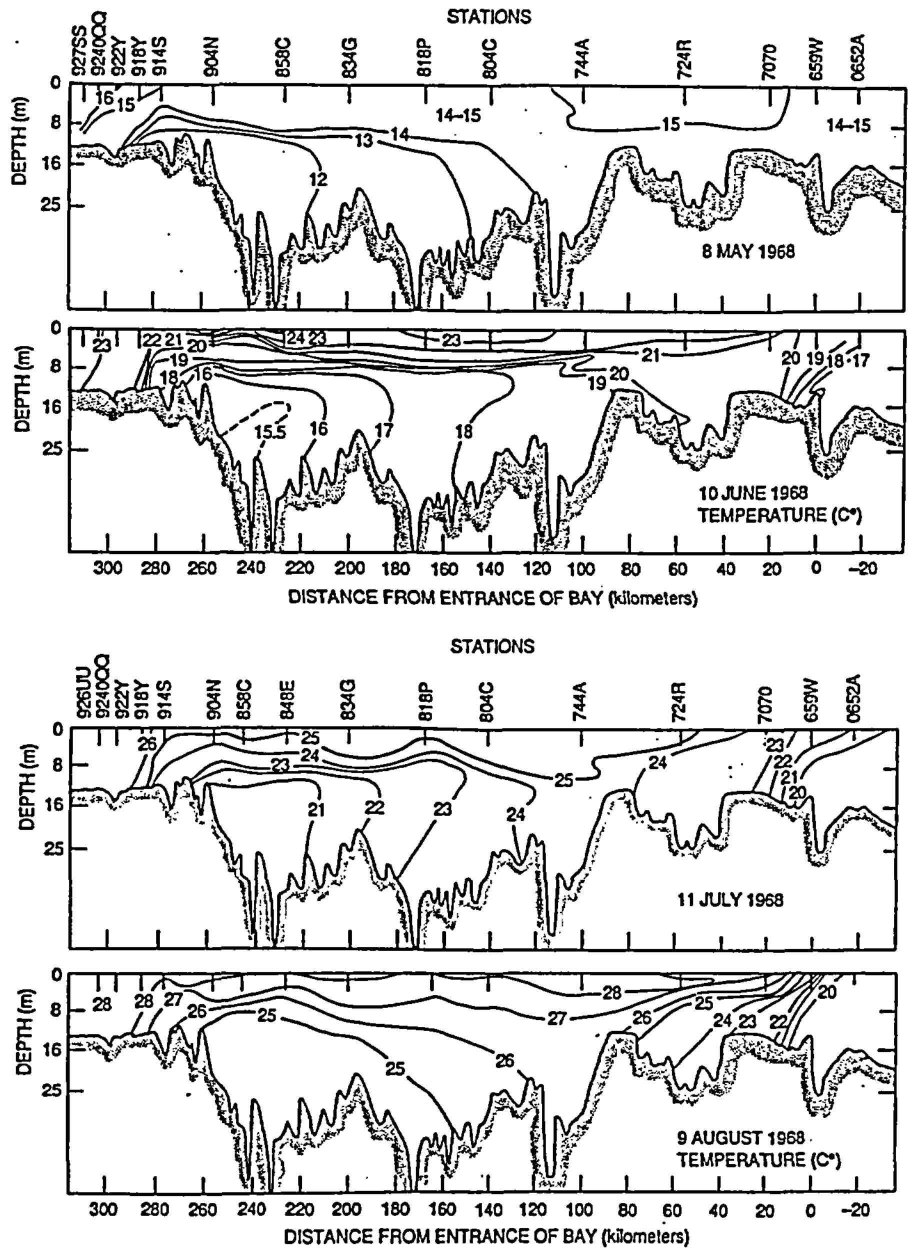

FIGURE 4.—Temperature profiles along the longitudinal axis of Chesapeake Bay for May–October, 1968, showing typical stratification, a summer pocket of cool water, and a summer temperature maximum filling the water column at a shallow sill near the mouth of the Rappahannock River with temperatures above 25°C (after Seitz 1971).

throughout the striped bass literature for the bay (for example, the high numbers of spawners and high juvenile indexes in Virgina tributaries in 1987 and 1988 while upper bay stocks were still depressed). These speculations require additional study for confirmation, but they indicate that thermal conditions in the sill area possibly have major importance for striped bass in Chesapeake Bay.

The records show considerable interannual variability in the "coolness" of the residual pocket of cool water in the upper middle bay, the warmth of the overlying strata, and the strength of the

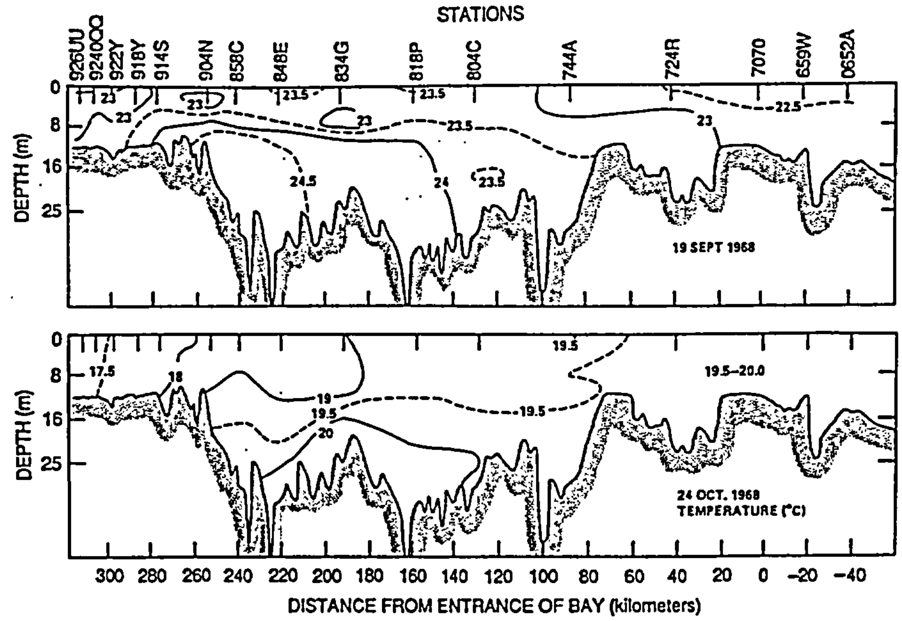

FIGURE 4.—Continued.

convergence of temperatures above 25°C with the sill (in terms of how high the temperatures are and the longitudinal distance covered by temperatures in excess of 25°C). These differences are due partly to sampling at slightly different times of year, but are most likely true interannual differences resulting from variable interactions of, for example, winter–spring freshwater flows, solar heating, air temperatures, ocean temperatures, and wind-driven circulation. Seliger et al. (1985) described some of these key climatic features that vary annually. The importance of variations in discharge of the Susquehanna River for stratification in the bay was emphasized by Schubel and Pritchard (1986). The thermal pattern of 1968 (Figure 4) is not anomalous, for the pattern shows clearly in Figure 5, which illustrates the average summer condition from 1949 to 1961 (Stroup and Lynn 1963).

The interannual variability in water temperatures, however, encompasses widely different conditions with respect to probable striped bass movements in response to temperature and thermal preferences. For example, bay water was sufficiently warm in 1968, the example year of Figure 4, to induce a thermal blockage at the sill (temperature above 25°C) with a longitudinal extent of over 74 km and to leave the cool pocket with temperatures only 1 degree below 25°C. Large striped bass remaining in the middle bay would have faced a severe thermal barrier if they tried to move south, and they would have occupied temperatures warmer than most would normally have frequented. In 1961, surface waters in the lower bay were exceptionally warm and the purported sill blockage was even more extensive than in 1968, but the entire zone of deep water from the Potomac River mouth to Pooles Island was filled with water of 21–24°C (Figure 6B; Stroup and Lynn 1963). In cooler 1958 (Figure 6A), the 25°C isotherm does not appear to have reached the bottom at the sill, so a migratory pathway was maintained.

Interannual variability in temperature patterns, therefore, encompasses conditions that could either stimulate or prevent migration out of the bay to coastal waters and conditions that could cause severe or little crowding in the residual cool water (based on temperature alone). It appears that strong density stratification, as seen in 1961 (Figure 6B), produces both especially high temperatures at the sill (and thus strong fish blockage) and preserves cool temperatures in the refuge. Historically, the two thermal effects may have compensated for each other somewhat in maintaining suitable striped bass habitat. Year-to-year differences in temperature distributions, and thus in striped bass distributions, may have been important contributors to the wide variations in year-class success of this species, for reasons that include physiolog-

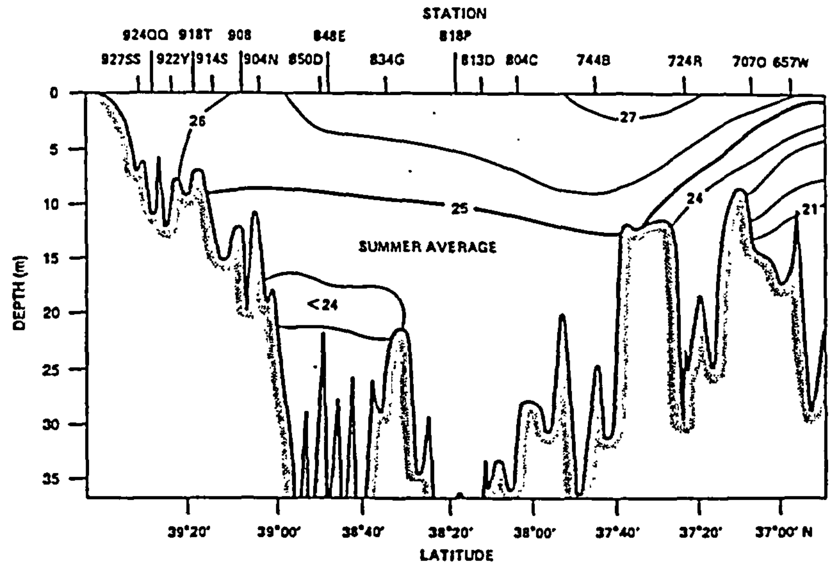

FIGURE 5.—Summer average temperature (°C) along the longitudinal axis of Chesapeake Bay, 1949–1961 (after Stroup and Lynn 1963).

ical effects on individuals, density dependence of feeding and growth, and other influences yet to be defined (discussed below).

There is only sketchy evidence to suggest a change in thermal patterns in the bay that correlates with drastic population declines of striped bass since the early 1970s. The EPA Chesapeake Bay Program's data set suggests that surface waters in the uppermost reaches of the bay may have been more consistently above 25°C since 1969 but that no such trend is evident for the main bay.

Dissolved Oxygen in Chesapeake Bay

Although, on the basis of temperature, the zone of cool water near Annapolis seems to be generally suitable summer habitat for the portion of subadult and adult striped bass blocked north of the Rappahannock sill, its suitability is compromised by depleted concentrations of dissolved oxygen. Telemetry studies in reservoirs have shown that water masses at acceptable temperatures but with dissolved oxygen concentrations less than about 2–3 mg/L will be actively avoided (Coutant 1985). The central basin of the Chesapeake Bay experienced some summer oxygen reduction naturally (Newcombe and Horne 1938; Taft et al. 1980). However, trends that suggest increasingly depleted oxygen resources, mostly in summer, have raised considerable concern among scientists and water quality regulators alike (Heinle et al. 1982; EPA 1983; Officer et al. 1984; Price et al. 1985; Seliger et al. 1985). It is the progressive worsening of summer anoxia in the presence of strong thermal limitations on suitable habitat that appear important for larger striped bass in Chesapeake Bay.

It is clear from the analyses by Officer et al. (1984) and Seliger et al. (1985) that summer oxygen depletion is fairly general in the bay, although two areas degraded most severely between 1950 and the present lie (1) in the purported "thermal refuge" near Baltimore and Annapolis, and (2) in the reach near the mouth of the Potomac River upstream of the sill. Historically, the reach just upstream of Annapolis seems to have maintained higher dissolved oxygen values in spite of oxygen depletion elsewhere, although the data are sparse (Hires et al. 1963; Figure 7). Heinle et al. (1982) included the refuge area in the zone called "heavily enriched" with nutrients, and the sill area in the zone where oxygen has shown marked change. Much of the deep-water zone between these two areas has also shown expansion of both the bottom area and the water column thickness affected by low dissolved oxygen.

Shrinking Habitat for Striped Bass Due to Temperature-Oxygen Squeeze

We analyzed the suitability of habitat in the water column during July of each year for the standard EPA bay zones. The cool thermal refuge is generally represented by data from zone CB-3, in

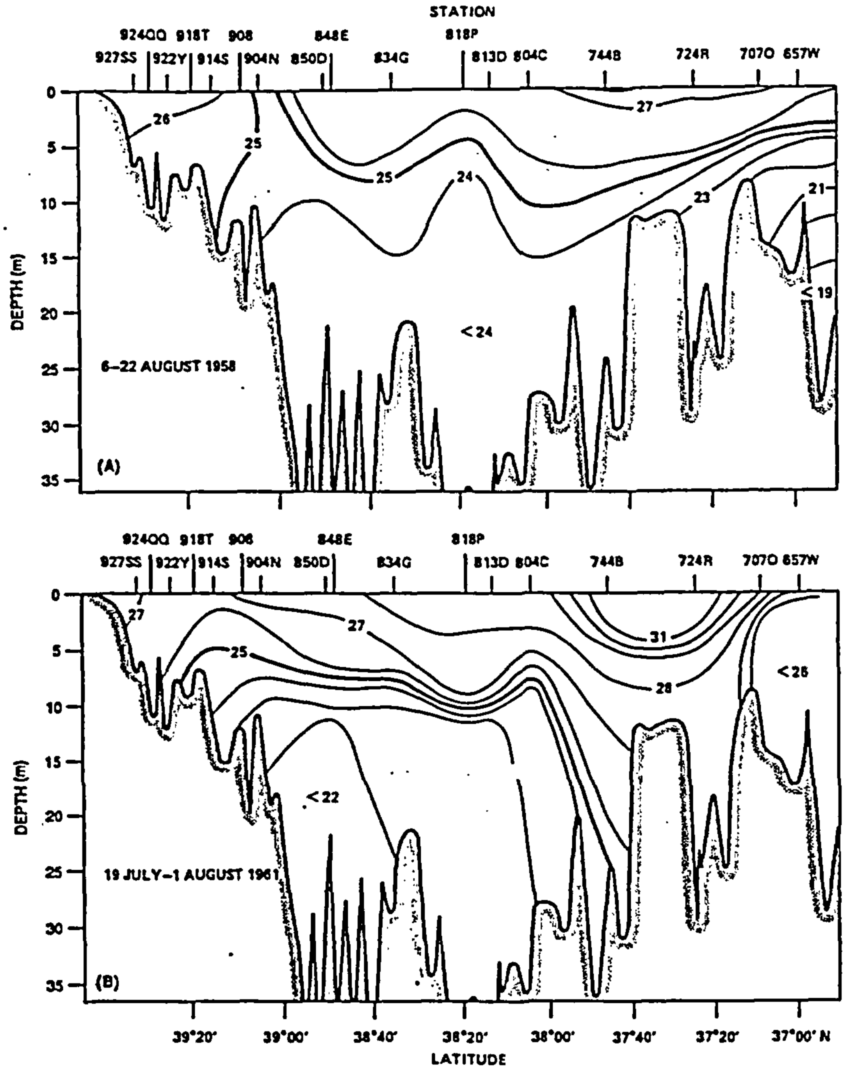

FIGURE 6.—Contrasting summer water temperature conditions along the longitudinal axis of Chesapeake Bay (after Stroup and Lynn 1963). In a cool year (A), the 25°C isotherm does not reach the sill off the Rappahannock River; in a warm year (B), temperatures there exceed 27°C. Strong density stratification seems to produce both especially high temperatures at the sill and cool temperatures in the residual pocket.

which most data were taken from the deep channel area. Zone CB-4 generally represents the upper part of the central basin, and CB-5 the lower part terminating near the sill. The pattern for zone CB-3 showed suitable habitat through a large segment of the water column in most earlier years. Habitat limitation there was principally by high temperature at the surface. In zone CB-4, however, a pronounced restriction of suitable temperature-oxygen habitat was noticeable from 1969 onward. The cause was both high temperature at the surface and low dissolved oxygen concentration in deeper waters. In the most recent years, 1984–1987, there has been no suitable habitat remaining in late July in area CB-4 (Table 1) or CB-5.

A dynamic picture of generally concurrent seasonal warming and deoxygenation in Chesapeake Bay has been outlined by Schubel and Pritchard (1986). These conditions appear to us to generate a habitat squeeze for large striped bass. The exact pattern varies from year to year as numerous climatic and other environmental factors (mentioned in the temperature section) vary. The onset of deoxygenation in the lower layers of the bay

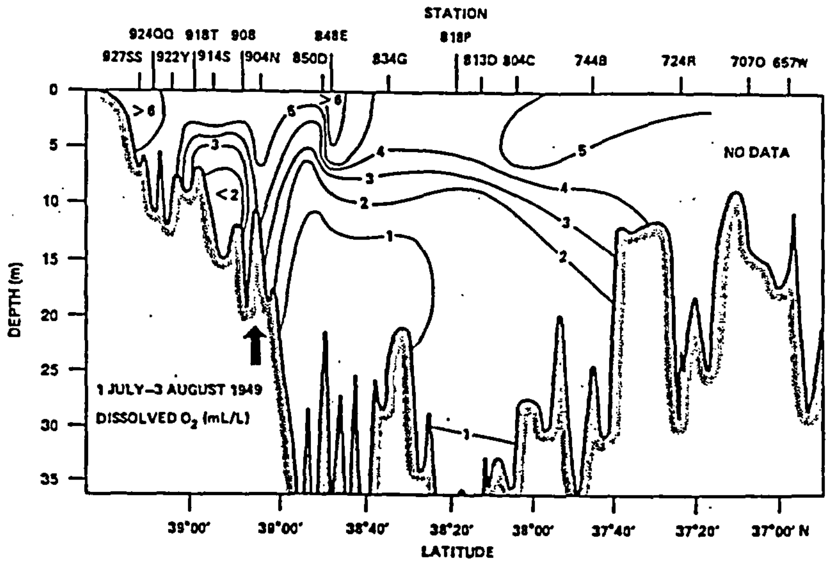

FIGURE 7.—Dissolved oxygen concentrations with depth along the longitudinal axis of Chesapeake Bay in summer 1949, showing a zone of high oxygen content extending to the bottom in the vicinity of Annapolis (arrow) (after Hires et al. 1963).

was ascribed by Schubel and Pritchard (1986) to (1) a sharp increase in stratification after fresher water from the spring freshet overlays the estuary, (2) a change in the thermal structure from near vertical homogeneity to a condition of warmer surface and cooler depths, which adds to the density differences due to vertical differences in salinity, and (3) a decrease in the intensity and frequency of high winds that accompanies the transition from spring to summer.

Timing and duration of high Susquehanna River flow in spring have major effects on initiation of low-oxygen conditions, according to Schubel and Pritchard (1986). Early freshets (winter) are dissipated in the bay by strong winds, and oxygen depletion is delayed until thermal input causes stratification in summer. Late freshets (April and May) cause strong salinity stratification which, augmented by rising surface temperatures, isolates the bottom waters and speeds the onset of dissolved oxygen depletion. Intensity of low-oxygen conditions (i.e., longitudinal extent and vertical thickness of layers with low dissolved oxygen concentrations) depends to a considerable extent on the accumulated freshwater discharge in May through July.

The duration of hypoxia in the upper bay through the summer and fall is also affected by Susquehanna River discharge. The end of the hypoxic period is associated with a weakening of vertical stratification and a downward mixing of higher-oxygen surface waters in the face of autumn winds and cooling temperatures, a process that normally begins in September but can occur as early as late August or as late as early October. Citing Goodrich (1985), Schubel and Pritchard (1986) described how the influx of fresh water in this period can strengthen vertical stratification in opposition to the forces that would otherwise weaken it. Overturn of the water column is delayed and hypoxic conditions persist until some time in October. In addition to these features, one should also consider the effects of the prominent tilting of density clines by winds, which would shift temperature and oxygen regimes over short time periods (Carter et al. 1978).

From the description by Schubel and Pritchard (1986) and our own water quality study from the perspective of striped bass habitat, we suggest a dynamic picture of how a habitat squeeze is generated for subadult and adult striped bass in the main portion of Chesapeake Bay, beginning in winter. Striped bass are known to overwinter in the deep basin that is oxygenated by vertical mixing in fall and winter and by a density underflow from the coast. Especially cold, windy winters probably have the coolest and best-oxygenated deep water. In spring, high freshwater flows from the Susquehanna River establish a strong density stratification. The greater the freshwater flow, the more intense is the stratification.

Vertical stratification is intensified in spring by warming riverine flows that attract spawning striped bass and by solar heating of the bay surface. Oxygen depletion begins in the deep basins, which striped bass of all ages abandon for surface waters. By late spring or early summer, riverine inflows from tributaries exceed 25°C and are avoided by large striped bass, and the bay surface is near 25°C. The warmest surface waters lie above the lower main basin. Low dissolved oxygen concentrations occur in progressively shallower depths in the basin, and the high-density return flow from the ocean is made largely anoxic from organic decomposition in the downstream end of the central basin. Striped bass subadults and adults begin to be squeezed vertically, largely by warm surface temperatures. Some escape the shrinking habitat space in the main basin by passing southward over the sill to the cooler lower bay and coast. Others follow their preferred temperatures northward and deeper in the main basin toward the residual cool water near Annapolis.

By midsummer, typically, warm water (above 25°C) impinges on the bottom at the sill, effectively blocking fish in the upper and middle bay from southward emigration. Low dissolved oxygen has risen to overlap warm surface water in all but the uppermost reach of the central basin, excluding large striped bass from much of its water mass. Subadults and adults trapped upstream of the sill congregate in the remaining cooler and oxygenated water near Annapolis; those downstream of the sill in Virginia waters can still follow the thermal gradient toward the cooler coast. Striped bass near Annapolis probably occupy a layer just above the depth at which dissolved oxygen concentrations fall below about 2–3 mg/L, as they do in many reservoirs in summer.

In autumn, declining surface temperatures and wind-induced destratification replenish striped bass habitat in the main basin and tributaries, and the fish respond by repopulating areas avoided in summer, particularly by dispersing southward from the Annapolis area. Some fish also disperse northward from coastal areas. As the bay surface becomes colder than the coastal waters in late autumn, some fish continue past the sill toward the warmer ocean that now has temperatures closer to those preferred.

In this hypothesized sequence of seasonal habitat changes, two areas are critical for striped bass well-being in summer—the thermal refuge near Annapolis and the sill across the main bay near the mouth of the Rappahannock River. As eutrophication of the basin north of the sill has intensified each year in the Chesapeake, the volume of residual cool water (roughly in the zone from Tilghman to Rock Hall and centered near Annapolis) that contains suitable dissolved oxygen for larger striped bass has diminished progressively. The sill acts to varying degrees from year to year to isolate both the geochemistry and the striped bass population of the middle and upper bay from coastal influences. Both temperature, which provides important behavioral cues to striped bass, and dissolved oxygen, which is being depleted by biological processes resulting from the long-term accumulation of nutrients from human activity, limit the present habitat for the species in summer.

Physiological Effects

The long-term trend of greater deoxygenation in the cool refuge near Annapolis must increasingly require summer resident subadults and adults to occupy warmer temperatures, lower dissolved oxygen concentrations, or both; physiological stress is inevitable. The relationship of temperature to oxygen metabolism in fishes, including the notion of a temperature optimum coinciding with the preferred temperature (Fry 1947), is relevant to Chesapeake Bay. Adult striped bass that occupy temperatures above the preferred 20–21°C (Coutant 1985) will have elevated metabolic rates and a high demand for dissolved oxygen. Yet oxygen in Chesapeake Bay in summer is often unavailable at preferred temperatures; it is low even in temperatures higher than those preferred. Both metabolism theory, based on concepts of F. E. J. Fry, and field studies in fresh water indicate that fish can optimize the competing metabolic demands of high temperature and low dissolved oxygen by occupying a zone of the coolest water available with dissolved oxygen concentrations of about 2–3 mg/L. Energy demands for the suboptimal metabolic activity are high there, however. If food is abundant, there may be little detrimental effect, because greater energy intake can compensate for high metabolic energy use. However, if food is scarce, either initially when striped bass enter the thermal refuge or due to depletion of food while fish congregate there, the fish will experience an energetic deficit. Under this deficit, more energy will be metabolized than can be replenished in feeding, and less energy will be available for growth and production of gametes.

Bioenergetics models (Kitchell 1983; Hewett and Johnson 1987) indicate that the detrimental effects of such an energetic deficit are a function of magnitude and duration. Moderate deficits caused by slightly suboptimal high temperatures at low oxygen concentrations can be tolerated for some time, even for the whole summer. More severe energetic deficits from exposure to temperatures far higher than optimum at the 2–3 mg/L oxygen interface can, however, cause marked decrease in body weight in short time periods as energy is taken from somatic and reproductive tissues to meet the needs of standard resting metabolism. The result is loss of body condition and increased susceptibility to disease, toxicants, and other environmental stressors. Tolerance of temperatures above 25°C for periods of time in the constrained habitat of a thermal refuge should be distinguished from temperature selection in open areas such as the sill, however, where avoidance of warm water, not its prolonged physiological disability, is the response to the thermal barrier.

Physiological stress of this type in a freshwater reservoir led to reduced reproductive capability by female striped bass the following spring (Coutant 1987). Survivorship of eggs and larvae was reduced after spawning, even though the number of eggs spawned was not significantly reduced. There is an abundant literature on many fish species, summarized by Coutant (1987), that relates poor feeding by adults to reduced egg quality and lowered reproductive capability. In many cases, poor feeding by the female causes smaller eggs or eggs containing smaller stores of energy for the developing larvae, which have poor survival.

Bioenergetic stress from a limitation in summer habitat may similarly induce poor reproductive success of adult Chesapeake Bay striped bass, particularly in the upper bay area where summer residence by prespawning females is most likely. These upper bay females are likely to spawn in the once-productive spawning grounds at the head of the bay, although coastal migrants may return to this area as well. Reduced survivorship in the early life stages has been characteristic of reproduction in the upper bay in recent years (NMFS 1989), as well as a progressively reduced spawning stock (although stock size has been improved by fishing restrictions since 1985). The nutritional state of striped bass larvae in field samples from the Chesapeake Bay, based on techniques developed by Wright and Martin (1982), suggests that starvation of the larvae may play a critical role in determining year-class strength (NMFS 1989). Starvation can have many causes, notably an absence of a nutritious food source. However, the measurements indicated greater stress due to starvation in 1981 larvae after 1980's severe summer anoxia (Officer et al. 1984) than in those sampled in 1982 after a less severe summer. Whereas researchers have focused attention on deficiencies in available food and feeding of young-of-the-year striped bass near the spawning areas (NMFS 1989), it seems reasonable also to implicate the status of maternally provided nutrient reserves and general vigor of the larvae that could be linked to the environment occupied by the parent when eggs were developing (Coutant 1987).

There is also evidence of stress severe enough to cause mortality of adult male striped bass in Chesapeake Bay. Chapman (1987) surveyed mitochondrial DNA genotypes in males from the relatively strong 1982 year class in the springs of 1984 and 1986 and found dramatic and significant change in this biological marker. Discounting the possibility of real errors of sampling and of different genotypes having different ages of maturation, the hypotheses Chapman advanced for the change in genotypes between years are (1) differential mortality of the genotypes sampled in 1984 or (2) immigration of a different stock (speculated to be from the York, James, or Hudson rivers) to the upper bay prior to the 1986 spawning season. Because the summer fishery is relatively small and thus few fish would have been caught in summer 1984, and because Maryland banned all fishing for striped bass as of January 1985, fishing mortality may be a minor source of the depletion of 1984 genotypes (unless there was an especially heavy autumn 1984 fishery). The information is consistent with environmentally induced stress and mortality of upper bay males during the hypoxic summer of 1984 and a partial replacement of them by northward dispersion of stocks from the lower bay that had summertime access to coastal waters beyond the sill.

Population Decline

We propose a cycle of reproductive impairment that may be a contributor to decline of striped bass stocks that had spawned at the head of the bay, and perhaps other upper bay tributaries. The cycle is based on our experience in freshwater reservoirs, the hatchery study of reproductive impairment of fish from a reservoir with reduced summer habitat, and the water quality and striped bass trends we have seen in Chesapeake Bay and other estuaries. There is established evidence for some linkages, whereas others are inferred and need to be confirmed. This cycle would extrapolate the effects of temperature and dissolved oxygen that are mainfested in individual fish in summer (distribution, physiological stress, and bioenergetic deficit) to possible effects at the population level. Other sources of mortality, such as fishing, would be superimposed on this cycle.

Beginning with adults, stressful conditions in compressed and suboptimal summer habitat may produce energetic inefficiency, poor feeding, and increased disease, any of which could lead to poor gonad development. The multiple effects of crowding may be severe enough to cause direct mortalities in warm, oxygen-poor years, as is seen in reservoirs. The following spring, reduced numbers of these bay-resident fish spawn at the head of the bay. Although the number of eggs per spawner is high, there is poor fertilization success and poor hatching rate, leading to reduced numbers of larvae. Larval survival may also be reduced by lower stores of yolk and oil derived from the parent. If there are few migrant spawners from the lower bay and coast, the result is a lowered index of juvenile abundance in the spawning areas. Even though the surviving juveniles may have normal development (or better, due to lessening of density-dependent effects) in the warm, shallow habitats they prefer, the recruitment to the spawning stock is lower than previously. After a few cycles of poor reproductive performance coupled with high fishing mortality, the stock has become depleted. Juvenile production in the head of the bay then becomes dependent on immigration of adults straying from other spawning tributaries and the lower bay, whereas production there may have previously been maintained by the upper bay residents.

Perspectives

The holistic view of environment and animal activity that F. E. J. Fry espoused seems as appropriate to understanding and resolving questions of striped bass success in Chesapeake Bay as stock assessment and traditional fishery management perspectives. In the Fry-inspired approach, a physiological and behavioral basis for habitat suitability is based on experimental determinations of the animal's activity and performance over a range of environmental conditions and on germane field experience. Population fluctuations can be related both retrospectively and predictively to changes in the amount of habitat that is within suitable bounds for the species and its life stages, even though the linkage between habitat space and population size is not well quantified. This habitat suitability (environmental) approach contrasts with more tranditional fisheries approaches, which emphasize the retrospective analysis of population statistics to infer population health, such as spawning stock size, recruitment numbers, age and size distributions, and records of fishing mortality (DeAngelis et al., in press). The traditional approach often considers the environment secondarily. Ideally, a blend of both approaches would be used to allow equal opportunity to identify and rectify both environmental and harvest causes for population crises. A value of the habitat perspective is its linking of fisheries interests with water quality and pollution control activities. Identification of habitat limitations for key estuarine fish and invertebrate species in summer, due to temperature preferences and seasonal patterns of temperature and dissolved oxygen, should be a productive tool for focusing water quality investigations.

How novel is the notion of a temperature–oxygen squeeze? A temperature–dissolved oxygen squeeze in summer is a real phenomenon that is not restricted to striped bass. It is well understood as a limiting factor in multistory fisheries in lakes and reservoirs. The extension to striped bass in estuaries differs largely by the inclusion of a shift in thermal preference as the fish age (which needs to be quantified for stocks within estuaries, not just by inference) and the more complicated regulation of stratification in estuaries. Thus, it is not a matter of proving that the general phenomenon is valid; it is a matter of establishing relevancy and potential power of the phenomenon for the particular situation, i.e., striped bass in Chesapeake Bay.

It is unusual to consider stresses on adults (other than fishing mortality) as determinants of year-class strength. Survival from eggs through juveniles is a recognized determinant of year-class success for Chesapeake Bay striped bass; the juvenile indexes have been powerful tools for predicting future yield of year-classes (Goodyear 1985). We view limitations on summer habitat space for adult or newly maturing striped bass in the bay not so much as factors in direct mortality (although this may occur in the extreme cases), but as influences on the quality, and perhaps quantity, of reproductive output. Influences on the prespawning populations that affect subsequent survival of eggs and larvae may be as critical for population health as more commonly identified conditions such as availability of spawning grounds and the direct effects of environmental conditions on survival of eggs and larvae.

Although we see temperature as a major directive and controlling factor (Fry 1947) for striped bass in the bay, changed temperatures alone are an unlikely cause of recent population problems. Thermal power stations (e.g., Calvert Cliffs) might be adding sufficient heat to affect some areas of the bay in marginal years. Global warming seems to be occurring (Kerr 1989), and it could have a large effect on bay temperatures and striped bass summer habitat in the future (Coutant 1990a). If there is a general temperature change important to striped bass, the cool refuge below 15 m in the Annapolis–Pooles Island reach and the bottom water over the sill just north of the mouth of the Rappahannock River should be the most important places to look for it. Oxygen depletion, on the other hand, results in large measure from anthropogenic water pollution. From a management perspective, the trend in deoxygenation is the part of the potential temperature–oxygen squeeze on striped bass that is likely to respond to remedial attention.

The degree to which Chesapeake Bay striped bass are affected by reduced thermal and oxygen habitat space likely depends on the age-class distribution of fish resident in the bay in summer. This distribution is now receiving much discussion and is the subject of some disagreement among fishery managers and scientists of coastal states. The segment of the stock that remains in the bay is central to management strategy, yet present data are insufficient to establish whether there have been trends with time in the proportion emigrating or in the age at which they emigrate. Not only does the significance of our hypothesis depend on this question, but a temperature–oxygen squeeze that markedly restricts available habitat space may well be forcing fish out of the bay at an earlier age. Thus, a current early departure of fish from the bay may be a strong confirmation that the temperature–oxygen squeeze acts on subadults rather than a reason why the squeeze would not be important for them.

A particular problem is our current understanding of the distribution and role of young striped bass females that are approaching sexual maturity. This is the age-class that, based on the earlier work of Mansueti and Hollis (1963), could have been the principal contributor to natural reproduction. This may, however, be an outdated view—a few large females may now be responsible for spawning success in most years. Because the current opinion is that most 4- and 5-year-old females leave the bay, bay water quality may not be particularly important. A decrease in age at which females emigrate to coastal waters in response to stressful conditions within the bay would serve to protect them from temperature–oxygen stress. But, if they are better adapted to the the bay environment—to its higher productivity and more abundant food—their emigration could still be a negative influence relative to historical conditions. Slower growth rates and longer time to sexual maturity in the coastal waters could be evidences of detriment.

The environmental situation faced by subadult and adult striped bass appears to differ markedly along the longitudinal axis of the bay. The perspective has sharpened since a general temperature–oxygen squeeze in the bay was suggested (Coutant 1985). In most summers, warm water over the sill may consign fish in the northern and southern bays to different environmental conditions. Seasonal temperatures and bathymetry indicate that fish in southern waters have free access to the coast in summer, whereas fish in the upper bay may become locked into the often-unsuitable conditions of the central and upper basin. This observation counters the frequently made point that a temperature–oxygen squeeze, although it may operate in closed systems such as large reservoirs, cannot occur in the (supposedly) open-ended Chesapeake Bay. The data also suggest that there is not a sharp division of stocks at the sill but a gradient of isolation extending from the coast to the upper bay. Spawning at the head of the bay may have been mostly by residents, which now have the greatest exposure to summer anoxia, whereas spawning in more southern Maryland and Virginia tributaries may have involved a higher percentage of migratory stock. Kohlenstein's (1981) estimated percentages of Chesapeake Bay striped bass that leave the bay at a given age were derived from the Potomac River, which has a somewhat intermediate geographic position in the bay.

Correlations of the juvenile index with water quality suggest that the percentages of subadults and adults that are summer residents in the upper bay and that contribute to reproduction at the head of the bay may have been underestimated. Juvenile indexes in spawning areas that are dominated by migrants from coastal waters would not be expected to show the associations with bay environmental conditions in the period 1969–1987 that we have shown. The mitochondrial DNA studies of Chapman (1987) give strong indication that the historical upper bay gene pool may have been eliminated or severely reduced, possibly by the factors discussed here, and replaced by genetic stock from the lower bay. Chapman (1990) has provided evidence for distinct populations within Chesapeake Bay. The genetic picture is unclear at present, but asymmetric migration is supported by the available evidence (R. W. Chapman, Johns Hopkins University, personal communication). The relative proportion of resident and migratory spawners at the head of the bay may also depend on the overall size of the population; a reduced population may leave mostly resident spawners, whereas a large population allows more migrants from the coast.

Our pursuit of the effects of temperature and dissolved oxygen conditions on Chesapeake Bay striped bass does not preclude other causes for population decline. It is unlikely that physiological problems caused by a temperature–oxygen squeeze can be a "grand unifying theory" for the decline. Certainly, high fishing mortality has been a major contributor to the decline, perhaps more important for the whole Atlantic coast striped bass population than water quality effects directly. Different mechanisms for population decline probably act in different locations in the bay; water quality may have its most significant role at the head of the bay. Because that location was historically the most important single producer of striped bass (NMFS 1989), the effect there could have been especially important for the extended east coast population.

A temperature–oxygen squeeze may affect other species in the bay, also. Populations of American shad *Alosa sapidissima* and blueback herring *Alosa aestivalis* have also declined over the same time period as striped bass, generally since the early 1970s (Richkus and DiNardo 1984). The consensus seems to be that adults of these species, too, do not occupy the bay in summer (E. Houde, Chesapeake Biological Laboratory, personal communication), an assumption that needs validation. Although less temperature preference information exists for these species than for striped bass, habitat restrictions discussed for striped bass would apply to any coolwater species or life stages. Adults of alewife *Alosa pseudoharengus*, one of the "river herrings" in the bay, displayed upper temperature avoidance in the field at 22°C (Wells 1968) and showed preference in laboratory experiments for 21.3°C (Reutter and Herdendorf 1974). If summer habitat is generally critically low, attempts to restore anadromous stocks of many species to the bay may be inhibited.

Critical testing of these ideas is needed. Future monitoring can be used for independent validation of the habitat change scenario developed here. Intensive monitoring of temperature and dissolved oxygen in the bay by EPA and state agencies has continued since 1987, but we have not incorporated these data in our analysis. Additional analyses of the older data sets could provide useful evidence. An expanded monitoring program could fruitfully examine other sites and dates for water quality information that can be compared statistically with juvenile index data. Models of the deoxygenation process (Taft et al. 1980; Officer et al. 1984; Seliger et al. 1985) could be combined with temperature and circulation models (e.g., Elliot 1976; Goodrich 1985) to estimate more quantitatively the timing, extent, and annual variability of habitat exclusion and probable fish movements.

Fisheries investigations involving hydroacoustics and telemetry to show geographical and temporal distributions of subadult and adult striped bass in relation to temperature and dissolved oxygen could aid understanding of the Chesapeake Bay situation, as they have in fresh water. Microchemical analyses of scales and otoliths for habitat markers in growth rings could show the timing of bay residence (Coutant 1990b), as well as changes in growth patterns due to physiological stress (this work can also be done on archived materials from past years). Hatchery experiments comparing spawning stocks from the upper and lower bay for spawning capability and larval survival after years of intense temperature–oxygen squeeze could test linkage between location and reproductive competence, as shown by Coutant (1987) for reservoirs. Resident and migrant fish would be distinguished by microchemical analyses of hard parts. In general, focused hypothesis testing in field and laboratory studies seems most appropriate. Modeling of fish populations can be a useful method for evaluating the long-term effects, but only if the alternative mechanisms for recruitment failure, both environmental and harvest, are included correctly.

There are rarely single, simple causes for any natural event. In the case of the decline of striped bass in Chesapeake Bay, several factors undoubtedly have contributed to the problem, but not necessarily always in the same degree. A temperature–oxygen squeeze that has been demonstrated clearly in fresh water and in the ocean undoubtedly occurs in estuaries such as Chesapeake Bay. But inference is not sufficient. It seems only reasonable to look directly for signs of similar behavioral, physiological, and population effects in the bay as potentially important contributors to the population success of this species we wish to manage.

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References

Barkley, R. A., W. H. Neill, and R. M. Gooding. 1978. Skipjack tuna, *Katsuwonus pelamis*, habitat based on temperature and oxygen requirements. U.S. National Marine Fisheries Service Fishery Bulletin 76: 653–662.

Boreman, J., and H. M. Austin. 1985. Production and harvest of anadromous striped bass stocks along the Atlantic coast. Transactions of the American Fisheries Society 114:3–7.

Brooks, T. J. 1983a. York River slack water data report. Temperature, salinity, dissolved oxygen, 1971–1980. Virginia Institute of Marine Science, Data Report 19, Gloucester Point.

Brooks, T. J. 1983b. Pamunkey River slack water data report. Temperature, salinity, dissolved oxygen, 1970–1980. Virginia Institute of Marine Science, Data Report 20, Gloucester Point.

Brooks, T. J. 1983c. Mattaponi River slack water data report. Temperature, salinity, and dissolved oxygen, 1970–1980. Virginia Institute of Marine Science, Data Report 21, Gloucester Point.

Brooks, T. J., and C. S. Fang. 1983. James River slack water data report. Temperature, salinity, and dissolved oxygen, 1971–1980. Virginia Institute of Marine Science, Data Report 12, Gloucester Point.

Carpenter, S. R., T. M. Frost, D. Heisey, and T. K. Kratz. 1989. Randomized intervention analysis and the interpretation of whole-ecosystem experiments. Ecology 70:1142–1152.

Carter, H. H., R. J. Regier, E. W. Schiemer, and J. A. Michael. 1978. The summertime vertical distribution of dissolved oxygen at the Calvert Cliffs Generating Station: a physical interpretation. Johns Hopkins University, Chesapeake Bay Institute Special Report 60, Baltimore, Maryland.

Chapman, R. W. 1987. Changes in the population structure of male striped bass, *Morone saxatilis*, spawning in three areas of the Chesapeake Bay from 1984 to 1986. U.S. National Marine Fisheries Service Fishery Bulletin 85:167–170.

Chapman, R. W. 1990. Mitochondrial-DNA analysis of striped bass populations in Chesapeake Bay. Copeia 1990:355–366.

Cheek, T. E., M. J. Van Den Avyle, and C. C. Coutant. 1985. Influences of water quality on distribution of striped bass in a Tennessee River impoundment. Transactions of the American Fisheries Society 114: 67–76.

Coker, C. M., and E. H. Hollis. 1950. Fish mortality caused by a series of heavy explosions in Chesapeake Bay. Journal of Wildlife Management 14:435–444.

Colby, P. J., and L. T. Brooke. 1969. Cisco (*Coregonus artedii*) mortalities in a southern Michigan lake, July 1968. Limnology and Oceanography 14:958–960.

Colvocoresses, J. A., and H. M. Austin. 1987. Development of an index of juvenile striped bass abundance for the Chesapeake Bay system: I. An evaluation of present measures and recommendations for future studies. Virginia Institute of Marine Science Special Scientific Report 120.

Coutant, C. C. 1985. Striped bass, temperature, and dissolved oxygen: a speculative hypothesis for environmental risk. Transactions of the American Fisheries Society 114:31–61.

Coutant, C. C. 1987. Poor reproductive success of striped bass from a reservoir with reduced summer habitat. Transactions of the American Fisheries Society 116:154–160.

Coutant, C. C. 1990a. Temperature-oxygen habitat for freshwater and coastal striped bass in a changing climate. Transactions of the American Fisheries Society 119:240–253.

Coutant, C. C. 1990b. Microchemical analysis of fish hard parts for reconstructing habitat use: practice and promise. American Fisheries Society Symposium 7:574–580.

Coutant, C. C., and D. S. Carroll. 1980. Temperatures occupied by ten ultrasonic-tagged striped bass in freshwater lakes. Transactions of the American Fisheries Society 109:195–202.

Coutant, C. C., K. L. Zachmann, D. K. Cox, and B. L. Pearman. 1984. Temperature selection by juvenile striped bass in laboratory and field. Transactions of the American Fisheries Society 113:666–671.

Cronin, W. B. 1971. Volumetric, areal, and tidal statistics of the Chesapeake Bay estuary and its tributaries. Johns Hopkins University, Chesapeake Bay Institute Special Report 20, Baltimore, Maryland.

DeAngelis, D.L., L. W. Barnthouse, W. Van Winkle, and R. G. Otto. In press. A critical review of population approaches in assessing fish community health. Journal of Great Lakes Research.

Elliot, A. J. 1976. A numerical model of the internal circulation in a branching tidal estuary. Johns Hopkins University, Chesapeake Bay Institute Special Report 54, Baltimore.

EPA (U.S. Environmental Protection Agency). 1983. Chesapeake Bay: a profile of environmental change. EPA Region 5, Philadelphia.

Fry, F. E. J. 1947. Effects of the environment on animal activity. University of Toronto Studies, Biological Series 55. (Publication of the Ontario Fisheries Research Laboratory Number 68:1–62.)

Goodrich, D. M. 1985. On stratification and wind-induced mixing in the Chesapeake Bay. Doctoral dissertation. State University of New York, Stony Brook.

Goodyear, C. P. 1978. Management problems of migratory stocks of striped bass. Marine Recreational Fisheries 3:75–84.

Goodyear, C. P. 1985. Relationship between reported commercial landings and abundance of young striped bass in Chesapeake Bay, Maryland. Transactions of the American Fisheries Society 114:92–96.

Grant, G. C. 1974. The age composition of striped bass catches in Virginia waters, 1967–1971, and a description of the fishery. U.S. National Marine Fisheries Service Fishery Bulletin 72:193–199.

Grant, G. C., V. C. Burrell, Jr., C. E. Richards, and E. B. Joseph. 1970. Preliminary results from striped bass tagging in Virginia, 1968–1969. Proceedings of the Annual Conference Southeastern Association of Game and Fish Commissioners 23:558–570.

Heinle, D. R., and six coauthors. 1982. Historical review of water quality and climatic data from Chesapeake Bay with emphasis on effects of enrichment. U.S. Environmental Protection Agency, Cheapeake Bay Program Report EPA 600/3-82-083, Annapolis, Maryland.

Hewett, S. W., and B. L. Johnson. 1987. A generalized bioenergetics model of fish growth for microcomputers. University of Wisconsin, Sea Grant Institute Publication WIS-SG-87-245, Madison.

Hires, R. I., E. D. Stroup, and R. C. Seitz. 1963. Atlas of the distribution of dissolved oxygen and pH in Chesapeake Bay 1949–1961. Johns Hopkins University, Chesapeake Bay Institute, Reference 63-4, Baltimore, Maryland.

Jackson, H. W., and R. E. Tiller. 1952. Preliminary observations on spawning potential in the striped bass (*Roccus saxatilis* (Walbaum)). Maryland Department of Research and Education 93:1–16, Annapolis.

Kerr, R. A. 1989. 1988 ties for warmest year. Science (Washington, D.C.) 243:891.

Kitchell, J. F. 1983. Energetics. Pages 312–338 *in* P. W. Webb and D. Weihs, editors. Fish biomechanics. Praeger, New York.

Kohlenstein, L. C. 1981. On the proportion of the Chesapeake Bay stock of striped bass that migrates into the coastal fishery. Transactions of the American Fisheries Society 110:168–179.

Kriete, W. H., J. V. Merriner, and H. M. Austin. 1979. Movement of 1970 yearclass striped bass between Virginia, New York, and New England. Proceedings of the Annual Conference Southeastern Association of Fish and Wildlife Agencies 32:692–696.

Kynard, B., and J. P. Warner. 1987. Spring and summer movements of subadult striped bass, *Morone saxatilis*, in the Connecticut River. U.S. National Marine Fisheries Service Fishery Bulletin 85:143–147.

Mansueti, R. J., and E. H. Hollis. 1963. Striped bass in Maryland tidewater. University of Maryland, Natural Resources Institute, Education Series 61, Solomons.

Massman, W. H. 1962. Water temperatures, salinities, and fishes collected during trawl surveys of Chesapeake Bay and York and Pamunkey rivers, 1956–1959. Virginia Institute of Marine Science Special Scientific Report 27.

Matthews, W. J., L. G. Hill, D. R. Edds, and F. P. Gelwick. 1989. Influence of water quality and season on habitat use by striped bass in a large southwestern reservoir. Transactions of the American Fisheries Society 118:243–250.

Matthews, W. J., L. G. Hill, and S. M. Schellhaas. 1985. Depth distribution of striped bass and other fish in Lake Texoma (Oklahoma–Texas) during summer stratification. Transactions of the American Fisheries Society 114:84–91.

Moss, J. L. 1985. Summer selection of thermal refuges by striped bass in Alabama reservoirs and tailwaters. Transactions of the American Fisheries Society 114:77–83.

Newcombe, C. L., and W. A. Horne. 1938. Oxygen poor waters of the Chesapeake Bay. Science (Washington, D.C.) 88:80–81.

NMFS (U.S. National Marine Fisheries Service). 1989. Emergency striped bass research study report for 1987. NMFS, Silver Spring, Maryland.

Officer, C. B., R. B. Biggs, J. L. Taft, L. E. Cronin, M. A. Tyler, and W. R. Boynton. 1984. Chesapeake Bay anoxia: origin, development, and significance. Science (Washington, D.C.) 223:22–27.

Price, K. S., and seven coauthors. 1985. Nutrient enrichment of Chesapeake Bay and its impact on the habitat of striped bass: a speculative hypothesis. Transactions of the American Fisheries Society 114: 97–106.

Reutter, J. M., and C. E. Herdendorf. 1974. Laboratory estimates of the seasonal final preferendum of some Lake Erie fish. Proceedings, Conference on Great Lakes Research 17:59–67.

Richkus, W. A., and G. DiNardo. 1984. Current status and biological characteristics of the anadromous alosid stocks of the eastern United States: American shad, hickory shad, alewife, and blueback herring. Atlantic States Marine Fisheries Commission, Fisheries Management Report 4, Washington, D.C.

Rudstam, L. E., and J. J. Magnuson. 1985. Predicting the vertical distribution of fish populations: analysis of cisco, *Coregonus artedii*, and yellow perch, *Perca flavescens*. Canadian Journal of Fisheries and Aquatic Sciences 42:1178–1188.

Schaich, B. A., and C. C. Coutant. 1980. A biotelemetry study of spring and summer habitat selection by striped bass in Cherokee Reservoir, Tennessee, 1978. Oak Ridge National Laboratory, ORNL/TM-7127, Oak Ridge, Tennessee.

Schubel, J. R., and D. W. Pritchard. 1986. Responses of upper Chesapeake Bay to variations in discharge of the Susquehanna River. Estuaries 9:236–249.

Seitz, R. C. 1971. Temperature and salinity distributions in vertical sections along the longitudinal axis and across the entrance of the Chesapeake Bay (April 1968–March 1969). Johns Hopkins University, Chesapeake Bay Institute Graphical Summary 5, Reference 71-7, Baltimore.

Seliger, H. H., J. A. Boggs, and W. H. Biggley. 1985. Catastrophic anoxia in the Chesapeake Bay in 1984. Science (Washington, D.C.) 228:70–73.

Setzler, E. M. and eight coauthors. 1980. Synopsis of biological data on striped bass, *Morone saxatilis* (Walbaum). NOAA (National Oceanic and Atmospheric Administration) Technical Report NMFS (National Marine Fisheries Service) Circular 433. (FAO [Food and Agriculture Organization of the United Nations] Fisheries Synopsis 121.)

Smith, C. L., editor. 1988. Fisheries research in the Hudson River. State University of New York Press, Albany.

Stewart-Oaten, A., W. W. Murdock, and K. R. Parker. 1986. Environmental impact assessment: "pseudoreplication" in time? Ecology 67:929–940.

Stroup, E. D., and R. J. Lynn. 1963. Atlas of salinity and temperature distributions in Chesapeake Bay 1952–1961 and seasonal averages 1949–1961. Johns Hopkins University, Chesapeake Bay Institute, Graphical Summary Report Number 2, Reference 63-3, Baltimore.

Taft, J. L., W. R. Taylor, E. O. Hartwig, and R. Loftus. 1980. Seasonal oxygen depletion in Chesapeake Bay. Estuaries 3:242–247.

Van Den Avyle, M. J., and J. W. Evans. 1990. Temperature selection of striped bass in a Gulf of Mexico coastal river system. North American Journal of Fisheries Management 10:58–66.

Vladykov, V. D., and D. H. Wallace. 1938. Is the striped bass (*Roccus lineatus*) of Chesapeake Bay a migratory fish? Transactions of the American Fisheries Society 67:67–86.

Vladykov, V. D., and D. H. Wallace. 1952. Studies of the striped bass, *Roccus saxatilis* (Walbaum), with special reference to the Chesapeake Bay region during 1936–1938. Bulletin of the Bingham Oceanographic Collection, Yale University 14:132–177.

Wells, L. 1968. Seasonal depth distribution of fish in southeastern Lake Michigan. U.S. Fish and Wildlife Service Fishery Bulletin 67:1–15.

Wright, D. A., and F. D. Martin. 1982. The assessment of starvation in larval striped bass using morphometric, histologic, and biochemical techniques. University of Maryland, Chesapeake Biological Laboratory, Annual Report UMCEES 82-88 CBL, Solomons.

Lake Anna Fisheries Management Report

2003

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Lake Anna is a 9,600-acre impoundment owned by the Dominion Virginia Power Company. The lake spans Louisa, Spotsylvania and Orange counties and serves as cooling water for the two-unit North Anna Nuclear Power Station. Fish stocking began in 1972 with introductions of largemouth bass, bluegill, redear sunfish and channel catfish. Subsequent stockings of redear, channel catfish, walleye, striped bass and largemouth bass (both Florida and northern strains) were made. Threadfin shad and blueback herring were successfully introduced in the 1980s. Striped bass and walleye have generally been stocked annually. A 12-15 inch slot length limit was established to restructure the largemouth bass population in 1985. Prior to that time, a 12-inch minimum size limit was in effect. A 20-inch minimum length limit regulates striped bass harvest.

A 2000-2001 daytime creel survey (a survey where anglers are interviewed about their fishing habits, preferences and success rates) indicated that annual fishing pressure was 24 hours/acre. This rate was below the previous Lake Anna sample (30 hours/acre in 1992); however, the 1992 survey was conducted only during warmer months and likely was an overestimate when expanded for the entire year. Fishing pressure at Lake Anna was among the lowest of large Virginia reservoirs and was similar to Kerr Reservoir (23 hours/acre).

Preferred species selected by anglers in 2000 included largemouth bass (69%), striped bass (15%), crappie (12%) and catfish (2%). These fishing preferences were remarkably similar to those documented nearly ten years earlier (for example, 72% selected largemouth bass and 14% selected striped bass in 1992). Dominant species *caught* (by number) were black crappie (56,308 or 53%) and largemouth bass (38,245 or 36%), but most largemouth bass were released. Thus, dominant species *harvested* (by number) were crappie (39,167 or 84%), channel catfish (2134 or 5%), and white perch (2,111 or 5%). Striped bass comprised only 4% of the total number of fish harvested but accounted for 30% of the biomass. Lake Anna and Smith Mountain Lake had similar, moderate (below average) largemouth bass catch and harvest rates, while Lake Anna crappie and catfish creel statistics were above average and similar to those at Kerr Reservoir. Dominant species harvested (by weight) were crappie (16,272 pounds or 49%) and striped bass (10,114 pounds or 30%). Compared to other Virginia reservoirs, anglers at Lake Anna harvested low numbers of largemouth bass but high numbers of crappie, catfish and striped bass. Average weights of fish harvested in 2000 at Lake Anna were 3.0 pounds for largemouth bass, 0.4 pound for black crappie, 5.9 pounds for striped bass and 1.8 pounds for channel catfish. Largemouth bass anglers released 99% of all bass caught at Lake Anna (only 502 were harvested during 12 months for a total weight of 1512 pounds). This release rate was even higher than the 97% largemouth bass release rate documented in 1992 and demonstrated the extent of the catch-and-release ethic.

The aquatic weed <u>Hydrilla verticillata</u> became established in Lake Anna during the late 1980s, and abundance increased rapidly--from 96 acres in 1990 to 832 acres in 1994. Sterile (triploid) grass carp (N=6185) were stocked into Virginia Power's Waste Heat Treatment Facility (WHTF) in 1994 to control <u>Hydrilla</u>. The WHTF is separated from Lake Anna by three dikes, and thermal effluent enters the lake via gravity flow under the third dike. All grass carp stocked in the WHTF were marked with coded wire micro tags. No grass carp were stocked in Lake Anna.

Historically, rotenone sampling at Lake Anna was conducted every three years to generate species composition and biomass estimates. This sampling involved the poisoning of four coves with a piscicide, and collected data were used to evaluate forage abundance (gizzard shad, threadfin shad, and blueback herring) for stocked predators and monitor overall fish community composition. However, due to extremely high variances in biomass estimates, heavy shoreline development (with the potential for public relations problems) and intensive manpower requirements; rotenone use at Lake Anna was discontinued after 1995. Increased gill netting with larger, multi-panel nets was determined to be an adequate replacement for community structure and forage evaluation while providing the needed data for predator stocking evaluation. Current annual sampling protocols include spring electrofishing for largemouth bass in the upper, middle and lower portion of the reservoir. Upper lake electrofishing is conducted above "the splits" on both major tributary arms; middle lake sampling is conducted below the splits to the vicinity of the Route 208 Bridge; and lower lake sampling is conducted between the Dam and Dike II. Gill net surveys are stratified by upper and lower lake (using Route 208 as the boundary), and specific sites are selected based on a random block design. A total of 36 net nights of effort are conducted annually (one net set overnight is one net night). Gill nets are 200 X 8 feet and have eight different 25-foot panels that allow the sampling of most sizes of fish present in the lake. Typically, with either gear; fish are measured for total length and weight and released. However, ear stones (otoliths) may occasionally be removed from fish to determine exact age. This information is crucial when evaluating certain population parameters and determining stocking success.

Stockings during the past decade included striped bass and walleye (Table 1). Stocking rates and locations were variable in attempts to maximize hatchery resources. Stocking evaluations are included below as part of a species-by-species summary of fish population status.

Largemouth Bass

Largemouth bass mean electrofishing catch rates (CPUE, or number caught per hour of electrofishing) for all size groups increased or remained stable over the past decade and were at or near record levels as recently as 2001 (Table 2). Size groups of largemouth bass are universally defined as stock (at least 8 inches), quality (at least 12 inches), preferred (at least 15 inches), and memorable (at least 20 inches). CPUE of fingerling and stock-size bass remained remarkably stable between 1993 and 2002. Stock-size fish are generally considered to be mature (or nearly so) and recruited to the population. Minimal variation in bass fingerling catch rate suggested Lake Anna is a stable system and produces consistent year classes (or cohorts) of bass from year-to-year. Minimal variability in stock-size bass catch rate similarly suggested the adult population was stable. The slight variation in stock bass catch over time (actual data points rather than the trend line) was likely due to sampling variability (Figure 1).

Catch rates of larger bass (e.g., quality and preferred-size) increased during the past decade and reached records in 2001 before declining in 2002 (Figure 2). However, it is believed that 2002 data were biased by the severe drought that affected the region during the latter half of 2001 and most of 2002. Lake Anna was never below full pool during spring electrofishing surveys until 2002 when it was down two feet. Total CPUE (fingerling + stock) remained nearly static over the period and averaged 60 bass/hour. These data are commensurate with other large Virginia reservoirs. Total CPUE was always significantly higher in the middle and upper lake portions than down lake. This was likely due to the noticeable productivity gradient, expected in a tributary storage impoundment, that supports higher biomass at upstream locations.

Largemouth bass structural indices (PSD and RSDs) paralleled catch rates and further suggested that population structure shifted upwards (towards larger individuals) recently (Table 3). PSD (proportional stock density) is an index that describes the size structure of a population and may be used in context of predator/prey relationships to determine balance within a fish community. Simply, the larger the number; the larger the proportion of big fish in a population. PSD for largemouth bass is determined by the ratio of the number of bass that are greater than eight inches but also greater than 12 inches. Similarly, RSD-P (relative stock density of preferred bass) is a ratio of the number of bass that are greater than eight inches but also greater than 15 inches. PSD and RSD-P were at or near record levels in 2000 and 2001 but declined to 65 and 29 in 2002. These levels were slightly below average but not believed to be indicative of a real shift in population size structure. PSD values between 40 and 60 are generally considered to represent balanced bass populations.

Otoliths from a subset of bass collected during electrofishing were removed annually during the last several years to evaluate growth and mortality. Bass growth rates were above average for young fish, as fish reached 7.2 inches, 10.6 inches and 13.1 inches by their first, second and third years (Figure 3). However, growth slowed in the upper portion of, and just over, the slot. A typical bass grew out of the slot at 4.4 years and averaged only about one inch per year until age eight or nine. Evidence suggested that bass at Lake Anna may be stockpiling and stunting, albeit at a more desirable size than typically occurs. Current growth patterns require a bass about ten years (at a conservative minimum) to reach citation length (22 inches). Based on growth curves, it's more likely that citation bass are at least 12 years old unless other factors are at work (e.g., cohort interactions, forage and growth variability). Fish up to age 13 were collected during recent investigations.

Total annual mortality (the percentage of the bass population that dies each year from all causes) was 27% for fish aged 2-12 based on a catch curve of bass sampled in 2002. When other years were combined, the overall mortality estimate was 31%. While these estimates assume constant recruitment (equal production of young fish from year-to-year), they are low and support current and previous findings at Lake Anna (e.g., high bass abundance and structural indices, rapid to slow growth pattern, low relative weight, and low harvest). Total annual mortality is composed of natural and fishing mortality. Estimates of annual natural mortality were similar to the rates listed above (for total mortality) and suggested fishing mortality was very low.

Relative Weights (Wr, a measure to describe the plumpness or well-being of a fish) were highest in upper lake bass and declined down lake. The lowest Wr values were from lower lake fish. Overall, Wr values at Lake Anna were lower than for largemouth bass from other district waters.

Stomachs taken from fish sacrificed for otoliths were analyzed, and 61% were empty. Bass that had stomach contents ate fish (35%), artificial lures (2%), crayfish (1%) and insects (1%). Many consumed fish were unidentifiable, but the following were observed in decreasing abundance: bluegill, white perch and threadfin shad. It is likely that many of the unidentifiable items were shad (either gizzard or threadfin).

Striped Bass

Striped bass were stocked annually at a variable rate (Table 1) in an effort to determine an optimum stocking rate for Lake Anna, as overstocking could result in reduced growth, survival and/or recruitment. Lake Anna striped bass stockings were evaluated with gill nets, and it was assumed that nets gave unbiased population samples of fish under age 5. Older (larger) individuals were caught periodically and provided useful information, but the maximum bar mesh size of 2 inches precluded reliable sampling of larger striped bass.

Generally, young fish grew quickly through age 3 (when they reached the legal 20-inch minimum size), but growth slowed thereafter (Figure 4). Striped bass averaged 10, 18 and 22 inches at ages 1, 3, and 5. Ages were rounded up, as fish were collected during winter before completing a 12-month growing cycle; however the growing season of the ensuing age had been completed. This pattern of striped bass growth (rapid growth of juvenile and sub-adult fish followed by slow growth of adults) is common in southeastern reservoirs with marginal habitat such as Lake Anna. Habitat needs shift as striped bass age, and summer conditions at Lake Anna typically find water temperature and dissolved oxygen combinations marginal for adult striped bass, especially in the lower portion of the reservoir. For comparison, striped bass at Smith Mountain Lake; a reservoir with good adult striped bass summer habitat, averaged 10, 21 and 26 inches at the ages 1, 3, and 5.

Several variables were evaluated to determine if relationships existed between stocking size and rate and size or abundance of fish following stocking. No significant relationship existed between stocking size and total length of age 0 fish, total length of age 0 fish and catch rate of age 0 fish, or number stocked and catch rate of age 0 fish. These findings suggest that the number of striped bass that recruit to the population is based, at least in part, on other variables (perhaps environmental effects or forage abundance). However, only six years of data were available for evaluation, and it is possible that relationships may become apparent as the data set is enhanced. It was noteworthy that catch of age 0 fish was lowest with the lowest stocking rate (5 per acre) but highest with intermediate stocking rates (10-11 per acre). Stocking rates of 20 or more per acre resulted in intermediate catch of young striped bass. The catch of age 1 fish may be a better indicator of year class strength or stocking "success", but additional data are required for analysis.

Cohort based mortality estimates were calculated for each striped bass year class with ample data (1997-2000). These estimates provided the total annual mortality rate – that is, the percentage of the year class that died each year from all causes. Essentially, each stocking was considered a subgroup, and these groups were followed through time to see how they survived. The oldest year classes had the most data points (or years of catch-per-unit-effort data) and provide the best (or most significant) relationship. The 1997 year class had only a 28% total annual mortality rate (fish age 0-5) which translated into a high 72% survival rate. Two other survival estimates, while not as significant, were similar and ranged from 75-80%. Only one estimate had lower survival, but it was the year class with the fewest data points. These findings suggest that the overall mortality rate for striped bass at Lake Anna is low.

Relative abundance of striped bass in Lake Anna was estimated by catch rate or catch per unit effort (CPUE). This was simply the number of striped bass caught per net night of effort. Since new netting protocols were established in 1997, CPUE for striped bass in gill nets has ranged from 3.0 (1998) to 4.8 (2000). CPUE in 2002 (3.7) was equivalent to the six-year average. Most striped bass were caught in the upper portion of the reservoir. The North Anna River from Rose Valley upstream to Route 719 and the Pamunky River from Jetts Island upstream to Terry's Run were typically very productive locations during November netting.

Walleye

Walleye were historically stocked sporadically at Lake Anna (Table 1). However, as a result of a statewide walleye study and recommendations by the DGIF Walleye Committee, stockings were stabilized after 1997 with at least 25 per acre stocked thereafter (Lake Anna was included in a statewide walleye research project, and a special addition of *Virginia Wildlife* Magazine was published in June 2001 detailing findings. Reprints are available from DGIF Regional Offices). In addition to increasing the stocking rate and frequency, new stocking sites and methods were added in an effort to spatially expand the population after it was discovered that most walleye were confined to the Pamuky River tributary arm. It was hypothesized that since all historical stockings had occurred in this arm of the upper reservoir, the population was exhibiting a homing tendency thereby limiting dispersion. Walleye stockings were evaluated with gill nets, and it was assumed that nets gave unbiased population samples of fish under age 4. Older (larger) individuals were caught periodically and provided useful information, but the maximum bar mesh size of 2 inches precluded reliable sampling of larger walleye.

Like striped bass, young walleye grew rapidly at Lake Anna attaining 19 inches after only three growing seasons (Figure 5). However, after reaching about 20 inches, growth declined and became sporadic. Further increases in total length occurred very slowly. Walleye averaged 11, 19 and 20 inches at ages 1, 3, and 5. Ages were rounded up, as fish were collected during winter before completing a 12-month growing cycle; however the growing season of the ensuing age had been completed. Walleye up to age 12 were collected, but sample sizes were low for fish older than age 3. Walleye growth at Lake Anna was better than in District small impoundments (e.g., Lakes Orange, Brittle and Burke).

Efforts to spatially expand the walleye population by adding stocking sites in the lower, middle and upper portions of the reservoir initially seemed successful but now appear dubious. Beginning in 1999 with Duke's Creek, one or more annual stocking sites were selected in portions of the reservoir where walleye stockings had not historically occurred (new sites were Christopher Run, Sturgeon Creek and the State Park). The percentage of walleye captured with gill nets in the upper vs. lower portion of Lake Anna should be a reasonable indicator of population dispersion (the assumption being given equal effort, catch in lower and upper reservoir portions should be similar). Historically, walleye catch in the upper lake was at or near 100% but dropped to around 50% in 1999 and 2000 after lower lake stockings. This indicated lower lake stockings were spatially expanding the population; however, lower lake catch was mostly age 0 (young-of-year) fish. Recent years (including 2002 when catch rate was at a record level) saw upper lake catch return to the 80-95% range. Thus, the upper lake (specifically the Pamunky River arm) appears to possess habitat preferred by Lake Anna walleye.

The catch rate (CPUE) of walleye in gill nets ranged from 0.4 (fish per net night) in 1998 to 2.6 in 2002. Before 2002, the previous high was 1.6 (2000). Although no trend was apparent, the record catch in 2002 suggested new stocking protocols were finally increasing population size.

Black Crappie

Black crappie were evaluated with experimental gill nets in 1997-2002. It was assumed that gill nets sampled to the entire population without bias. Otoliths were removed from all fish captured in 2002 to develop estimates of growth and mortality. Crappie were typically the most abundant fish in gill nets, and although gill net effort was equal; most crappie (94%) were caught in the upper lake. Mean CPUE (catch per unit effort) in gill nets averaged 11.0 fish per net night between 1997-2002 with 1997 producing the highest (15.0) and 2000 the lowest (5.5) CPUE. CPUE in 2002 was above average after two years of below average catch.

Black crappie size structure was good in 2002. Average size was about 8 inches, but strong representation of 12-inch and over fish was present along with ample juvenile production. Crappie growth was moderate but highly variable (Figure 6). For example, age 3 fish averaged 8.3 inches total length but ranged from 5.8-12.4 inches. The mean length of age 3 crappie in other District waters (four small impoundments) was 8.5 inches in 2002. Sample sizes of crappie older than age 5 were small, thus the latter half of the growth curve (Figure 6) was biased. Fish up to age 13 were collected in 2002, and an age 16 crappie was sampled several years ago. This fish was a nine-inch male; further illustrating the highly variable growth of Lake Anna crappie.

Catfish

Catfish populations were evaluated with experimental gill nets in 1997-2002. The five species caught (in decreasing abundance) were channel catfish, white catfish, yellow bullhead, brown bullhead and blue catfish; however, only the former two contributed significantly to overall biomass. Channel catfish were usually the fourth or fifth most prevalent species taken in gill nets. Channel and white catfish CPUE (catch per unit effort) fluctuated during the period with no apparent trend within or between species. Highest CPUE occurred in 1998 for both channel (5.7 fish per net night) and white catfish (4.5 per net night), but lowest CPUE occurred in 1997 for channel catfish (2.3 per net night) and in 2002 for white catfish (1.5 per net night). Catch of channel catfish was above average in 2002, while catch of white catfish was below average.

Channel catfish was one of the few species sampled in nearly equivalent numbers in the upper and lower portions of the reservoir - over 40% were collected from the lower reservoir, but average size was significantly greater in the upper reservoir. White catfish lengths were identical from both portions of the lake, but only 28% were collected below Route 208. Average total length of channel catfish was 15 inches, but several large specimens were observed including a potential world record. This monster was caught in a gill net and released in good condition near Dike III in December 2002 after weighing in at over 55 pounds.

Two small blue catfish were caught (one in 1997 and 1998). Their origin is unknown, as no stocking records exist for this species in Lake Anna; however, blue catfish were stocked in the Lake Anna watershed (Lake Orange) during the 1980s.

Forage

The forage base (members of the shad and herring family or clupeidae) includes gizzard and threadfin shad and blueback herring at Lake Anna. Most of the forage biomass is composed of gizzard shad, although blueback herring have been a challenge to effectively assess, and threadfin shad abundance is cyclic – based largely on minimum water temperatures, as this species has the proclivity to "winter kill".

Estimates of gizzard shad biomass from historical rotenone samples ranged from near 100 to over 300 lbs/acre, while gill net CPUE (catch per unit effort) varied from 6.2 to 27.1 and averaged 14.0 fish per net night. The highest CPUE was in 2000, and the lowest was in 2002. It is unknown to what extent drought conditions in 2002 affected either the gizzard shad population or sampling efficiency, but reservoir levels were reduced in late 2001 when CPUE was 21.0. It is possible that even with increased effort (the current level of 36 net nights), sampling variability was still too high to effectively estimate true shad abundance. Further analysis will be necessary, and 2003 net samples may yield further insight into the low catch rate of gizzard shad in 2002.

Gill nets were compared to night electrofishing for forage assessment in 2000 and were found to give acceptable (unbiased) estimates of size structure and had lower associated sampling variability. The size structure of the gizzard shad population fluctuated frequently but usually had a bimodal length distribution. Size distribution was good in 2002 with three peaks indicating a good diversity of forage and an average size of 8.9 inches. Most shad (87%) were caught in the upper lake.

Other Species

Lake Anna is home to many other species – some of various recreational importance including redear sunfish and white perch and others important ecologically such as creek chubsucker and white sucker. Habitats are variable throughout the lake, and species abundance can be sporadic. For example, chain pickerel (a native top level predator and sport fish) prefer slow moving coastal plain systems where tannins from leaf litter frequently stain the water and reduce pH to a level lower than typically found in the piedmont. Contrary Creek, while suffering from acid mine drainage, offers a unique habitat in Lake Anna and supports a thriving chain pickerel population. These species are sampled periodically in gill nets, and their abundance can be gauged by catch per unit effort or number caught per net night (Table 4).

Table 1. Fish Stocking in Lake Anna 1993-2002 (numbers rounded to the nearest thousand; STB = striped bass, WAE = walleye).

	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
STB	172	146	132	148	96	196	98	108	48	199
/ac	18	15	14	15	10	20	10	11	5	21
WAE	0	53	58	97	0	480	240	259	240	243
/ac		6	6	10		50	25	27	25	25

Table 2. Mean electrofishing catch per unit effort (CPUE) of various size groups of largemouth bass at Lake Anna, 1993-2002 (fingerlings are less than eight inches, stock are at least 8 inches, quality are at least 12 inches, preferred are at least 15 inches, and memorable are as least 20 inches); note no sample conducted in 1994.

	1993	1995	1996	1997	1998	1999	2000	2001	2002	Mean
fingerling	13	4	7	5	8	8	7	7	10	8
stock	54	55	45	54	59	50	49	60	49	53
quality	31	36	28	41	42	37	39	45	32	37
preferred	15	17	12	19	21	19	21	25	14	18
memorable	2	2	0	3	2	1	4	2	1	2
total(f+s)	67	59	52	59	67	58	56	67	59	60

Table 3. Largemouth bass structural indices from electrofishing surveys at Lake Anna, 1993-2002 (PSD=proportional stock density, RSD=relative stock density; see narrative for explanation)..

	1993	1995	1996	1997	1998	1999	2000	2001	2002	Mean
PSD	60	65	60	75	74	75	80	75	65	70
RSD-P	29	33	27	36	35	39	43	42	29	35
RSD-M	5	4	2	4	3	5	7	4	2	4
sites	2	3	6	2	4	3	3	3	3	
N	180	297	441	198	381	290	278	337	294	

Table 4. Catch per unit effort (number of fish per net night) for 25 fish species sampled at Lake Anna with gill nets. Fish listed in decreasing order of abundance for mean catch.

Species	1997	1998	1999	2000	2001	2002	Mean
Gizzard shad	8.5	11.8	9.3	27.1	21.0	6.2	**14.0**
Black crappie	15.0	11.2	13.7	5.5	8.2	12.2	**11.0**
White perch	2.6	8.1	12.5	11.3	15.1	8.5	**9.7**
Channel cat	2.3	5.7	3.5	4.1	5.5	4.7	**4.3**
Striped bass	4.4	3.0	3.1	4.8	3.5	3.7	**3.8**
White catfish	1.9	4.5	3.4	2.2	2.4	1.5	**2.7**
Blueback	1.4	0.7	0.1	8.5	1.0	0.0	**2.0**
Threadfin	1.6	1.0	0.4	3.6	1.6	1.3	**1.6**
Largemouth	1.4	1.2	0.8	1.0	0.7	1.9	**1.2**
Walleye	0.6	0.4	1.0	1.6	1.0	2.6	**1.2**
Spottail shiner	0.6	0.2	0.6	1.0	0.8	0.4	**0.6**
White sucker	0.5	0.8	0.3	1.0	0.7	0.1	**0.6**
Bluegill	0.1	0.2	0.3	0.3	1.1	0.3	**0.4**
Redear	0.2	0.5	0.4	0.2	0.8	0.2	**0.4**
B. bullhead	0.0	0.0	0.1	0.3	0.3	0.3	**0.2**
C. chubsucker	0.1	0.0	0.3	0.0	0.9	0.1	**0.2**
Common carp	0.1	0.1	0.2	0.3	0.3	0.2	**0.2**
Y. bullhead	0.3	0.4	0.1	0.0	0.2	0.2	**0.2**
Chain pickerel	0.1	0.0	0.1	0.1	0.2	0.0	**<0.1**
Quillback	0.0	0.0	0.0	0.3	0.1	0.1	**<0.1**
Yellow perch	0.0	0.1	0.1	0.1	0.1	0.0	**<0.1**
Golden shiner	0.1	0.0	0.0	0.0	0.1	0.1	**<0.1**
Redbreast	0.0	0.1	0.1	0.0	0.1	0.0	**<0.1**
Warmouth	0.0	0.1	0.0	0.1	0.1	0.0	**<0.1**
Blue catfish	0.1	0.1	0.0	0.0	0.0	0.0	**<0.1**

Figure 1 - LMB electrofishing CPUE for fingerling and stock-size fish

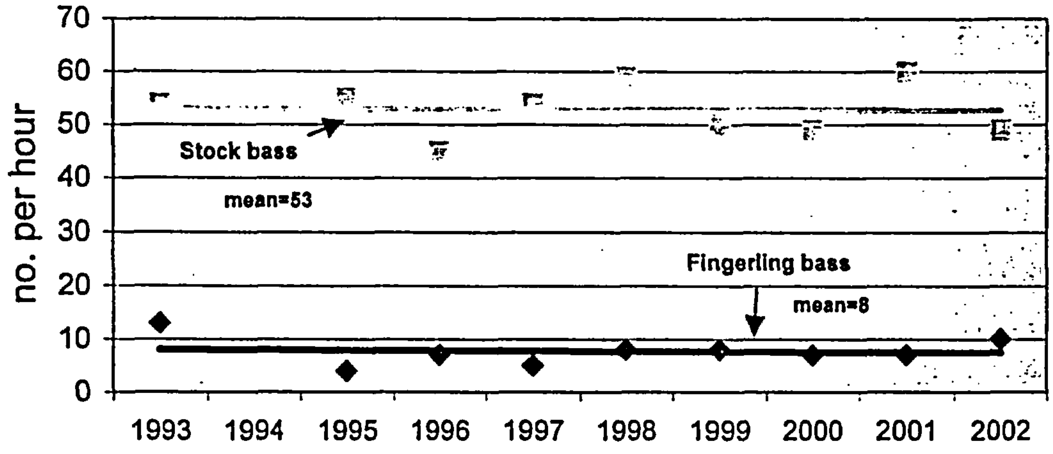


Figure 2 - LMB electrofishing CPUE for quality and preferred fish

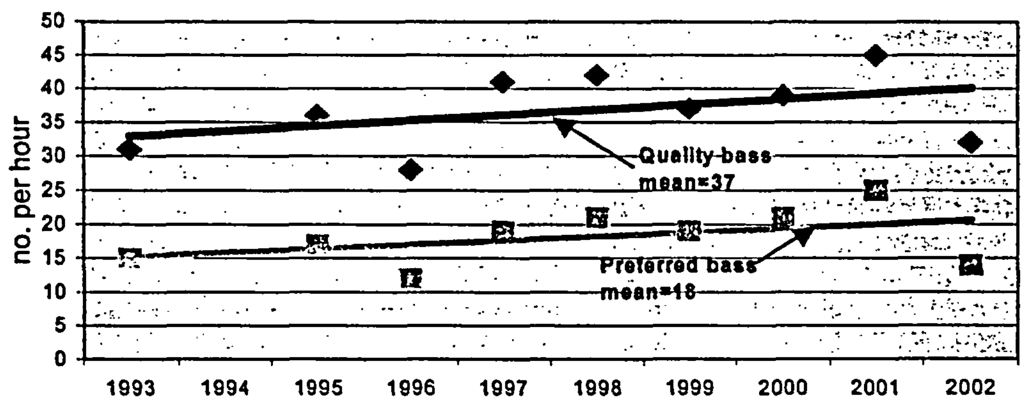


Figure 3. Largemouth bass growth at Lake Anna based on otoliths,mean total length at age.

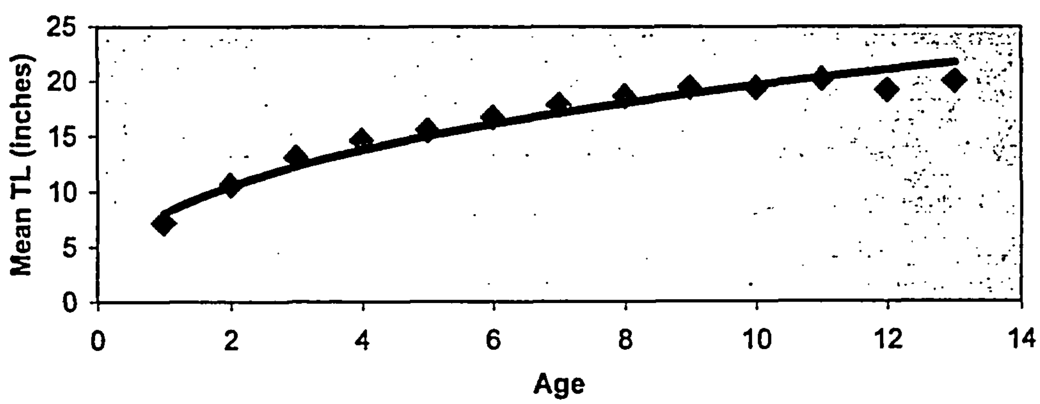


Figure 4. Striped bass growth at Lake Anna based on otoliths, mean total length at age.

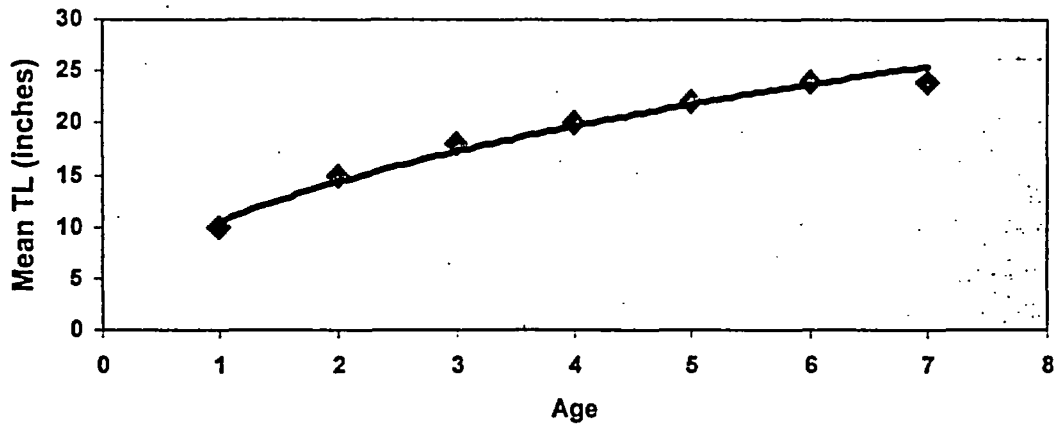


Figure 5. Walleye growth at Lake Anna based on otoliths, mean total lengh at age.

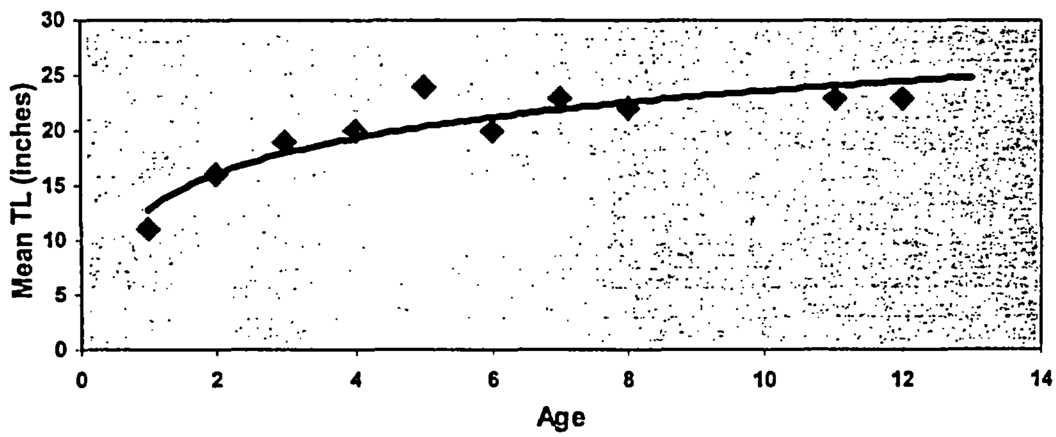
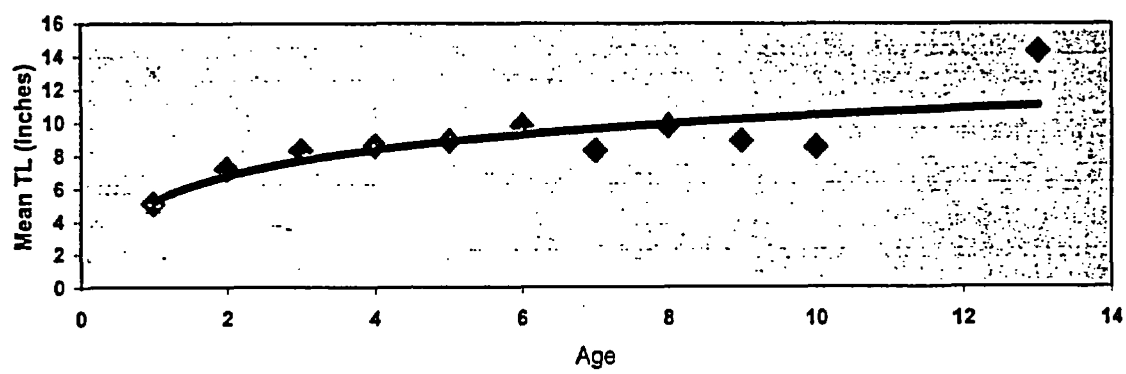


Figure 6. Black crappie growth at Lake Anna based on otoliths, mean total length at age.



Pages 122–136 *in* G. E. Hall and M. J. Van Den Avyle, editors.
Reservoir Fisheries Management: Strategies for the 80's.
Reservoir Committee, Southern Division American Fisheries Society, Bethesda, Maryland. 1986.

Spatial Heterogeneity in Fish Parameters within a Reservoir

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Abstract

Various components of the Lake Norman fish community exhibited spatial heterogeneity. Harvest of sport fish exhibited a longitudinal trend within the reservoir as did total phosphorus and chlorophyll *a* concentration. Harvest of largemouth bass (*Micropterus salmoides*), crappie (*Pomoxis* spp.), striped bass (*Morone saxatilis*), and white bass (*Morone chrysops*) was lowest at the most downlake area (3 kg/hectare), increased steadily to the uplake riverine area (51 kg/hectare), and highest at the discharge of a steam-electric station (316 kg/hectare). Fishing pressure varied similarly. Threadfin shad (*Dorosoma petenense*) standing stocks in October exhibited a longitudinal gradient that was similar to the gradient observed for phytoplankton standing crop.

Interreservoir predictive models did not account for the intrareservoir variability in fish parameters, most likely because the models failed to consider the heterogeneity of habitat and physicochemical variables within the reservoir. The existence of heterogeneity in fish parameters indicates that management decisions based on data collected from one or two stations within the reservoir could be erroneous and that managing the reservoir as a biological entity may be ineffective. An understanding of gradients within reservoirs would help managers collect representative samples with improved precision.

Spatial heterogeneity in fish standing stock, harvest, and mortality in Lake Norman indicates that the potential of the fishery is not realized because of species-specific habitat and physical constraints. Density-independent mortality appeared to regulate the biomass of striped bass and threadfin shad in the reservoir because of their relatively narrow thermal requirements. Removal of these constraints would allow the system to become regulated by density-dependent phenomena, thus improving the efficiency and stability of the system.

Variability in fishery parameters such as harvest and standing stock among reservoirs and natural lakes has received considerable attention during the past two decades (Rawson 1960; Ryder 1965; Jenkins 1967; Jenkins and Morais 1971; Oglesby 1977a; Jenkins 1982). These contributions have implied that a relationship exists between nutrient dynamics and fisheries (Ryder 1982) that is useful for understanding and predicting differences in fish yields among bodies of water. However, consideration has rarely been given to spatial variability in fishery parameters within a body of water. Intrareservoir heterogeneity in fish parameters might be expected based on nutrient gradients documented within reservoirs (Gloss et al. 1980; Paulson and Baker 1980; Kennedy et al. 1982; Thornton et al. 1982). Also, reservoirs are usually physically diverse, and spatial heterogeneity in fishery parameters is expected due to species-specific behavior and habitat preferences.

Research conducted from 1974 through 1982 on Lake Norman, North Carolina, has indicated spatial variations in fishery parameters including standing stock and angler harvest, success, and pressure as well as other biological, chemical, and physical variables. The objectives of this paper are to document the spatial heterogeneity in selected fishery parameters, assess relationships between these parameters and morphometric, physico-chemical, and biological variables, and discuss the management implications of these relationships.

Study Site

Lake Norman, located on the Catawba River in the Piedmont of North Carolina, was impounded in 1963 to provide water for hydroelectric power and cooling of steam-electric stations. It is a warm-monomictic reservoir with an oligo-mesotrophic status based on primary production and phytoplankton biomass (Rodriguez

Table 1. Morphometric, physical, and chemical characteristics of Lake Norman, North Carolina.

Characteristic	Description
Drainage area	771 km^2 (excludes drainage area of upstream reservoir)
Surface area	13,156 hectares (full pool)
Mean depth	10.2 m (full pool)
Maximum depth	36.6 m (full pool)
Outlet depth (midline depth)	5 m (full pool, controlled by height of skimmer weir)
Thermocline depth (1 Aug)	11 m (typical), 8 m (using definition in Jenkins [1967])
Elevation	231.6 meters mean sea level (full pool)
Mean annual fluctuation	2.6 m
Storage ratio	0.57
Shoreline development	21.5 (with islands)
Dissolved solids	30 mg/liter
Chemical type-inflow[a] (μ equivalents/liter)	HCO_3-240, Na-155, Ca-139, Mg-109, K-39
Sediment load[b]	<280 mg/liter
Growing season[a]	200 days

[a] Perkins and Whisenant (1982).
[b] Jenkins (1967).

1982a). Physical and chemical characteristics of the reservoir are summarized in Table 1.

Several power generation facilities (Fig. 1) influence hydrological, thermal, and biological components of the reservoir. Lookout Shoals Hydroelectric Station on the Catawba River discharges water from 11 to 17 m below full pool from Lookout Shoals Reservoir and provides the primary input of water into Lake Norman. Marshall Steam Station, a 1,900-megawatt coal-fired steam electric station, began operation in 1965. The intake design of Marshall is atypical of most steam stations in North Carolina, in that a skimmer wall built across the mouth of the intake cove permits only bottom water to enter the cooling system of the plant. Water temperatures in the Marshall Steam Station discharge can be as high as 11 C above ambient surface temperatures during winter. During summer, discharge temperatures are similar to ambient surface water temperatures, but the discharge has chemical characteristics of the hypolimnetic water of Lake Norman (Hogan and Adair 1982). McGuire Nuclear Station (2,360 megawatts) was under construction during most of the study period but began circulating unheated water in 1978 and heated water during periods of 1981 and 1982. Cowans Ford Hydroelectric Station (360 megawatts) is housed in the dam that forms Lake Norman and discharges epilimnetic water due to a submerged weir located in the dam forebay which retains water below 11 m (at full pool).

METHODS

Lake Norman was stratified into nine sampling zones (Fig. 1). Boundaries for Zones 1 and 4 were chosen according to areas affected or projected to be affected by discharges of McGuire and Marshall Stations, respectively. Zone 7 was the intake cove for Marshall Steam Station and was not sampled in this study because it was inaccessible by boat from the reservoir. Zones 8 and 9 were the discharge canals of Marshall and McGuire Stations, respectively. Zones 2, 3, and 5 were defined according to main drainage areas of the reservoir. Zone 6 included the tailrace of Lookout Shoals Dam and the riverine portion of the reservoir. Area, volume, mean depth, shoreline length, and drainage area were determined for each zone from preimpoundment topographic surveys (Table 2).

Fishing pressure (angler-hours per hectare) and distribution of sport fishermen were estimated by counting boat and bank/pier fishermen during randomly scheduled airplane or helicopter flights (greater than 60 per year, allocated seasonally) from December 1977 through November 1978 and December 1981 through November 1982. Fishing success (kilograms and number of fish per angler-hour) was estimated by interviewing fishermen by boat (192 days annually) during the above time periods. Harvest by species was estimated as the product of success and pressure and excluded night fishing. Fishing pressure, success, and catch composition was estimated seasonally for each survey zone.

Population and standing stock estimates of threadfin shad (*Dorosoma petenense*) were made in October 1979 through 1982, December 1979 and 1980, February 1980 and 1981, and April 1979 through 1982. All samples were taken at night with a midwater Tucker trawl (Siler 1983). Population estimates, based on approximately 90 samples per sampling period, were made using the direct enumeration methodology (Regier and Robson 1967), whereby randomly selected segments of the reservoir were sampled, and catch rates were expanded to determine the population size of all ages of threadfin shad in each of the sampling zones (Siler 1985). Additionally, densities of clupeid larvae were estimated weekly

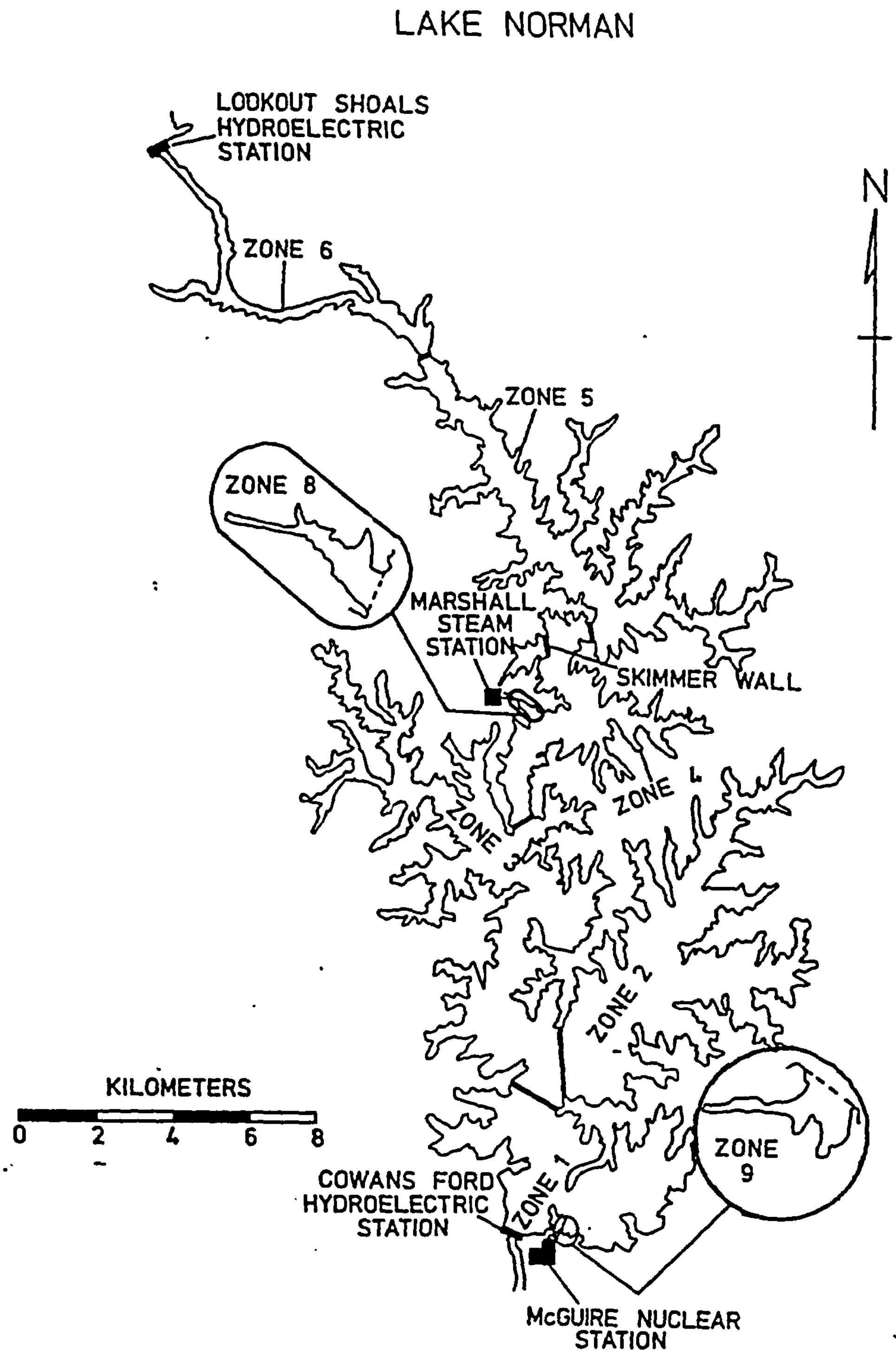

Figure 1. Lake Norman, North Carolina, with sampling zones and electric generating stations.

Table 2. Morphometric characteristics of sampling zones on Lake Norman, North Carolina.

Zone	Area (hectares)	Volume (m^3)	Mean depth (m)	Shoreline length (km)	Shoreline development	Cumulative drainage area (km^2)[a]	Immediate drainage area to volume ratio (m^2/m^3)[b]
1	2,261	2.58×10^8	11.4	86.6	5.1	765.8	0.09
2	3,300	3.33×10^8	10.1	133.4	6.1	742.7	0.21
3	3,555	4.02×10^8	11.3	243.6	11.5	674.1	0.37
4	1,216	1.42×10^8	11.7	124.5	10.1	524.1	0.14
5	2,125	1.93×10^8	8.7	197.4	12.1	503.9	1.08
6	341	8.18×10^6	2.4	51.5	7.9	304.3	37.18
8	24	2.26×10^6	9.4	3.8	2.1	—	—
9	22	2.22×10^6	10.1	3.5	2.2	—	—

[a] Excludes drainage area of an upstream reservoir.
[b] Immediate drainage excludes drainage area of upstream reservoir or zone.

during March through August 1975 from nine locations, representing five of the sampling zones.

Mark-recapture population estimates using single-census techniques (Ricker 1975) and abundance estimates at randomly selected segments of shoreline were conducted for largemouth bass (*Micropterus salmoides*) at Zones 1 through 5 during April 1982. Sampling was conducted at night with electrofishing gear. Population estimates were limited to largemouth bass longer than 200 mm. Standing stock estimates of largemouth bass and other species were obtained from cove rotenone sampling during August 1978 through 1981 at six 1.2-hectare locations in Zones 1, 3, 5, 8, and 9.

Total phosphorus, orthophosphate-phosphorus, specific conductance, and turbidity data were collected monthly in 1982 and 1983 at 19 fixed locations representing Zones 1 through 6. Additionally, 50 total phosphorus and turbidity samples were randomly collected reservoir-wide during November 1982. All samples were replicated and taken at the surface. Analytical methods were those approved by U.S. Environmental Protection Agency (1974). Chlorophyll *a* concentrations were determined (Strickland and Parsons 1972) biweekly during 1979 at nine sampling locations representing Zones 1 through 6. Water was collected at depths of 0, 2.5, and 5 m and mixed to provide one composite sample representative of the epilimnion. Samples were taken monthly in 1982 at 10 locations representing Zones 1 through 5. Water samples were collected at the surface, the bottom of the euphotic zone, and at one-half the depth of the euphotic zone. Replicate chlorophyll determinations were made for a composite of these samples. Surface chlorophyll *a* concentrations were determined at 90 randomly selected locations throughout the reservoir in parallel with the April and October 1982 threadfin shad population samples. Fishery, total phosphorus, and chlorophyll *a* data were compared among zones using analysis of variance.

Results

Fishing Pressure

Fishing pressure exhibited considerable spatial heterogeneity in Lake Norman (Table 3). Relatively large increases occurred longitudinally from downlake (Zones 1 and 2) to uplake (Zones 5 and 6). This pattern was similar for boat and bank fishing pressure and varied little among seasons and years. The major exception to this trend was the high fishing pressure at the discharge canals from steam-electric stations (Zones 8 and 9), especially during winter and spring.

Sport Fish Harvest and Abundance

Harvest of largemouth bass (Table 3) gradually increased in the uplake direction, with the exception of the small discharge zones (8 and 9). The discharge zones had high catches per unit area but accounted for only a small portion of the total reservoir harvest because of their small area. Densities determined from population estimates of largemouth bass and catch rates from randomly chosen electrofishing samples (Table 4) showed the same spatial characteristics as harvest data. Electrofishing catch rates were significantly ($P < 0.0001$) higher in Zone 5 than other zones. Zones 3 and 4 were statistically similar, and Zone 4 had a higher catch rate than Zones 2 and 1. Cove rotenone data from August were variable and indicated no differences among zones except at Marshall discharge (Zone 8), where

Table 3. Creel survey estimates (95% confidence limits in parentheses) by sampling zones, Lake Norman, North Carolina, 1982.

Zone	Annual fishing pressure (angler-hours/hectare)	Fishing success: Number/angler-hour	Fishing success: kg/angler-hour	Annual harvest (kg/hectare): Largemouth bass	Crappies	Striped bass	White bass	Ictalurids	All species
1	21.9 (±4.9)	0.47 (±0.87)	0.13 (±0.18)	1.26 (±0.52)	1.39 (±0.77)	0.12 (±0.15)	0	0.05 (±0.05)	2.93 (±1.02)
2	23.0 (±3.4)	0.76 (±1.24)	0.19 (±0.18)	1.22 (±0.63)	2.10 (±0.95)	0.69 (±0.45)	0	0.13 (±0.18)	4.46 (±1.33)
3	42.8 (±5.4)	0.88 (±0.99)	0.19 (±0.18)	2.06 (±0.89)	5.08 (±1.64)	0.19 (±0.12)	0.18 (±0.24)	0.19 (±0.21)	7.97 (±2.09)
4	69.6 (±11.3)	0.70 (±0.82)	0.13 (±0.11)	2.87 (±1.05)	4.26 (±1.99)	0.98 (±0.84)	0.34 (±0.45)	0.18 (±0.14)	9.16 (±2.87)
5	114.4 (±12.5)	1.29 (±0.85)	0.25 (±0.18)	3.09 (±1.11)	19.48 (±5.75)	1.08 (±1.69)	0.47 (±0.73)	1.85 (±1.18)	28.30 (±5.87)
6	275.1 (±30.5)	0.53 (±0.57)	0.21 (±0.65)	5.77 (±2.71)	7.48 (±3.41)	19.66 (±8.94)	17.48 (±9.97)	3.35 (±2.31)	57.97 (±14.32)
8	3,392.5 (±52.2)	0.38 (±0.30)	0.24 (±0.22)	24.17 (±18.6)	14.83 (±22.8)	192.49 (±115.9)	84.71 (±50.7)	56.8 (±33.1)	829.04 (±388.82)
9	846.1 (±29.8)	0.37 (±0.50)	0.21 (±0.24)	19.24 (±19.1)	3.84 (±5.06)	126.90 (±102.0)	7.51 (±10.9)	12.7 (±12.3)	179.34 (±103.27)

standing stocks averaged 16 kg/hectare and were almost three times the stocks in other zones (Table 5).

Average electrofishing catch rate per distance of shoreline correlated well with the annual harvest rate for each zone ($r = 0.91$, $P < 0.05$, N = 5) and spring harvest rates ($r = 0.90$, $P < 0.05$, N = 5) in 1982. Density estimates (number/hectare) in each zone (Table 4) also were correlated with harvest estimates in spring ($r = 0.97$, $P < 0.01$, N = 5) and with annual rates ($r = 0.94$, $P < 0.01$, N = 5).

Crappie (*Pomoxis* spp.) harvest varied considerably among zones, and was highest in Zone 5 in 1979 and 1982 (Table 3). Crappie harvest from downlake Zones 1 and 2 was less than 50% of the harvest in other zones. Standing stock estimates of crappie from cove rotenone samples were highest in Zone 8 (14 kg/hectare), followed by Zones 3 and 5 which averaged 6 kg/hectare (Table 5). Crappie standing stocks averaged less than 1 kg/hectare in Zone 1.

White bass (*Morone chrysops*) and striped bass (*M. saxatilis*) harvests (kg/hectare) were higher at the riverine and discharge areas than at the large downlake zones (1 through 5) (Table 3). Both species make spawning migrations to the inflows at Zones 6, 8, and 9. These areas comprised only 3% of the total area of the reservoir but accounted for 64% and 76% of the total 1982 harvest of striped bass and white bass, respectively.

Annual harvest of ictalurids was greatest in the discharge areas followed by Zones 6 and 5 (Table 3). Mean standing stocks of ictalurids were greatest in Zones 5 (15 kg/hectare) and 8 (12 kg/hectare) and ranged from 4 to 6 kg/hectare in Zones 1, 3, and 9 (Table 5). Channel catfish (*Ictalurus punctatus*), flathead catfish (*Pylodictis olivaris*), and white catfish (*I. catus*) comprised the major portion of the uplake ictalurid stock. Bullheads (*Ictalurus* spp.) were absent from the most uplake cove, but along with the white catfish dominated the downlake ictalurid stock. Flathead catfish were absent and channel catfish were uncommon downlake.

Prey Species Abundance

Threadfin shad, sunfish (*Lepomis* spp.), and yellow perch (*Perca flavescens*) are the major prey fishes in Lake Norman (Siler et al. 1982). Sunfish and yellow perch were insignificant in the sportfish harvest because of their small average size.

Table 4. Electrofishi
in parentheses) for l

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3	
4	
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Gizzard shad (*Dor*
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Zones 1 and 2 (Fig. 2).
1981, threadfin shad we
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were collected at any
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in April were similar to
the shad were more disp
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The population size
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of spawners in the prev
a low population size o
produced a high popu

Table 4. Electrofishing catch rates, densities, and population estimates (95% confidence intervals in parentheses) for largemouth bass in Lake Norman, North Carolina, April 1982.

Zone	Electrofishing catch rate (number/100 m)	Population estimates	
		Number/hectare	Number in zone
1	2.2 (±0.71)	4.0 (2.0–8.6)	8,253 (4,097–18,053)
2	2.9 (±0.96)	7.7 (3.6–17.7)	23,082 (10,905–53,265)
3	4.5 (±1.65)	11.1 (5.5–24.2)	36,073 (17,909–78,910)
4	6.6 (±2.01)	13.8 (7.6–27.5)	15,826 (8,743–31,651)
5	11.3 (±2.27)	14.9 (8.4–28.7)	28,982 (16,433–55,930)

Sunfish standing stocks averaged 25 kg/hectare in Zone 5 as compared to 10 to 17 kg/hectare in Zones 1, 3, 8, and 9 (Table 5). Yellow perch standing stocks were highest in Zones 9 (17 kg/hectare) and 8 (8 kg/hectare) and ranged from 3 to 5 kg/hectare in Zones 1, 3, and 5.

Gizzard shad (*Dorosoma cepedianum*) were usually too large to be consumed by sportfish based on predator-prey equations of Jenkins and Morais (1978). Standing stocks in Zones 8 and 9 averaged 77 and 87 kg/hectare, respectively; mean stocks in Zones 1, 3, and 5 ranged from 30 to 33 kg/hectare (Table 5). Juvenile gizzard shad were not abundant in samples from Lake Norman but were always more numerous in uplake areas (Table 6).

Threadfin shad distribution in Lake Norman was heterogeneous. Larval clupeid (primarily threadfin shad) abundance was considerably higher uplake except for Zone 6 (Table 6). During October 1979, 1980, and 1981, threadfin shad standing stocks were highest in Zone 5, but not in October 1982. During December 1979 and 1980 standing stocks were lower in Zones 1 and 2 than in Zones 3 and 4, and Zone 5 had the highest standing stock (Table 6), but differences were statistically significant ($P < 0.01$) only between uplake Zones 3, 4, and 5 and downlake Zones 1 and 2 (Fig. 2). In February of 1980 and 1981, threadfin shad were most abundant in areas warmed by the thermal plume of Marshall Station (Zones 4 and 8) (Fig. 3); few threadfin shad were collected at any location with water temperatures below 7 C. Spatial distribution patterns in April were similar to those in February except the shad were more dispersed around the thermal plume.

The population size of threadfin shad in October appeared to be independent of the number of spawners in the previous April; for example, a low population size of spawners in April 1981 produced a high population size of recruits in October 1981 (Table 6). Numbers of new recruits in October per adult from the preceding April ranged from 10 to 181 recruits/spawner from 1979 through 1982. Additionally, an index of the number of clupeid larvae produced in Zone 1 did not coincide with the estimated population size of spawners in Zone 1 or the entire reservoir for 1979, 1980, and 1981.

Limnological Characteristics

Lake Norman's annual surface temperatures range from 1.6 to 33 C (excluding power plant discharge zones) with minimum temperatures of 1.6 to 8 C occurring in February and maximum temperatures of 29 to 33 C typically occurring in July and August. Thermal stratification generally begins in mid-April with a weak thermocline being established at 10 to 12 m. Usually, this thermal barrier is difficult to detect, and dissolved oxygen data more clearly define the limits of the epilimnion and hypolimnion in Lake Norman. Dissolved oxygen generally disappears below 11 m by August. Cooling and convective mixing begins in early fall (September–October) with overturn usually complete by mid-November. Discharge zones are generally 8 C warmer than the open reservoir during February and 2 C warmer in August.

Total phosphorus concentrations in Lake Norman range from undetectable (<5 mg/m³) to 150 mg/m³. The highest concentrations, those exceeding 30 mg/m³, are found during the winter-spring runoff period, and the lowest concentrations are observed during the summer. Longitudinal gradients of total phosphorus are most pronounced during the spring runoff period. Spatial distribution of total phosphorus in the reservoir is closely associated with turbidity ($r = 0.90$, $P < 0.0001$, $N = 59$). In general, total phosphorus concentrations are two times higher in uplake than downlake regions (Table 7). Total phosphorus data from summer 1982 and spring

Table 5. Mean standing crop estimates (95% confidence intervals in parentheses) for selected species determined from cove rotenone sampling in Lake Norman, North Carolina, 1978-1981.

Zone	Mean standing crop (kg/hectare)							
	Gizzard shad	Common carp	Ictalurids	Largemouth bass	Crappie	Sunfish	Yellow perch	All species
1	33.6 (±9.0)	38.8 (±13.4)	5.5 (±2.6)	5.1 (±2.1)	<0.1 (±<0.1)	15.9 (±3.4)	3.2 (±2.0)	107.4 (±25.6)
2	33.7 (±11.3)	27.1 (±11.1)	5.8 (±3.8)	5.7 (±1.1)	6.0 (±5.8)	15.1 (±4.1)	4.6 (±2.6)	137.7 (±60.7)
3	30.2 (±15.4)	48.2 (±17.5)	15.2 (±6.7)	6.3 (±1.9)	6.4 (±5.6)	25.1 (±12.9)	4.2 (±0.8)	174.5 (±77.9)
4	76.8 (±23.8)	41.2 (±15.9)	12.0 (±6.0)	16.0 (±5.3)	13.7 (±7.7)	16.8 (±8.4)	8.3 (±4.2)	190.1 (±44.0)
5	87.4 (±43.8)	17.9 (±8.5)	4.0 (±2.9)	2.5 (±0.4)	1.4 (±1.0)	10.6 (±5.1)	17.0 (±14.3)	157.0 (±23.7)

1983 were more variable in uplake than downlake areas due to variable inputs from rainfall and runoff. Samples collected in November 1982 illustrate the total phosphorus gradient during a period of low runoff. Zone 6 had significantly ($P < 0.0001$) higher total phosphorus concentrations than other areas; Zones 4 and 5 were similar but had significantly higher phosphorus concentrations than Zones 1, 2, and 3.

Longitudinal gradients in chlorophyll *a* concentrations were also observed. Uplake regions typically had 50 to 100% higher concentrations than the downlake areas except in October 1982, when conditions were more uniform (Table 7). Concentrations were usually lower in Zone 6 than other zones. Reservoir-wide random samples collected in April and October 1982 revealed significant spatial variability during both months (Table 7). In April 1982, phytoplankton was more abundant in uplake areas. Chlorophyll *a* concentrations were highest in Zone 5, intermediate in Zones 3, 4, and 6, and lowest in Zones 1, 2, 8, and 9. Significant differences ($P < 0.001$) observed among zones in October 1982 did not reveal any gradient along the reservoir; however, these data were atypical because of an extensive *Microcystis aeruginosa* bloom in the uplake areas.

INTERRELATIONSHIPS

Components of the Lake Norman fish community exhibited spatial heterogeneity. Possible explanations for the heterogeneity include trophic interactions, and species-specific habitat, behavioral, or physical preferences.

Distribution of fishing pressure in the reservoir might account for the spatial heterogeneity in sport fish harvest. Harvest was highly correlated with angler effort among zones in 1978 ($r = 0.97$, $P < 0.01$, N = 6) and 1982 ($r = 0.999$, $P < 0.0001$, N = 8). However, based on "fished for" success data (kg/hour) for largemouth bass, which increased slightly uplake, high correlations between fishing pressure and largemouth bass abundance estimates from electrofishing surveys and population estimates, and observations of fisherman distribution relative to striped bass concentrations, the spatial distribution of fishing pressure in Lake Norman seems to be a function of sportfish distribution patterns. Therefore, fishermen maximize their success by distributing their effort proportional to the abundance of sportfish. Campbell et al. (1978) reported a relatively stable catch rate and a high correlation

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between angler effort and harvest among a sample of 24 reservoirs; they suggested that anglers shifted their effort to other waters when a certain minimum success rate occurred. We assume that the spatial and temporal heterogeneity in harvest reflects actual heterogeneity in sportfish abundance in Lake Norman.

Various indices of productivity based on physical, chemical, and biological variables have been successful for predicting heterogeneity in fish harvest and standing stocks among reservoirs and lakes (Rawson 1960; Ryder 1965; Jenkins 1967; Oglesby 1977a; Jenkins 1982). The morphoedaphic index (MEI = total dissolved solids [TDS] divided by mean depth) is the most notable of these and has been widely applied. The basic concept of the MEI is that nutrients transported by energy influence fish production (Ryder 1982). Jenkins' (1982) MEI for reservoirs accurately predicted the Lake Norman harvest, but it failed to accurately reflect variation within the reservoir (Fig. 4). Possible explanations for this disparity are that intrareservoir habitat differences account for the variability of harvest, that TDS varies little within the reservoir and is not a correlate of the limiting nutrient, or that the index was intended to predict variation on a much broader scale of the MEI. As Oglesby (1977b) reported, numerous exceptions occur where TDS is unrelated to the availability of a limiting nutrient. Ryder (1982) suggested that in cases where phosphorus is the limiting ion TDS should be replaced with phosphorus.

A longitudinal gradient in chlorophyll *a* occurs in Lake Norman and is related to a total phosphorus gradient except in the riverine area. Phytoplankton standing crops are usually low in riverine systems because of continual washout (Oglesby 1977b) and high turbidity that limits light penetration (Kennedy et al. 1982). Rodriguez (1982b) reported that the phytoplankton community of Lake Norman was limited by phosphorus availability during the summer-stratified period.

The majority of the phosphorus in Lake Norman appears to be physically and/or chemically associated with clays, and total phosphorus was closely correlated with turbidity both temporally and vertically in the water column (Rodriguez 1982b). We observed that the relationship also occurs spatially within the reservoir. Internal phosphorus loading via hypolimnetic release in Lake Norman is probably not important relative to external loading; orthophosphate-phosphorus is usually undetectable in the bottom waters (Rodriguez 1982b). These characteristics are common in reservoirs (Serruya et al. 1974; Hannan and Broz 1976; Jones and Bachmann 1978; Canfield and Bachmann 1981) and emphasize the importance of external nutrient sources and the resuspension of sediments in the shallow areas to the productivity of the reservoir. Downlake areas of Lake Norman are somewhat less productive than uplake areas because of biological, physical, and chemical removal of nutrients in the uplake waters.

The importance of the phosphorus and chlorophyll *a* gradients to Lake Norman fish poulations was most apparent for threadfin shad. Threadfin shad abundance in October and December was generally correlated with the phytoplankton standing crop gradient, except in October 1982. Threadfin shad standing stocks in October and December 1979 correlated with chlorophyll *a* concentrations ($r = 0.95$, $P < 0.01$, $N = 6$; and $r = 0.93$, $P < 0.01$, $N = 6$, respectively). Threadfin shad larvae in Lake Norman feed on zooplankton, but juveniles and adults feed primarily on phytoplankton (W. T. Horton, Duke Power Company, Huntersville, North Carolina, USA [personal communication]), suggesting a direct association between threadfin shad abundance and algal standing crop. Furthermore, an uncharacteristic bloom of *Microcystis aeruginosa*—sometimes toxic to fish—in uplake areas in October 1982, coinciding with a similarily uncharacteristic decline in threadfin shad abundance, suggests an association between threadfin shad abundance and algal species composition.

Trophic interactions associated with the nutrient gradient also appeared related to the abundance and distribution of other fish species in Lake Norman, but the relative importance of these interactions was difficult to separate from species-specific behavior and habitat preferences. Because of the chemical and morphometric nature of dendritic reservoirs with long retention times like Lake Norman, mean depth, shoreline development, and size of the immediate drainage area can be correlates for habitat preferences for littoral species and total phosphorus. Total harvest, largemouth bass harvest and abundance, crappie harvest, and ictalurid standing stock and harvest correlated significantly with total phosphorus concentration,

Table 6. Abundance estimates from trawling for clupeids by sampling zones, Lake Norman, North Carolina, 1979-1982.

Zone	Average clupeid larval densities (number/ 1,000 m³)	Total threadfin shad standing stock (kg/hectare) October 1979	1980	1981	1982	December 1979	1981
1	811	13.0	19.5	20.4	10.0	11.3	9.1
2	–	9.2	22.5	22.7	11.8	16.1	11.7
3	847	12.5	22.8	18.5	14.7	20.6	18.7
4	2,813	25.2	21.8	22.1	7.4	21.6	16.0
5	2,229	33.2	51.9	36.3	13.9	36.4	34.7
6	25	1.5	0.6	0.7	0.1	<0.1	0.1
8	–	2.9	14.8	15.3	0.3	13.4	0.6
9	–	0.1	0.7	23.2	2.6	12.6	0.7
Mean standing stock (area weighted)		16.5	26.3	23.3	12.0	21.2	17.6
95% Confidence interval		(±3.5)	(±5.8)	(±4.9)	(±3.2)	(±5.5)	(±3.1)
Total population size (millions)		304.4	589.6	560.9	246.6	187.2	194.8
95% Confidence interval		(±57.3)	(±165.6)	(±111.2)	(±68.5)	(±41.5)	(±50.6)

chlorophyll *a* concentration, and the physical features listed above. These correlations may represent associations between sport fish and preferred spawning habitat, as interactions were particularly pronounced during spawning periods of these species; they may also represent interactions between sport fish and available habitat for these littoral species because the uplake areas were shallower and more dendritic, and spatial distribution patterns for these species remained similar for spring, summer, and fall. The correlations also may reflect interactions between sport fish and abundant prey, which are related to the nutrient gradient.

Spatial heterogeneity of some species was influenced by water temperature. Water temperature controlled the distribution of threadfin shad during winter. High density-independent overwinter mortality and changes in distribution of threadfin shad emphasize the importance of the thermal plume from Marshall Station in sustaining this population in Lake Norman. Standing crop estimates in February 1980 and 1981 correlated with water temperature at the sample sites (respectively, $r = 0.44$, $P = 0.001$, N = 88; and $r = 0.55$, $P = 0.001$, N = 88). Similarly, the thermal characteristics of Marshall discharge in winter directly or indirectly attracted largemouth bass, crappie, white bass and striped bass, concentrating these species where they are more available to fishermen. Distribution of sportfish in winter was associated with the abundance of prey, but a direct attraction to the warm water could also be important.

Striped bass were distributed according to preferred or required water temperatures during summer and fall. Creel data indicated a downlake migration of striped bass coincident with the development of anoxic conditions in the hypolimnion which progressed downlake. When the hypolimnion of downlake areas became anoxic, striped bass apparently stopped feeding as they could no longer be caught by fishermen. Mortalities were observed in August 1983 and emaciated striped bass were observed during all previous years. Vertical distribution studies conducted in Zone 1 of Lake Norman indicate a change in distribution of striped bass from the surface waters of littoral and limnetic areas in May to the cooler limnetic waters of the metalimnion and hypolimnion in June through September (R. E. Lewis, in press). In late summer and early fall, striped bass at downlake areas were collected at some of the coolest water available and at dissolved oxygen concentrations below 1 mg/liter. Similar distributional shifts have been documented for striped bass in other waters (Waddle et al. 1980; Coutant and Carroll 1980; Schaich and Coutant 1980; Combs and Peltz 1982).

Table 6. Extended.

To February 1980	1981
6.7	0.1
2.1	0.1
8.7	3.3
70.2	24.6
4.5	0.9
0.0	0.0
68.4	3.9
0.0	0.0
12.4	3.6
(±6.1)	(±2.2)
83.1	17.5
(±48.7)	(±9.3)

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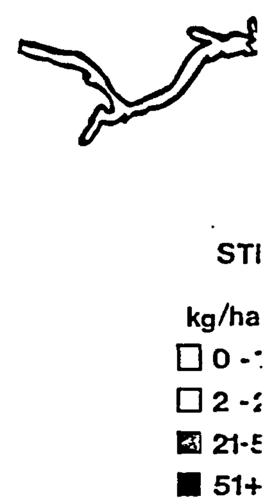

Figure 2. Distribution North Carolina.

Table 6. Extended.

Total threadfin shad standing stock (kg/hectare)						Juvenile gizzard shad standing stock (kg/hectare)	
February		April				October	
1980	1981	1979	1980	1981	1982	1979	1980
6.7	0.1	<0.1	0.4	<0.1	<0.1	0.0	0.0
2.1	0.1	0.1	0.3	0.1	0.3	0.0	0.1
8.7	3.3	10.1	4.3	0.2	0.5	0.0	0.0
70.2	24.6	10.8	12.5	2.3	3.2	0.3	0.1
4.5	0.9	26.0	7.1	3.1	3.1	0.7	0.6
0.0	0.0	0.7	2.4	0.0	0.1	0.4	0.0
68.4	3.9	4.5	65.0	35.8	8.8	0.0	0.0
0.0	0.0	0.0	0.0	0.9	<0.1	0.0	0.0
12.4 (±6.1)	3.6 (±2.2)	8.2 (±2.5)	4.0 (±1.5)	0.9 (±0.5)	1.0 (±0.5)		
83.1 (±48.7)	17.5 (±9.3)	31.6 (±10.3)	15.5 (±5.7)	3.1 (±1.8)	2.8 (±1.4)		

The shift in distribution patterns of striped bass in Lake Norman occurred primarily with larger individuals. Food habits of large striped bass (>40 cm) during the stratified period suggest that they were somewhat isolated by habitat requirements from threadfin shad, whereas smaller striped bass occupied the waters of the epilimnion and fed on threadfin shad (R. E. Lewis, in

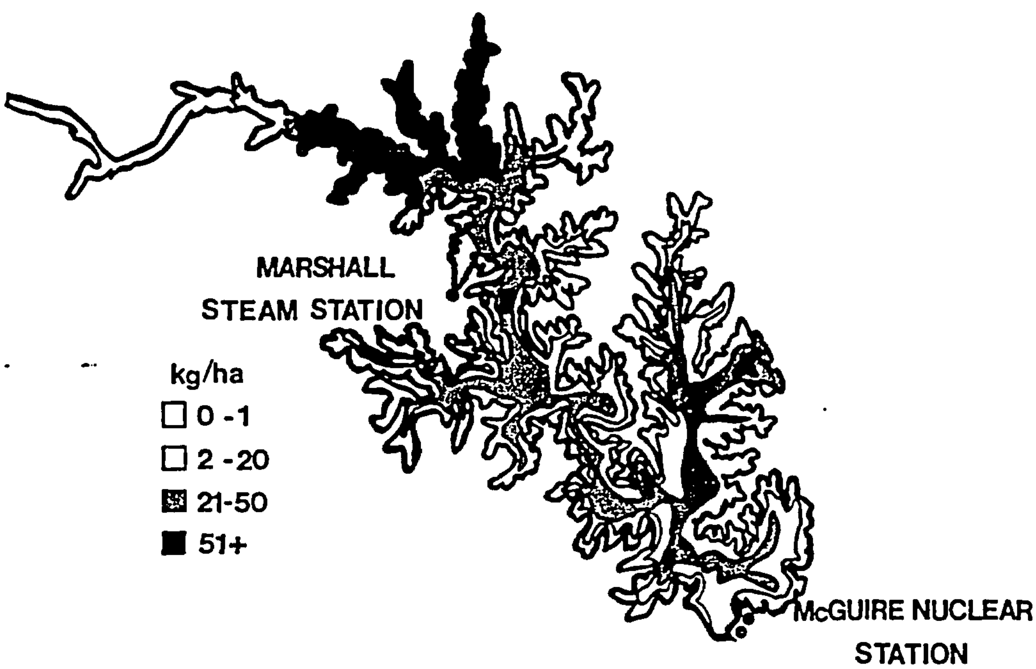

Figure 2. Distribution characteristics of threadfin shad during October 1980, in Lake Norman, North Carolina.

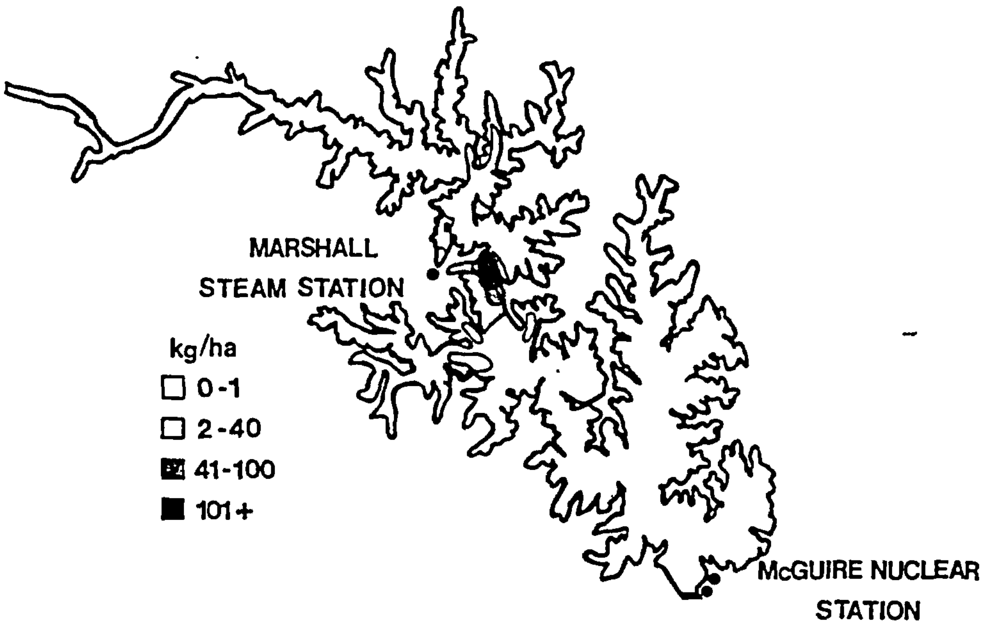

Figure 3. Distributional characteristics of threadfin shad in February 1981, in Lake Norman, North Carolina.

press). Schaich and Coutant (1980) reported that larger striped bass seemed to prefer cooler temperatures than smaller ones in Cherokee Reservoir, Tennessee. Following turnover in Lake Norman, striped bass dispersed from the metalimnion-hypolimnion and again utilized threadfin shad.

Spatial heterogeneity of some species was related to spawning requirements. For example, harvest of striped bass and white bass occurred principally in spring, when they migrated to the riverine area and the discharges of Marshall and McGuire Stations to spawn. These inflows attract white bass and striped bass, making them more accessible to boat or bank fishermen. Also, the differences between uplake and downlake species composition of ictalurids at times is likely related to spawning requirements of individual species. Although spawning requirements for some ictalurids are not well documented, others are known to have strict requirements. For example, channel catfish, a rheophilic species (Trautman 1957), requires turbid water characteristic of riverine systems to reproduce successfully (Pflieger 1975). Channel catfish were mostly restricted to upper Lake Norman, which is more dendritic, more turbid, shallower, and closer to inflows of major tributaries than lower Lake Norman.

No growth responses associated with the nutrient/productivity gradient have been observed. Growth of largemouth bass, bluegill (*Lepomis macrochirus*), and yellow perch varied little spatially, except in the discharge of Marshall where growth rates were higher (Siler et al. 1982). Increased growth in the discharge was an apparent manifestation of prolonged growing season. The observed nutrient gradients in the reservoir apparently enhanced survival of these species and had no noticeable long term effect of growth. Moore (1941) hypothesized that population size and not growth is enhanced by abundant food, and Nakashima and Leggett (1975) observed this response for yellow perch. McConnell (1965) suggested that increased growth is the principal mechanism by which fish biomass initially adjusts to higher productivity, but increased survival becomes more important with time.

Management Implications

Nutrient and productivity gradients have been documented in other reservoirs (Gloss et al. 1980; Paulson and Baker 1980; Thornton et al. 1980;

Table 7. Total phosphorus and chlorophyll *a* concentrations (95% confidence intervals in parentheses) for sampling zones on Lake Norman, North Carolina. Spring represents March, April, and May, and summer represents June, July, and August.

	Total phosphorus (mg/m³)			Chlorophyll *a* (mg/m³)					
Zone	Summer 1982	Spring 1981	November 1982	Summer 1979	Summer 1982	April 1982	October 1979	October 1982	December 1979
1	13(±1.9)	18(±3.6)	9.1(±0.5)	4.1(±1.7)	[illegible]	1.7(±0.2)	3.7	4.6(±0.5)	5.1
2	15(±1.6)	17(±1.4)	9.8(±1.0)	4.0(±1.4)	6.2(±2.5)	1.6(±0.2)	4.3	6.3(±0.5)	4.8
3	15(±1.7)	23(±8.9)	10.6(±1.4)	[illegible]	[illegible]	2.6(±0.1)	5.9	5.2(±0.6)	4.8
4	19(±1.2)	15(±9.4)	13.0(±1.1)	[illegible]	[illegible]	[illegible]	7.4	4.7(±0.6)	6.0
5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

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Table 7. *Total phosphorus and chlorophyll a concentrations (95% confidence intervals in parentheses) for sampling zones on Lake Norman, North Carolina. Spring represents March, April, and May, and summer represents June, July, and August.*

Zone	Total phosphorus (mg/m^3) Summer 1982	Spring 1983	November 1982	Chlorophyll *a* (mg/m^3) Summer 1979	Summer 1982	April 1982	October 1979	October 1982	December 1979
1	13 (±1.9)	18 (±3.6)	9.1 (±0.5)	4.3 (±1.7)	4.7 (±1.3)	1.7 (±0.2)	3.7	4.6 (±0.5)	5.1
2	15 (±1.6)	17 (±3.4)	9.8 (±1.0)	4.0 (±1.4)	6.2 (±2.5)	1.6 (±0.2)	4.3	6.3 (±0.5)	4.8
3	15 (±1.7)	27 (±8.9)	10.6 (±1.4)	5.0 (±1.0)	10.0 (±7.7)	2.6 (±0.3)	5.9	5.2 (±0.6)	4.8
4	19 (±1.2)	35 (±9.4)	13.0 (±1.1)	5.6 (±0.6)	13.0 (±6.0)	3.0 (±0.4)	7.4	4.7 (±0.6)	6.0
5	21 (±3.9)	34 (±6.6)	14.2 (±1.3)	7.2 (±1.3)	11.2 (±8.3)	4.8 (±0.6)	10.7	6.4 (±0.9)	6.9
6	59 (±38.2)	36 (±17.3)	20.3 (±5.6)	7.0 (±2.4)	—	3.7 (±0.5)	3.2	1.4 (±0.6)	3.5
8	65 (±83.7)	34 (±14.1)	21.0	1.7 (±0.7)	—	2.0 (±0.9)	4.0	—	5.9
9	12 (±2.0)	18 (±7.0)	9.0	—	—	1.7 (±0.2)	—	—	—

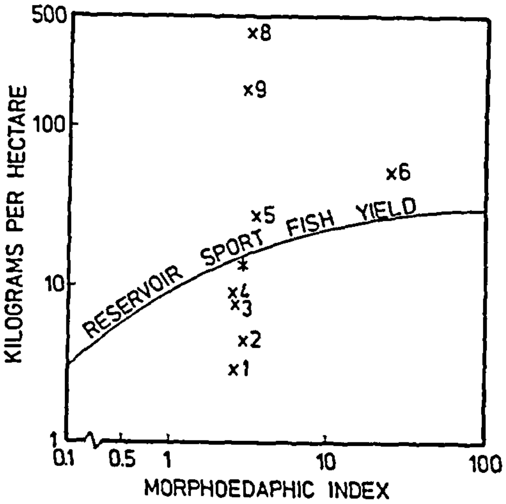

Figure 4. Sport fish harvest as a function of the morphoedaphic index (from Jenkins 1982) with respective observed values for sampling Zones 8, 9, and 1 through 6 and for reservoir-wide average harvest (*) from Lake Norman, North Carolina.

Kennedy et al. 1982; Thornton et al. 1982), as well as within natural lakes which receive substantial inflows or point source pollution (Gascon and Leggett 1977). Nutrient gradients have been linked with fish distribution patterns (Nakashima and Leggett 1975; Gascon and Leggett 1977; Rinne et al. 1981). Van Den Avyle et al. (1982) observed spatial heterogeneity in plankton and larval fish abundance in Center Hill Reservoir, Tennessee, but observed no consistent uplake-downlake gradient. These observations have strong implications to the design of limnological (Thornton et al. 1982) and fisheries sampling programs. Management decisions based on data collected from one or two stations within such bodies of water are quite apt to be erroneous. Simiarly, the approach of managing a reservoir as a biological entity may be ineffective considering the apparent heterogeneity of reservoirs; therefore, management strategies and research demonstrations might be more practical if they were designed to account for various gradients among areas within reservoirs.

The application of the concepts implied by the nutrient gradients and interreservoir models is rarely suggested. However, Prentki et al. (1981) suggested that a proposed waste water treatment facility on Lake Mead would reduce nutrient inputs into the reservoir, thereby reducing the fishery. They further stated that pumped storage facilities could be designed to enhance the productivity of reservoirs by redistributing nutrients. Fisheries managers should become active in environmental regulation, not only to prevent degradation, but to enhance fisheries where applicable. Sources for addition or redistribution of nutrients offer the potential to enhance the fisheries of particular reservoirs.

Implications of fish distribution relative to habitat requirements were also apparent. Habitat requirements were less important for the indigenous species, such as largemouth bass and crappie, than for introduced species such as striped bass and threadfin shad that have relatively narrow thermal requirements. Threadfin shad and striped bass may be regulated to some extent by density-independent factors (i.e., water temperature). These two species, despite their favorable characteristics, have some undesirable attributes; previous years' production or a major part of the adult population can be eliminated with normal annual climatic cycles. Threadfin shad biomass dropped drastically due to over-winter mortality and was lowest during optimum growing conditions of many predators; conversely, large striped bass died from high ambient summer water temperatures. The potential of striped bass may not be realized because of limited summer habitat; however, they can continue to provide a significant fishery through restocking. Increased thermal loading might add stability to threadfin shad populations in cooler reservoirs but could adversely impact striped bass populations. The yield of fisheries in Lake Norman and other reservoirs might be increased if the influences of density-independent factors, such as temperature, on survival could be reduced. This could enhance utilization of available nutrients and improve the yield of the entire system. Hybridization and selective breeding of fishes having different habitat requirements offer further solutions to this problem.

Acknowledgments

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References

Campbell, W. J., E. Hayes, W. R. Chapman, and W. Seawell. 1978. Angling pressure and sport fish harvest in the predator-stocking-evaluation reservoirs. Proceedings of the Annual Conference of the Southeastern Association of Game and Fish Commissioners 30:114–119.

Canfield, D. E., Jr., and R. W. Bachmann. 1981. Prediction of total phosphorus concentrations, chlorophyll *a*, and Secchi depths in natural and artificial lakes. Canadian Journal of Fisheries and Aquatic Sciences 38:414–423.

Coutant, C. C., and D. S. Carroll. 1980. Temperatures occupied by ten ultrasonic-tagged striped bass in freshwater lakes. Transactions of the American Fisheries Society 109:195–202.

Combs, D. L., and L. R. Peltz. 1982. Seasonal distribution of striped bass in Keystone Reservoir, Oklahoma. North American Journal of Fisheries Management 2:66–73.

Gascon, D., and W. C. Leggett. 1977. Distribution, abundance, and resource utilization of littoral fishes in response to a nutrient/production gradient in Lake Memphremagog. Journal of the Fisheries Research Board of Canada 34:1105–1117.

Gloss, S. P., L. M. Mayer, and D. E. Kidd. 1980. Advective control of nutrient dynamics in the epilimnion of a large reservoir. Limnology and Oceanography 25:219–228.

Hannan, H. H., and L. Broz. 1976. The influence of a deep-storage and an underground reservoir on the physicochemical limnology of a permanent central Texas river. Hydrobiologia 51:43–63.

Hogan, J. E., and W. D. Adair, editors. 1982. Lake Norman summary. Duke Power Company, DUKE PWR/82-02, Charlotte, North Carolina, USA.

Jenkins, R. M. 1967. The influence of some environmental factors on the standing crop and harvest of fishes in U.S. reservoirs. Pages 298–321 *in* Reservoir fishery resources symposium. Southern Division American Fisheries Society, Bethesda, Maryland, USA.

Jenkins, R. M. 1982. The morphoedaphic index and reservoir fish production. Transactions of the American Fisheries Society 111:133–140.

Jenkins, R. M., and D. I. Morais. 1971. Reservoir sport fishing effort and harvest in relation to environmental variables. Pages 371–384 *in* G. E. Hall, editor. Reservoir fisheries and limnology. Special Publication 8, American Fisheries Society, Bethesda, Maryland, USA.

Jenkins, R. M., and D. I
ator relations in the
reservoirs. Proceedi
of the Southeastern
life Agencies 30:141

Jones, J. R., and R. W
phorus removal by
reservoirs. Proceedi
sociation of Theore
16:1007–1017.

Kennedy, R. H., K. W. T
Jr. 1982. The estab
dients in reservoirs.
Journal 7:71–87.

Lewis, R. E. (In press).
vertical distribution
stratification. Proce
Conference of the So
and Wildlife Agenci

McConnell, W. J. 196
growth to rate of gr
cosms. Limnology an

Moore, W. G. 1941.
of fishes. Ecology 22

Nakashima, B. S., and W
perch (*Perca flavesce*
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1785–1797.

Oglesby, R. T. 1977a.
phytolankton standi
phoedaphic factors.
search Board of Can

Oglesby, R. T. 1977b
standing crop and a
tions of phosphorus
factors. Journal of t
of Canada 34:2255–

Paulson, L. J., and J.
interactions among
River. Pages 1647–1
water impoundment
Engineers, Minneap

Perkins, J. C., and T. L
chemistry. Pages 10
D. Adair, editors. La
Power Company, D
North Carolina, US

Pflieger, W. L. 1975.
souri Department of
Missouri, USA.

Prentki, R. T., L. J. Pau
Chemical and biolo
sediments. Technical
Limnological Resear
vada, Las Vegas, Ne

Rawson, D. S. 1960. A
twelve large lakes in
nology and Oceanog

Regier, H. A., and D. S.

JENKINS, R. M., AND D. I. MORAIS. 1978. Prey-predator relations in the predator-stocking-evaluation reservoirs. Proceedings of the Annual Conference of the Southeastern Association of Fish and Wildlife Agencies 30:141–157.

JONES, J. R., AND R. W. BACHMANN. 1978. Phosphorus removal by sedimentation in some Iowa reservoirs. Proceedings of the International Association of Theoretical and Applied Limnology 16:1007–1017.

KENNEDY, R. H., K. W. THORNTON, AND R. C. GUNKEL, JR. 1982. The establishment of water quality gradients in reservoirs. Canadian Water Resources Journal 7:71–87.

LEWIS, R. E. (In press). Temperature selection and vertical distribution of striped bass during lake stratification. Proceedings of the 37th Annual Conference of the Southeastern Association of Fish and Wildlife Agencies.

MCCONNELL, W. J. 1965. Relationship of herbivore growth to rate of gross photosynthesis in microcosms. Limnology and Oceanography 10:593–643.

MOORE, W. G. 1941. Studies on the feeding habits of fishes. Ecology 22:91–96.

NAKASHIMA, B. S., AND W. C. LEGGETT. 1975. Yellow perch (*Perca flavescens*) biomass responses to different levels of phytoplankton and benthic biomas in Lake Memphremagog, Quebec-Vermont. Journal of the Fisheries Research Board of Canada 32: 1785–1797.

OGLESBY, R. T. 1977a. Relationships of fish to lake phytolankton standing crop, production, and morphoedaphic factors. Journal of the Fisheries Research Board of Canada 34:2271–2279.

OGLESBY, R. T. 1977b. Phytoplankton summer standing crop and annual productivity as functions of phosphorus loading and various physical factors. Journal of the Fisheries Research Board of Canada 34:2255–2270.

PAULSON, L. J., AND J. R. BAKER. 1980. Nutrient interactions among reservoirs on the Colorado River. Pages 1647–1656 *in* Symposium on surface water impoundments. American Society of Civil Engineers, Minneapolis, Minnesota, USA.

PERKINS, J. C., AND T. L. WHISENANT. 1982. Water chemistry. Pages 107–152 *in* J. E. Hogan and W. D. Adair, editors. Lake Norman summary. Duke Power Company, DUKE PWR/82-02, Charlotte, North Carolina, USA.

PFLIEGER, W. L. 1975. The fishes of Missouri. Missouri Department of Conservation, Jefferson City, Missouri, USA.

PRENTKI, R. T., L. J. PAULSON, AND J. R. BAKER 1981. Chemical and biological structure of Lake Mead sediments. Technical report number 6, Lake Mead Limnological Research Center, University of Nevada, Las Vegas, Nevada, USA.

RAWSON, D. S. 1960. A limnological comparison of twelve large lakes in northern Saskatchewan. Limnology and Oceanography 5:195–211.

REGIER, H. A., AND D. S. ROBSON. 1967. Estimating population number and mortality rates. Pages 31–66 *in* S. D. Gerking, editor. The biological basis of freshwater fish production. Blackwell Scientific Publications, Oxford, England.

RICKER, W. E. 1975. Computation and interpretation of biological statistics of fish populations. Bulletin 191, Fisheries Research Board of Canada, Ottawa, Canada.

RINNE, J. N., W. L. MINCKLEY, AND P. O. BERSELL. 1981. Factors influencing fish distribution in two desert reservoirs, Central Arizona. Hydrobiologia 80:31–42.

RODRIGUEZ, M. S. 1982a. Phytoplankton. Pages 154–260 *in* J. E. Hogan and W. D. Adair, editors. Lake Norman summary. Duke Power Company, DUKE PWR/82-02. Charlotte, North Carolina, USA.

RODRIGUEZ, M. S. 1982b. Relationships between phytoplankton growth rates and nutrient dynamics in Lake Norman, N.C. Duke Power Company, DUKE PWR/82-01, Charlotte, North Carolina, USA.

RYDER, R. A. 1965. A method for estimating the potential fish production of north-temperate lakes. Transactions of the American Fisheries Society 94:214–218.

RYDER, R. A. 1982. The morphoedaphic index—use, abuse, and fundamental concepts. Transactions of the American Fisheries Society 111:154–164.

SCHAICH, B. A., AND C. C. COUTANT. 1980. A biotelemetry study of spring and summer habitat selection of striped bass in Cherokee Reservoir, Tennessee, 1978. Oak Ridge National Laboratory, ORNL/TM-7127, Oak Ridge, Tennessee, USA.

SERRUYA, C., M. EDELSTEIN, U. POLLINGHER, AND S. SERRUYA. 1974. Lake Kinneret sediments: nutrient composition of the pore water and mud water exchanges. Limnology and Oceanography 19:489–508.

SILER, J. R. 1983. Description of a trawl handling structure for a bow-fished Tucker trawl. The Progressive Fish-Culturist 45:217–220.

SILER, J. R. 1985. A comparison of area and volumetric-based population estimates from midwater trawl catch statistics. Research report PES/85-16, Duke Power Company, Charlotte, North Carolina, USA.

SILER, J. R., R. E. LEWIS, B. K. BAKER, G. E. VAUGHAN, AND R. A. HANSEN. 1982. Fish. Pages 411-460 *in* J. E. Hogan and W. D. Adair, editors. Lake Norman summary. Duke Power Company, DUKE PWR/82-02, Charlotte, North Carolina, USA.

STRICKLAND, J. D. H., AND T. R. PARSONS. 1972. A practical handbook of seawater analysis. Fisheries Research Board of Canada, Ottawa, Canada.

THORNTON, K. W., R. H. KENNEDY, J. H. CARROLL, W. W. WALKER, R. C. GUNKEL, AND S. ASHBY. 1980. Reservoir sedimentation and water quality—a heuristic model. Pages 654–661 *in* Symposium on surface water impoundments. American Society of Civil Engineers, Minneapolis, Minnesota, USA.

THORNTON, K. W., R. H. KENNEDY, A. D. MAGOUN, AND G. E. SAUL. 1982. Reservoir water quality sampling design. Water Resources Bulletin 18:471–480.

TRAUTMAN, M. B. 1957. The fishes of Ohio. Ohio State University Press, Columbus, Ohio, USA.

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY. 1974. Methods of chemical analysis of water and wastes. Office of Technology Transfer, Washington, D.C., USA.

VAN DEN AVYLE, M. J., R. S. HAYWARD, R. A. KRAUSE, AND A. J. SPELLS. 1982. Spatial variation in abundance of phytoplankton, zooplankton, and larval fishes in Center Hill Reservoir. Canadian Water Resources Journal 7:189–214.

WADDLE, H. R., C. C. COUTANT, AND J. L. WILSON. 1980. Summer habitat selection by striped bass, *Morone saxatilis*, in Cherokee Reservoir, Tennessee, 1977. Oak Ridge National Laboratory, ORNL/TM-6927, Oak Ridge, Tennessee, USA.

Pages 137–143 *in* G. E. Hall an
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From: <Margaret_Bennett@dom.com>
To: <jxc9@nrc.gov>
Date: 4/12/05 4:35PM
Subject: 05-209: Dominion Nuclear North Anna, LLC North Anna Early Site PermitApplication Response to Supplemental Request for Additional Information

(See attached file: 05-209_Ltr&Att.pdf)

Mail Envelope Properties (425C3073.CE2 : 8 : 52450)

Subject:	05-209: Dominion Nuclear North Anna, LLC North Anna Early Site PermitApplication Response to Supplemental Request for Additional Information
Creation Date:	4/12/05 4:31PM
From:	<Margaret_Bennett@dom.com>
Created By:	Margaret_Bennett@dom.com

Recipients
nrc.gov
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Expiration Date:	None
Priority:	Standard
Reply Requested:	No
Return Notification:	None
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Security:	Standard

Dominion Nuclear North Anna, LLC
5000 Dominion Boulevard, Glen Allen, VA 23060

Dominion

April 12, 2005

U. S. Nuclear Regulatory Commission
Attention: Document Control Desk
Washington, D.C. 20555

Serial No. 05-209
ESP/JDH
Docket No. 52-008

DOMINION NUCLEAR NORTH ANNA, LLC
NORTH ANNA EARLY SITE PERMIT APPLICATION
RESPONSE TO SUPPLEMENTAL REQUEST FOR ADDITIONAL INFORMATION

In its March 18, 2005 letter titled "*Supplemental Request for Additional Information* (RAI) Regarding the Environmental Portion of the Early Site Permit (ESP) Application for the North Anna Site," the NRC requested additional information regarding certain aspects of the environmental portion of Dominion Nuclear North Anna, LLC's North Anna Early Site Permit application. The RAI consisted of four questions. This letter contains our response to the question listed below:

- RAI 4

Our response to the remaining three questions will be provided separately. No update to the North Anna ESP application is required as a result of this response.

If you have any questions or require additional information, please contact Mr. Tony Banks at 804-273-2170.

Very truly yours,

Eugene S. Grecheck
Vice President-Nuclear Support Services

Enclosures:

1. Response to RAI 4
2. Documentation of Commitment Made to the Commonwealth of Virginia Regarding Striped Bass

Commitments made in this letter: None

cc: (with enclosures)

U. S. Nuclear Regulatory Commission, Region II
Sam Nunn Atlanta Federal Center
61 Forsyth Street, SW
Suite 23T85
Atlanta, Georgia 30303

Mr. Jack Cushing
U. S. Nuclear Regulatory Commission
Washington, D.C. 20555

Mr. J. T. Reece
NRC Senior Resident Inspector
North Anna Power Station

Ms. Belkys Sosa
U. S. Nuclear Regulatory Commission
Washington, D.C. 20555

COMMONWEALTH OF VIRGINIA

COUNTY OF HENRICO

The foregoing document was acknowledged before me, in and for the County and Commonwealth aforesaid, today by Eugene S. Grecheck, who is Vice President, Nuclear Support Services, of Dominion Nuclear North Anna, LLC. He has affirmed before me that he is duly authorized to execute and file the foregoing document on behalf of Dominion Nuclear North Anna, LLC, and that the statements in the document are true to the best of his knowledge and belief.

Acknowledged before me this 12th day of April, 2005

My Commission expires: August 31, 2008

Margaret B. Bennett
Notary Public

(SEAL)

Enclosure 1

Response to Supplemental Environmental RAI 4

RAI 4 (NRC 3/18/05 Letter)

Provide documentation of any commitments Dominion has made to the Commonwealth of Virginia regarding mitigation measures affecting the striped bass.

Response

Dominion's commitment regarding mitigation measures affecting the striped bass is stated in Dominion's January 12, 2005 letter to the Virginia Department of Game and Inland Fisheries (VDGIF). The VDGIF responded to Dominion's commitment by letter dated February 9, 2005. In addition, two e-mails between Dominion and VDGIF on February 17, 2005 are included because they serve to clarify the commitment.

Copies of the following letters and e-mails are provided in Enclosure 2:

- Letter from Pamela F. Faggert, Vice President and Chief Environmental Officer, Dominion, to Mr. Gary F. Martel, Director, Fisheries, Virginia Department of Game & Inland Fisheries, January 12, 2005.
- Letter from Gary F. Martel, Director, Fisheries Division, Commonwealth of Virginia, Department of Game and Inland Fisheries, to Ms. Pamela F. Faggert, Vice President & Chief Environmental Officer, Dominion Power, February 9, 2005.
- E-mail from Bill Bolin, Dominion, to Gary Martel, Virginia Department of Game and Inland Fisheries, February 17, 2005, and the e-mail from Gary Martel, Virginia Department of Game and Inland Fisheries, to Bill Bolin, Dominion, February 17, 2005.

Application Revision

None.

Enclosure 2

**Documentation of Commitment Made
to the Commonwealth of Virginia
Regarding Striped Bass**

Dominion

Pamela F. Faggert
Vice President and Chief Environmental Officer
5000 Dominion Boulevard, Glen Allen, VA 23060
Phone 804-273-3467

January 12, 2005

Mr. Gary F. Martel
Director, Fisheries
Virginia Department of Game & Inland Fisheries
4010 West Broad Street
Richmond, VA 23230

Dear Mr. Martel:

You recently had several conversations with Bill Bolin of my staff regarding Dominion's application to the U.S. Nuclear Regulatory Commission (NRC) for an Early Site Permit at our North Anna Power Station site. As you know, this is a federal licensing action to obtain NRC's determination that the North Anna site is suitable for siting additional nuclear units. However, NRC issuance of an ESP would not constitute an approval to construct or operate new units; nor would it affect the need to obtain other environmental permits and other authorizations that would be required before any new units could be built and operated.

You had raised issues regarding the predicted increase in lake water temperature that would result from an additional unit and the potential impact on the lake's stocked striped bass population. To address your concern and to ensure that Lake Anna remains a healthy, viable fishery and a successful recreational venue, Dominion proposes the following commitment to the Department:

> If Dominion obtains approval and decides to construct and operate an additional nuclear unit at its North Anna site, the company will work with the Department to support a healthy and viable Lake Anna fishery and to assist in maintaining its successful recreational fishing venue. Our commitment includes providing financial assistance to aid in the development and stocking of a more thermally-tolerant species (such as a sterile white bass/striped bass hybrid), or such other species as the Department reasonably determines to be most suitable in maintaining an equally viable and enjoyable recreational fishery.

Please let us know whether this proposal is sufficient to resolve the Department's concerns, and if you have any questions regarding this statement or need additional information. Bill Bolin can be reached at 804-271-5304.

Sincerely,

Pamela F. Faggert

Pamela F. Faggert

[illegible]

Rec'd FEB 10 2005 EPIC

COMMONWEALTH *of* VIRGINIA

Department of Game and Inland Fisheries

W. Tayloe Murphy, Jr.
Secretary of Natural Resources

William L. Woodfin, Jr.
Director

February 9, 2005

Ms. Pamela F. Faggert
Vice President & Chief Environmental Officer
Dominion Power
5000 Dominion Boulevard
Glen Allen, VA 23060

Dear Ms. Faggert:

Thank you for your letter of January 12. I have had my staff contact other states to review options for a thermally tolerant species to supplement and/or substitute for striped bass in Lake Anna. At this time, we have not been able to find a readily available source of sterile hybrid striped bass/white bass, nor have we been able to identify a replacement species that would substitute in a recreational fishery for striped bass. However, I do feel confident that with Dominion's commitment to the development of the sterile hybrid that we should be able to develop and utilize this option through either outside contracts or by utilizing facilities and staff within our department.

We are moving forward to begin either an internal or contractual development of hybrids and will work closely with Bill Bolin of your staff to coordinate such development. Again, thank you for getting in touch with us.

Sincerely,

Gary F. Martel
Director, Fisheries Division

GFM/tha

cc: J.W. Kauffman

4010 WEST BROAD STREET, P.O. BOX 11104, RICHMOND, VA 23230-1104
(804) 367-1000 (V/TDD) *Equal Opportunity Employment, Programs and Facilities* FAX (804) 367-9147

Bill Bolin
02/17/2005 02:15 PM

To: Tony Banks/NUC/VANCPOWER@VANCPOWER
cc:
Subject: Re:

----- Forwarded by Bill Bolin/LR/FH/VANCPOWER on 02/17/2005 02:14 PM -----

"Gary Martel"
<Gary.Martel@dgif.virginia.gov>
02/17/2005 12:06 PM

To: <Bill_Bolin@dom.com>
cc: "Charlie Sledd" <Charlie.Sledd@dgif.virginia.gov>, "John Kaufman" <John.Kaufman@dgif.virginia.gov>, "John Odenkirk" <John.Odenkirk@dgif.virginia.gov>
Subject: Re:

You are correct in pointing out that the sterile striped bass/white bass Hybrid is an acceptable replacement. I was not considering the hybrid as a species in my letter.

I would like to further point out that the standard non-sterile hybrid is actually preferable in the reservoir fishery, however there are significant concerns over possible out migration and genetic impact through breeding with the Chesapeake stocks. This is the reason that the sterile hybrid development is being evaluated. There has never been an evaluation of out migration of striped bass or hybrids from Lake Anna. Dominion may wish to consider this as an option if approved through ASMFC and the Chesapeake Bay Program, Living Resources Subcommittee.

Please contact me if I can provide further clarification or if other questions arise.

Gary

>>> <Bill_Bolin@dom.com> 02/17/05 10:19AM >>>
Gary,

Your letter of February 9, 2005 to Dominion states "nor have we been able to identify a replacement species that would substitute in a recreational fishery for striped bass". As we discussed today, please confirm our understanding that this statement refers to replacement species other than the hybrid white bass/striped bass (i.e. that a sterile hybrid white bass/striped bass would be considered a replacement species that could substitute in North Anna's recreational fishery for the striped bass). Your confirmation of this understanding in an email response to this message would be greatly appreciated. Could you respond with the "Reply with History" feature so that this message and your reply are kept together? Thanks

Bill

From: "Gary Martel" <Gary.Martel@dgif.virginia.gov>
To: <JXC9@nrc.gov>
Date: 4/27/05 10:09AM
Subject: Re: Dominion's Commitment

Sorry for the delay in response, I was checking with staff on any new information. In answer to your question:

We are comfortable that Dominion will work with us or another entity such as a university or private supplier to provide a solution. A clear solution in the form of a producer or alternate species is not available at this time. Ultimately the responsibility for a substitute fish to replace striped bass lost due to habitat changes rests with Dominion Power. If we determine that we can produce the fish with financial support from Dominion, and this is the best solution then that would be an acceptable alternative.

If you have further question please feel free to contact me.

Gary Martel
Director of Fisheries
Va. Dept. Game & Inland Fisheries

>>> "Jack Cushing" <JXC9@nrc.gov> 04/21/05 01:03PM >>>
Dear Mr. Martel,

In your email to Ellie Irons, you stated that "Our agency is willing to work with Dominion Power toward a solution, however the responsibility to provide an acceptable alternative lies with Dominion."

On 1/12/05, Dominion committed to the Virginia Department of Game and Inland Fisheries (VDGIF) to provide financial assistance to VDGIF to develop a more thermally resistant species.

Does the committment that Dominion made to the Virginia Department of Game and Inland Fisheries (VDGIF), to provide financial assistance to VDGIF to develop a more thermally resistant species, satisfy VDGIF that Dominion will work with VDGIF?

Thank You

Jack Cushing
Senior Project Manager
License Renewal and Environmental Impacts
Division of Regulatory Improvement Programs
USNRC
Phone 301-415-1424
email JXC9@NRC.GOV

CC: "Andrew Zadnik" <Andrew.Zadnik@dgif.virginia.gov>, "John Kauffman" <John.Kauffman@dgif.virginia.gov>, "Ray Fernald" <Ray.Fernald@dgif.virginia.gov>

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Subject:	Re: Dominion's Commitment
Creation Date:	4/27/05 10:08AM
From:	"Gary Martel" <Gary.Martel@dgif.virginia.gov>
Created By:	Gary.Martel@dgif.virginia.gov

Recipients
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John.Kauffman CC (John Kauffman)
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Virginia Lakes

Claytor Lake

- **2004 Biologist/Fisheries Report**

Claytor Lake, a 4,475-acre impoundment of the New River, stretches northeastward across the Pulaski County countryside for 21 miles. Possible catches from Claytor Lake range from bass to carp. Smallmouth, largemouth, and spotted bass (collectively called "black bass") are the "bread and butter" fishes of this lake. About 58 percent of the anglers at Claytor Lake fish for "black bass." The three black bass species in Claytor Lake are regulated by a 12-inch minimum size limit and anglers may harvest five per day (all three species combined). Anglers are encouraged to practice catch-and-release of trophy-size bass from the lake. Claytor's steep and rocky shorelines make it particularly good for smallmouth bass. In 2001, Claytor Lake produced 15 smallmouth bass certificates (more than five pounds or over 20 inches).

Claytor Lake holds fewer largemouth bass than other Virginia lakes, and they grow slowly in this mountain reservoir. Claytor Lake's largemouth bass populations appear to be increasing. In 1990, largemouth bass made up about 10 percent of the black bass according to electrofishing catch results by fisheries biologists studying the lake. Largemouth bass increased to about 30 percent of the black bass electrofishing catch by 1998. Anglers can find this species in coves throughout the lake, but they are most abundant in Peak Creek. The Claytor Lake record for largemouth bass was a 14- pound, 6-ounce giant caught in June 1991.

Spotted bass in Claytor are generally smaller than the other black basses. They rarely reach 2 pounds in size. In fact, most anglers that think they are catching small largemouth bass are probably catching small spotted bass, particularly in the upper lake area (above Lighthouse Bridge) where spotted bass are more numerous.

Anglers fishing for black bass in the lake can use information collected on bass food habits during a recent study at Claytor Lake to select lures and techniques for these species. Smallmouth bass and spotted bass have very similar diets, with both relying mostly on crayfish. Techniques and lures that mimic crayfish are most likely to be successful in producing catches of these fish. Both of these bass species eat a lot of bluegill as well as some alewife and gizzard shad, so they may also hit lures that imitate fish. Largemouth bass diets are quite different than smallmouth and spotted bass diets, which may be one reason they are doing so well in the lake. Largemouth bass eat bluegill, alewife, gizzard shad, and crayfish, depending on the season of the year and whether these prey are abundant in a given year. Lures that imitate fish are the best choice for largemouth bass, but they may also hit crayfish imitations.

The Department maintains the striped bass population in Claytor Lake through annual stocking. The Department experimented with increased stocking rates for striped bass in Claytor Lake in 1998, 2001, and 2002. Doubling the stocking rate in 1998 and 2001, combined with good spawns of alewife and gizzard shad, has resulted in two prominent year classes of stripers in the lake. The 1998 stripers are now running from 28 to 32 inches in length and they weigh between seven and 12 pounds. The 2001 stripers are in the 15 to 18 inch range, so they will reach harvestable size in 2003. Recent sampling indicates that the some of the 2000 stripers will be represented in future catches at the lake. It is still too early to tell whether the 2002 stripers will produce similar numbers of adult fish to those from the 1998 and 2001 stockings.

Claytor Lake produced 15 certificate (more than 20 pounds or over 37 inches) stripers in 2001. At least one striper over thirty pounds in size is caught each year in this lake. Stripers can be caught year-round, although most anglers have their greatest success from late September through May. Water temperatures at or below 70 degrees seem to produce the best fishing.

Recent striper diet studies at Claytor Lake showed that stripers rely mostly on alewife and gizzard shad. Therefore, it is no surprise that Claytor Lake anglers experience the best success using these species as bait. Gizzard shad and alewives are most easily caught using a cast net near the back ends of coves. Peak Creek is a great place for finding bait, but don't overlook smaller coves in the lake. Many stripers are taken with topwater baits (Redfins, Rapalas, etc.) and bucktails in the spring and fall. Fish points and flats adjacent to deep water for best topwater action. Trolling bucktails in 20-60 feet of water can produce good catches.

During the summer and early fall months stripers primarily "hole up" in the middle and lower lake areas close to the lake's thermocline (30-40 feet deep), where they find suitable temperature and oxygen levels. When the lake begins to cool in October, stripers begin chasing shad and alewife schools around the lake and are more difficult to locate. If you are lucky enough to see them chasing shad at the surface, you can catch them on top water lures. In winter months, look for stripers in the middle and upper lake areas, from the mouth of Peak Creek up to the Lighthouse Bridge. At this time of year, a good depth finder is the single most important piece of equipment needed to locate fish, because stripers are likely to be located in 40-60 feet of water. Find the bait schools and you are likely to find the stripers nearby.

Hybrid striped bass were introduced to Claytor in 1992 and are stocked each year. Many of the fish from the earliest stockings are 8-12 pounds today! These striped bass hybrids are a hard fighting fish that are good to eat! Since they can tolerate higher water temperatures, hybrids often chase schools of shad at the lake's surface at night in the summer months. Most of the time, hybrids live at similar depths and locations as the stripers in the lake. Their diet is very similar to stripers, so they can be caught using the same techniques.

White bass are found in Claytor Lake, but their numbers are down from historic levels. The best opportunity to catch white bass from the lake is during April and May when they run upstream to Allisonia, where the New River flows into Claytor Lake.

Anglers should keep in mind that the harvest of stripers and hybrids is limited to 4 fish per day (the two species combined), all of which must be longer than 20 inches. White bass are regulated by a creel limit of five per day, with no size limit. Anglers should study the differences between these fish carefully. Helpful identification information is available in the Department's recent publication, "The Angler's Guide to Virginia Freshwater Sportfish," which is available from Department offices statewide.

Walleye are still occasionally caught from the lake, but their numbers have dropped off since stocking was discontinued in 1996. Anglers have recently been catching yellow perch in the one-pound range. Black crappie caught from the lake typically average a little less than a pound. According to the Department's creel survey in 1998, many anglers take home a limit of 25 bluegill that average 0.5-pound each. Flathead and channel catfish (up to 20 pounds) can also be caught from the lake. With catches of 20-30 pound carp possible, anglers from as far away as England come to fish for them at Claytor.

Claytor Lake State Park, located on the north side of the lake, provides 497 acres of park with camping, cabins, picnic areas, and a swimming beach, as well as a marina. For more information on the park, call 540-643-2500.
Boat access to the lake is available for a small fee at private ramps at Claytor Lake State Park, Lighthouse Bridge, and at Conrad Brothers and Rockhouse Marinas on the Peak Creek arm of the lake. The Department maintains no-fee ramps at Allisonia (in the upper lake area) and near the entrance to the state park (Dublin Ramp). Harry's Point boat ramp, a no-fee ramp located in the mid-lake area within Pulaski County's Harry DeHaven Park, has a double ramp and courtesy piers. Harry's Point also has a handicapped-accessible fishing pier, where many of the lake's species can be caught throughout the year. During the fall and winter months, anglers are likely to catch striped bass and hybrid striped bass swimming near the pier.

The easiest way to get to Harry's Point from I-81 is to take the Route 605 exit (near the south end of Radford), and then follow the brown trailblazer signs to Harry DeHaven Park. From the I-81 exit ramp, take Route 605 (Little River Dam Road). Follow Route 605 until you reach Route 663 (Owens Road), go right on 663, then look for signs marking the park when you get near the lake.

If you have fishing questions about Claytor Lake, call the VDGIF Blacksburg office at 540- 951-7923.

- 2003 Biologist/Fisheries Report