EFFECTS OF A PUMPED STORAGE HYDROELECTRIC PLANT ON RESERVOIR TROUT HABITAT

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Abstract: Jocassee Reservoir (3,063 ha) is the upper pool for a 610-MW pumped storage hydroelectric plant in northwestern South Carolina. Trout (200-225 mm long) have been stocked annually since 1972. The volume of trout habitat during summer has decreased annually from 1973 to 1976, and is associated with increases in the temperature and volume of water pumped from the lower reservoir. The top of the thermocline during September was lowered from about 9 m in 1973 to nearly 19 m in 1976, and trout habitat was reduced by about 65%. On the basis of a regression presented, we predict that trout habitat will be reduced to nil when plant operation reaches 63% of capacity (perhaps by 1981).

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Natural trout habitat in the South is limited to the mountains and foothills of the Blue Ridge range of the Appalachian Mountains in Virginia, North Carolina, South Carolina, Georgia, and Alabama. However, trout fishing has been extended southward by stocking trout in cool tailrace streams below impoundments and in large reservoirs which maintain adequate water temperatures and dissolved oxygen (DO) levels in or below the thermocline during summer (Wilkins et al. 1967, Baker and Mathis 1967, Axon 1971, 1974). Such reservoirs are said to support a "two-story fishery" because of the vertical position of trout in relations to endemic warmwater species during the summer (Kirkland and Bowling 1966). However, during the other seasons, when temperature and DO levels are adequate, trout inhabit the upper levels of the reservoir.

Many temperature and DO values, ranging from lethal limits to those considered optimum for growth and reproduction, have been used to define trout habitat. Temperature and DO requirements for trout in southeastern reservoirs have been described as 21.1 C and 3 to 4 mg/l (Axon 1974, Baker and Mathis 1967, Kirkland and Bowling 1966, Wilkins et al. 1967). H. Boles and J. D. Little (in preparation) established "trout water" as all water with prevailing temperatures of less than 21.1 C that contained no less than 5.0 mg/l of DO. Brungs and Jones (1977) established maximum weekly average temperatures for growth at 19.0 C for rainbow trout (*Salmo gairdneri*) and 17.0 C for brown trout (*S. trutta*). Fast (1973) found that rainbow trout avoided water 21 C or warmer throughout the summer. The U.S. Environmental Protection Agency (1972) recommends a minimum concentration of 5.0 mg/l DO to maintain good fish populations.

South Carolina's trout habitat is generally limited to about 378 km of streams and Jocassee Reservoir, a 3,063 ha impoundment in the northwest corner of the state (Fig. 1). The reservoir is a part of Duke Power Company's Keowee-Toxaway Project. This complex includes Keowee Reservoir (7,411 ha), which serves as a cooling reservoir for the 2,658 MW Oconee Nuclear Station, and as the lower pool for the Jocassee Pumped Storage Station. The 610 MW pumped storage hydoelectric plant is located at the Jocassee Reservoir Dam. Jocassee Reservoir is the upper pool for the pumped storage plant and will later (1985) serve as the lower pool for a second pumped storage plant (Bad Creek Project, 1,000 MW).

Keowee and Jocassee Reservoirs are warm monomictic reservoirs exhibiting characteristic summer stratification. Keowee Reservoir reached full pool elevation of 243.8 m above sea level in April 1971. It has a mean depth of 15.8 m and a storage volume of 11.8 x 10^8 m^3. Main portions of this reservoir have generally warmed each year since the nuclear plant began operating in 1973 (Ruelle et al. 1977). The use of Keowee Reservoir's hypolimnetic water during summer for nuclear plant cooling has lowered the top of the thermocline from 6 to 8 m in 1972 to 25 m in 1976.

Jocassee Reservoir reached full pool elevation of 338.3 m above sea level in December 1973. It has a mean depth of 47 m (maximum, 107 m) and a storage volume of 14.3 x

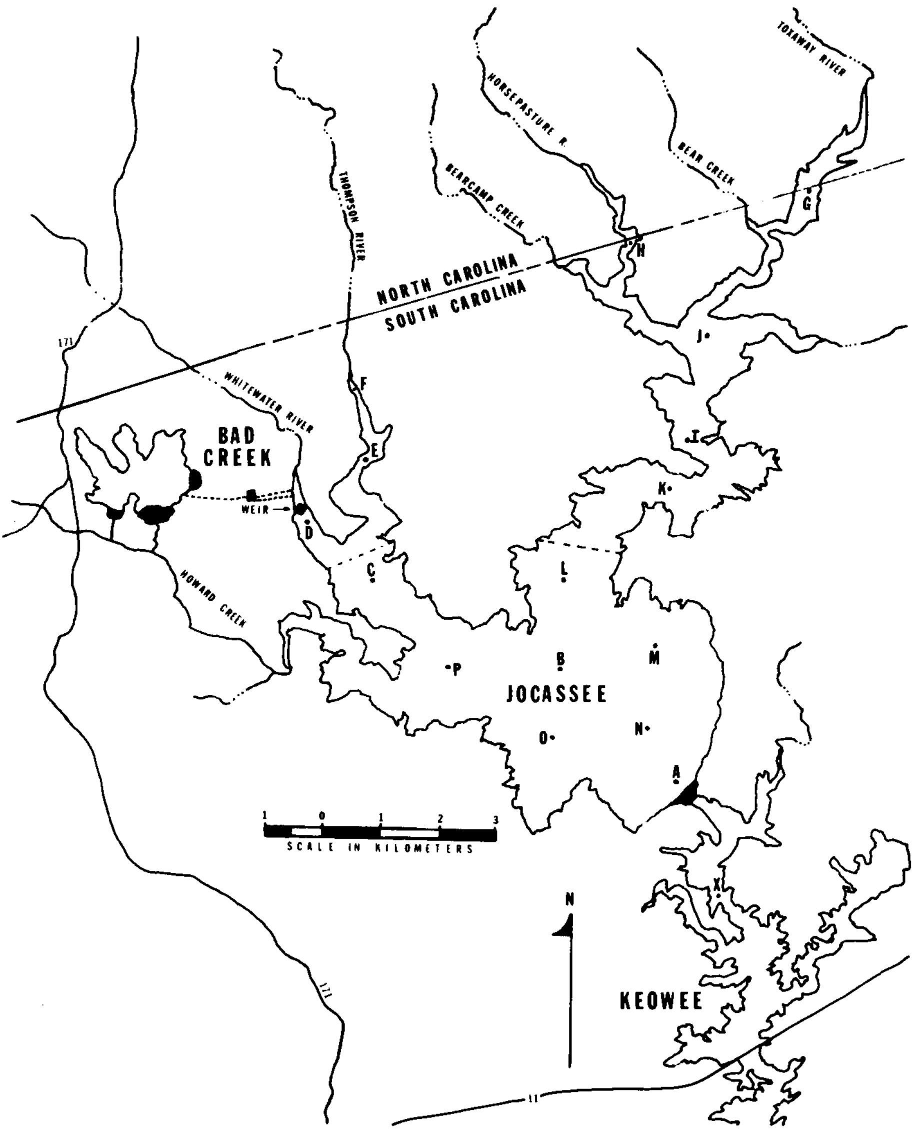

Fig. 1. Jocassee Reservoir and portions of Keowee Reservoir, showing sampling stations. Station A is 50 m from intake-discharge structures. Broken line separates main reservoir from major tributaries.

10^8 m^3. Water level may fluctuate about 2 m weekly as a result of generating and pumping cycles. Water from a depth of 12.8-20.1 m in Keowee Reservoir is lifted 90 m and discharged at a depth of 13.1-20.4 m into Jocassee Reservoir at a maximum rate of 781.5 m^3/sec. Pumping began in December 1973 and occurs mainly at night and on weekends, when excess electricity is available from Oconee Nuclear Station or other steam generating plants. Electricity is generated during times of need.

Jocassee Reservoir contained about 25 endemic fish species. Threadfin shad (*Dorosoma petenense*) were stocked by the South Carolina Wildlife and Marine Resources Department in 1972 and 1974 and reproduction occurred each year after 1972. The Department also stocked 200-225 mm trout annually since 1972. Through February 1977, 135,000 rainbow trout and 30,000 brown trout were stocked. Trout 1.4 to 2.7 kg—occasionally 5 kg—have been caught. The State plans to stock trout annually in Jocassee Reservoir to maintain this two-story fishery (Logan 1976). Trout survival depends on the presence of cool, well oxygenated water in or below the thermocline during summer.

The objectives of this study were to (1) define and describe the amount of trout habitat in Jocassee Reservoir, and (2) develop a regression equation for predicting the effect of future pumping on the volume of trout habitat.

METHODS

Temperature and DO profiles were taken monthly at 3 stations (A, E, I) in Jocassee Reservoir from August 1973 to December 1976 and at one station (X) in the tailwaters from April 1972 to December 1976 (Fig. 1). Thirteen stations were added during summer and fall 1976. Profiles were taken with a YSI Model 54 Temperature-Oxygen Meter (Use of trade names does not imply government endorsement.)
equipped with a 70 m cable. Measurements were taken at the surface and at 1 m intervals, to 25 m, in 1973-75 and 35 m in 1976, and at 5 m intervals at greater depths to 70 m.

The volume of trout habitat was estimated for the main portion of the reservoir and the 2 major tributary arms. Water volumes were calculated for each 1.5 m stratum, based on U.S. Geological Survey topographical maps. Monthly temperature and DO profiles were used to describe each stratum and to calculate the volume of water that provided water temperatures and DO levels satisfactory for long-term trout survival. Two sets of criteria were used: (1) water temperature should not exceed 20 C and DO should not be below 5 mg/l and (2) water temperature should not exceed 21 C and DO should not be below 3 mg/l.

Correlation coefficients (Pearson Product-moment) were calculated between volume of trout habitat and certain environmental factors that could affect the amount of trout habitat. Since the time element in the action of these factors was unknown, various time-lagging-weighting manipulations were performed on independent variables (environmental factors) to determine the best relationships. Those appearing most useful were:

1. Jocassee Hydrostation pumping rate—percentage of total capacity 1 month before the estimate of trout habitat volume, based on an operating level of 70 hr/week at 691 m^3/sec.
2. Jocassee Reservior tailrace temperature—average temperature (C) from 12.8 to 20.1 m (intake opening) in the tailrace of Jocassee Dam 1 month before habitat-volume estimate.
3. Oconee Nuclear Station operational level—percentage of total capacity modified by adding operational level during month of habitat volume estimation to one-half the level lagged 1 mo plus one-fourth the level lagged 2 mo.
4. Winter equilibrium temperature (C)—temperature which a water body tends to approach under a given set of meteorological conditions. Temperatures for December, January, and February were correlated against habitat-volume in July, August, and September.

Stepwise multiple regression analysis was used to determine combined influence of independent variables on trout habitat.

RESULTS

Temperature of the water pumped from Keowee Reservoir (Station X) to Jocassee Reservoir during late summer increased about 8 C between 1973 and 1975-76 (Fig. 2). Water temperatures near the surface were significantly correlated to meteorological conditions. However, water temperatures at the pumping intake depth (12.8-20.1 m) were strongly correlated ($r = 0.84$; $\alpha = 0.01$) to the operating level of Oconee Nuclear Station (Table 1). Winter water temperatures in Keowee Reservoir (Station X) were similar over the 4 years. During the spring, water at the intake level warmed earlier and was about 5 C higher in 1976 than in 1973.

Summer temperature profiles at Station A in Jocassee Reservoir have changed since pumped storage operations began (Fig. 2). The top of the thermocline has been lowered from about 9 m in 1973 to about 19 m in 1975 and 1976. Monthly temperature profiles from 13 additional stations in 1976 showed that Station A accurately depicted temperature

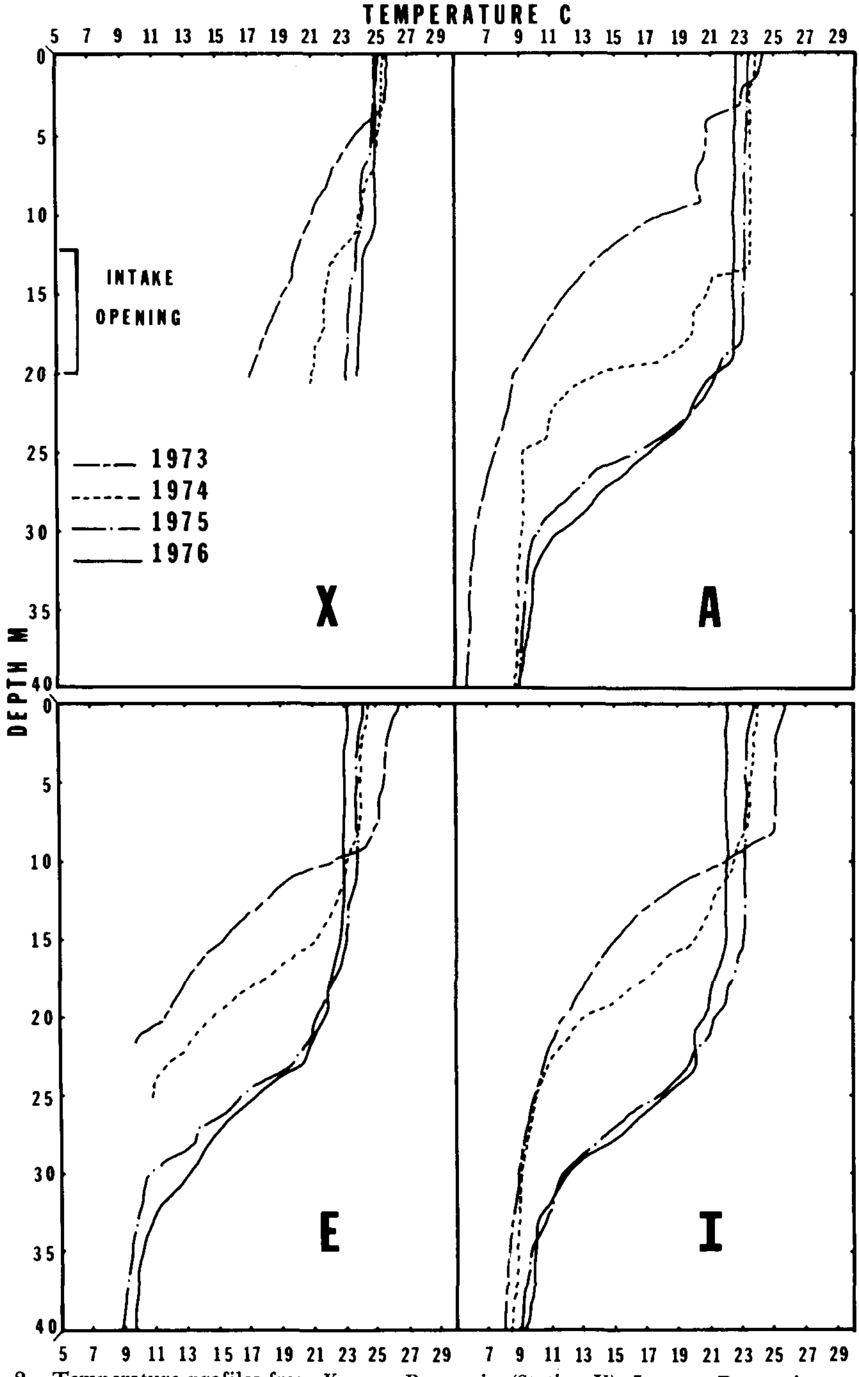

Fig. 2. Temperature profiles from Keowee Reservoir (Station X), Jocassee Reservoir near the intake-discharge structures (Station A), and the two reservoir arms (Stations E and I) during September.

Table 1. Correlation coefficients for trout habitat, hydrostation pumping rates (HPR), Jocassee tailrace water temperatures (JTT), operational level of Oconee Nuclear Station (ONS), and winter equilibrium temperatures (WET), Jocassee Reservoir 1973-76.

	HPR	*JTT*	*ONS*	*WET*
Jocassee Trout Habitat (m^3)	-0.66^a	-0.65^a	-0.49	-0.30
Hydrostation Pumping Rate (% Capacity)		0.73^b	0.93^b	0.13
Jocassee Tailrace Temperature (°C)			0.84^b	0.39
Oconee Nuclear Station (% Capacity)				0.11

[a] $\alpha < 0.05$

[b] $\alpha < 0.01$

df = 10 for JTH comparisons and 11 for all other comparisons

profiles throughout the main body of Jocassee Reservoir. Profiles at Station E and I in the reservoir arms showed trends similar to those at Station A. Water temperatures at Stations A, E, and I were nearly the same each year except in 1973. During September 1973, water temperature at Station A was lower than at Station E and I by 2 C at surface, 4 C at 15 m, and 3 C at 25 m.

Habitat suitable for trout existed from the surface to a depth of 35-40 m during November-April each year (Fig. 3). During May, thermal stratification developed, surface temperatures increased, and the upper boundary of trout habitat was lowered continuously until late September. Fall overturn in October returned cool water to the surface.

The upper boundary for trout habitat during September-October became established at a depth of about 9 m in 1973, 16 m in 1974, and 22 m in 1975 and 1976 (Fig. 3). The choice of temperature criteria (20 or 21 C) resulted in a difference of about 1 m in the upper boundary of trout habitat each year. Additional profiles taken during 1976 showed the upper boundary to be similar throughout the entire reservoir.

During all years the lower boundary, determined by the lowermost depth at which DO was 5 mg/l, remained stable at about 30-35 m during September-October in the main body of Jocassee Reservoir (Fig. 3). Choice of the 3 mg/l DO criterion resulted in an increase of about 5 m in depth of trout habitat in 1974 and 1975. During September 1973 and 1976, however, the lower boundary was about 15-20 m deeper than in the other years. On the basis of the 20 C and 5 mg/l DO criteria, September trout habitat in the reservoir proper was reduced from a stratum 23.2 m thick in 1973 to 19.5 m in 1974, 11.5 m in 1975, and 8.4 m in 1976.

Water temperatures in the arms of the reservoir were similar to those at corresponding depths in the main portion of the reservoir. However, DO levels satisfying our criteria either were not found in the arms or were present only as a narrow band in late summer. The thickness of trout habitat (20 C and 5 mg/l DO) in the arms during September was 1.1 m in 1973, 5.5 m in 1974, 1.5 m in 1975, and nil in 1976. Application of the 21 C and 3 mg/l DO criteria yielded layers 10.0 m, 12.2 m, 11.4 m and 11.9 m thick in 1973-76, respectively.

Total volume of September trout habitat (20 C and 5 mg/l DO) was reduced from 4.07×10^8 m^3 when pumping began in 1973 to 1.41×10^8 m^3 in 1976 (Table 2). The total percentage of the lake volume that met the 20 C, 5 mg/l DO criteria during September was 28.5 in 1973 and 9.8 in 1976. Overall, there was a 65.4 percent loss in September trout habitat from 1973 to 1976. The proportion of trout habitat lost between 1973 and 1975 was similar when the 21 C and 3 mg/l DO criteria were applied. However, a more complete turnover in the fall of 1975, resulted in an increase in summer habitat in 1976 over that in 1975.

Trout habitat in Jocassee Reservoir during summer had a negative correlation ($\alpha = 0.05$) with both pumping rate and temperature of the water being pumped (Table 1). Operating level of Oconee Nuclear Station and winter equilibrium temperature were negatively, but not significantly, associated with trout habitat.

Stepwise multiple regression analysis was used to determine the combined effect of the different variables (Table 1) on trout habitat in Jocassee Reservoir. The only variable

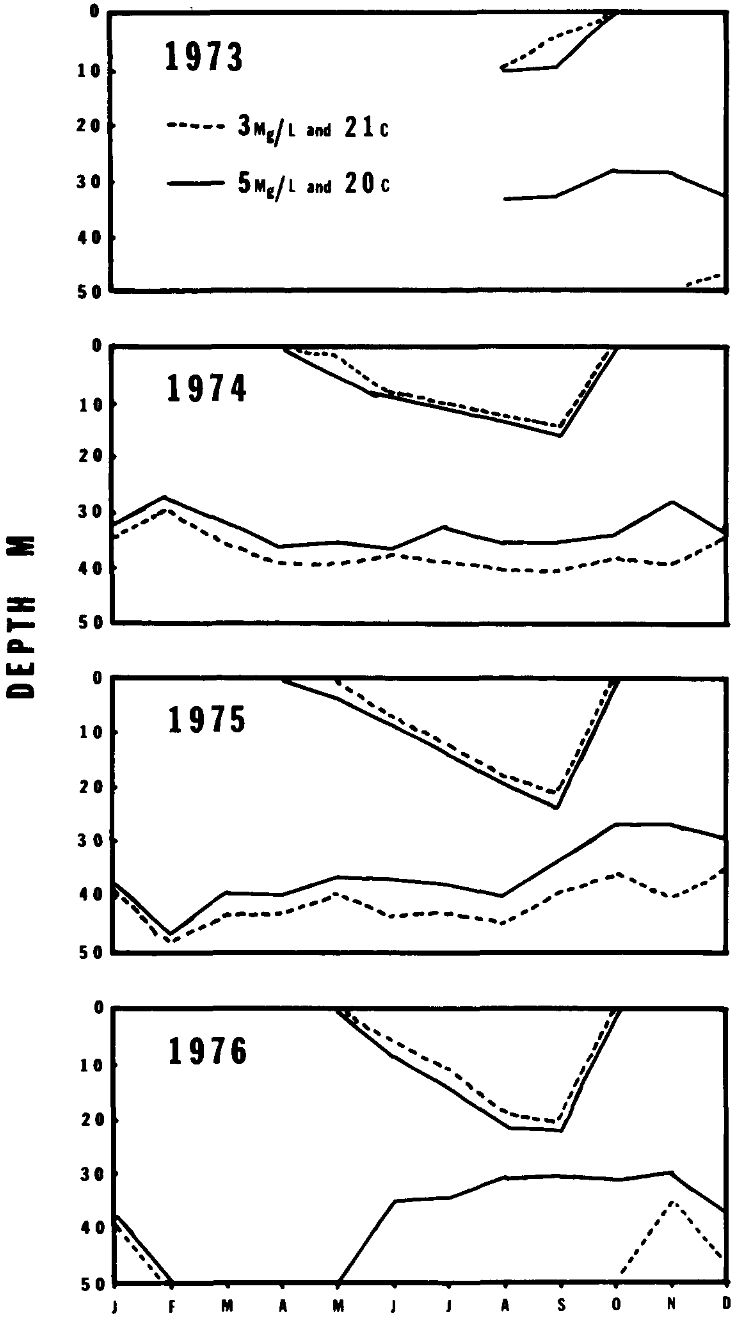

Fig. 3. Trout habitat available in different months in the main portion of Jocassee Reservoir, 1973-76. Solid lines enclose strata containing at least 5 mg/l dissolved oxygen and temperatures no higher than 20 C. Broken lines enclose strata containing at least 3 mg/l dissolved oxygen and temperatures no higher than 21 C.

Table 2. Volume of Jocassee Reservoir trout habitat (temperature ≤ 20 C and dissolved oxygen ≥ 5 mg/l) in September 1973-76.

Year	*Habitat Volume* (m^3 x 10^8)	*Decrease from Previous Year* (%)
1973	4.07	
1974	3.52	13.3
1975	1.94	44.7
1976	1.41	27.3

showing a significant association with trout habitat was pumping rate (r^2 = 0.44, α = 0.10). Jocassee tailrace temperature, which was significant in the correlation analysis (Table 1), was excluded from multiple regression analysis because of the strong inter-correlations within this set of variables. We overcame the synergistic effect between these variables, by combining them into a single variable (PVT), determined by multiplying the total volume pumped 1 month before a trout habitat volume estimate by average temperature of the water pumped over this interval. The PVT had a significant (α = 0.05) negative association of 0.70 and accounted for 50 percent of the variability in trout habitat volume estimates.

Plotting the PVT variable against volume of trout habitat in September illustrates the declining habitat (Fig. 4), and provides an esimate of when it might disappear if this relation holds as pumping increases. The line intercepts the X axis at 112, or at a pumping volume of about 4.71 x 10^8 m^3 of water (63% of capacity) in August, with intake water temperatures similar to those in 1975 and 1976.

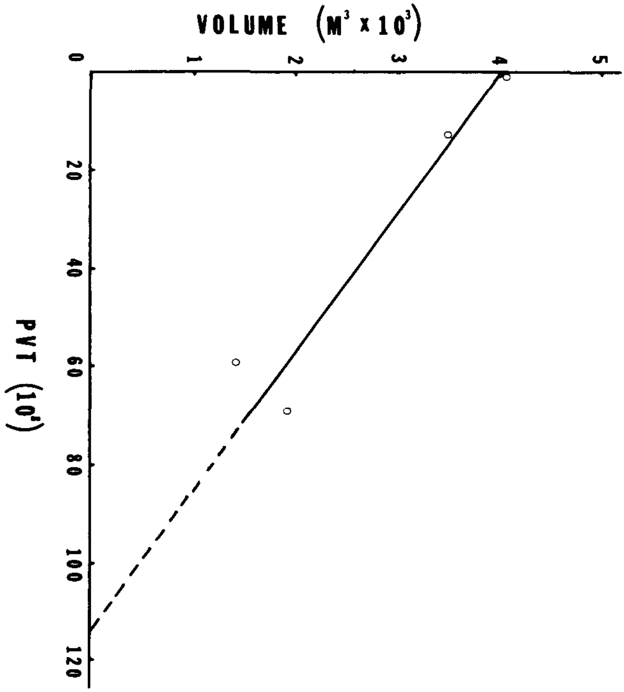

Fig. 4. Relation between September trout habitat volume and PVT (volume of water pumped [m^3 x 10^8] for 30 days before habitat estimate, multiplied by average temperature [C] of water pumped), Jocassee Reservoir 1973-76. Habitat volume = 3.99-.036 PVT (r = 0.96).

DISCUSSION

We have chosen 2 sets of criteria which best fit the limits described in the literature. On the basis of work by Brungs and Jones (1977) and H. Boles and J. D. Little (in preparation), the criteria which appear to be optimum call for water temperature that does not exceed 20 C and DO that is not below 5 mg/l.

These criteria do not consider other fish species present in Jocassee Reservoir. The DO throughout the upper water strata is satisfactory during summer for other species. However, it is known that many warmwater endemic species have preferred summer temperatures higher than the upper limits that can be tolerated by trout (Coutant 1977). Trout rely on many of these species for food, and the possibility exists that trout could be isolated from their principal prey during the summer. Kirkland and Bowling (1966) pointed out that trout moved into warm zones to feed for short periods. Their example suggested movement of not more than 12 m to the surface—about half the distance to the surface during September 1976 in Jocassee Reservoir. Time spent outside their natural temperature zones, and physiological stress imposed upon them during these feedings (if any) are unknown.

Regardless of the exact water quality criteria chosen, there has been a continuous decrease in cool, well oxygenated water during summer each year since Jocassee pumped storage hydroelectric plant began operating at the end of 1973. We have emphasized the pumping aspect of this project. Undoubtedly, the discharge of water from Jocassee Reservoir when the generator is operating would produce similar temperature profiles at Stations A and X. Since the ratio between pumping and generating on a weekly or longer basis was constant, it is difficult to partition the effects of the 2 processes. Since the summer water temperatures throughout Keowee Reservoir have increased each year, and because water temperatures were higher than those in Jocassee Reservoir, we believe that most of the profile alterations in Jocassee Reservoir were due to pumping. On the basis of our regression equation and 1973 water temperatures, if intake water (Station X) were not heated, September trout habitat would be reduced about 39 percent at the plant's 1976 operating capacity, instead of the 65 percent reduction observed between 1973 and 1976.

Our equation predicts disappearance of trout habitat at present intake water temperatures and at 63 percent of the plant's operating capacity which, based on data provided by the Federal Power Commission (1977), should occur by 1981. Our prediction has 2 weaknesses—only 4 years of data are available and the prediction lies outside the range of observations. From 1973 through 1976, the pumped water was discharged directly into trout habitat and resulted in a steady depression of the upper boundary of trout habitat. The September 1976 upper boundary was about 20-22 m, near the lower level of the discharge structure (20.4 m). Future discharges in August and September with higher temperatures and/or pumping rates than in 1976 will flow into a region above the trout habitat and, because of the density-temperature relationship of water, should remain at the level of the discharge structure or rise. The rate of loss could possibly decrease or become negligible with further increase in pumping over the 1975-76 level.

Meteorological conditions also have an effect on the volume of trout habitat. Winter air temperatures determine baseline water temperatures from which warming in the spring begins. If rate of warming remains constant, there should be more trout habitat in September after a relatively cold winter. However, correlation analysis did not indicate a significant relation between winter air temperature and summer trout habitat (Table 1). Winter air temperatures also control the depth to which a reservoir turns over. A deep overturn assures suitable oxygen in lower depths, and consequently more trout habitat. Fall 1975 was the first time Jocassee Reservoir turned over to a depth greater than 50 m, and considerably more trout habitat was available in deep water throughout 1976.

A number of other pumped storage hydroelectric plants are in various stages of planning and development throughout the southeastern states. All differ in physical characteristics to conform with terrain in which they are or will be located. All, however, will (potentially at least) return water to the upper reservoir warmer than that discharged during generation. Therefore, fishery management agencies must consider the probability that habitat will be altered as a result of pumped storage hydroelectric operations when they plan stocking or other fishery programs.

ADDENDUM

The collection of water quality data in 1977 provided us the opportunity to test our regression model. Our predicted volume of trout habitat for September 1977 was lower than the observed volume because the level of the deep habitat boundary (determined by dissolved oxygen) was deeper than in 1973-76. Our model was developed during years of incomplete reservoir turnover and the deep boundary remained relatively stable during August and September of those years. However, the winter of 1976-77 was exceptionally cold and resulted in the reservoir mixing to depths greater than in earlier years. Consequently, oxygen levels meeting our 5 mg/l criteria during September were about 40 m deeper than measured previously.

We adjusted our model to include minimum winter water temperatures as a second independent variable since the amount of oxygen in the deep waters is determined by the depth of turnover (not monitored) and is related to winter water temperatures. The relation is expressed by the equation: Trout habitat volume = 12.076 - 0.32 PVT - 0.903 minimum winter water temperature ($N = 5$ Prob. > 0.15 $R^2 = 0.85$). This model improves our ability to describe trout habitat with the 1977 data included, but statistically this model is not significant, probably because of the small sample size. We think our first model is reliable for normal South Carolina winters. Data collected in the future will help us test and validate our regressions.

LITERATURE CITED

Axon, J. R. 1971. An evaluation of the trout fishery in Lake Cumberland, Kentucky. Pages 235-242 *in* G. E. Hall, ed. Reservoir Fisheries and Limnology. Am. Fish. Soc., Spec. Publ. No. 8.

____________. 1974. Review of coldwater fish management in tailwaters. Proc. Annual Conf. Southeastern Assoc. Game and Fish Comm. 28:351-355.

Baker, R. F., and W. P. Mathis. 1967. A survey of Bull Shoals Lake, Arkansas, for the possibility of an existing two-story lake situation. Proc. Annual Conf. Southeastern Assoc. Game Fish Comm. 21:360-368.

Brungs, W. A., and B. R. Jones. 1977. Temperature criteria for freshwater fish: protocol and procedures. EPA-600/3-77-061. Office of Research and Development, U.S. Environmental Protection Agency, Ecological Research Series, Duluth, Minnesota. 130 pp.

Coutant, C. C. 1977. Compilation of temperature preference data. J. Fish. Res. Board Can. 34(5):739-745.

Fast, A. W. 1973. Effects of artificial hypolimnion aeration on rainbow trout (*Salmo gairdneri* Richardson) depth distribution. Trans. Am. Fish. Soc. 102(4):715-722.

Federal Power Commission. 1977. Bad Creek Project No. 2740—South Carolina, Final environmental impact statement. U.S. Federal Power Commission, Washington, D. C. 20426.

Kirkland, L., and M. Bowling. 1966. Preliminary observations on the establishment of a reservoir trout fishery. Proc. Annual Conf. Southeastern Assoc. Game Fish Comm. 20:364-374.

Logan, J. 1976. The trout story. S. C. Wildl. 23(4):45-48.

Ruelle, R. W. Lorenzen, and J. Oliver. 1977. Population dynamics of young-of-the-year fish in a reservoir receiving heated effluent. Pages 46-67 *in* W. Van Winkle, ed. Proc. Conf. Assessing Effects of Power-Plant Induced Mortality on Fish Populations, Oak Ridge National Laboratory, Oak Ridge, Tenn. 361 pp.

U.S. Environmental Protection Agency. 1972. Water Quality Criteria 1972: A Report of the Committee on Water Quality Criteria Environmental Studies Board, National Acad. Sciences. U.S. Government Printing Office, Washington, D. C. 594 pp.

Wilkins, P., L. Kirkland, and A. Hulsey. 1967. The management of trout fisheries in reservoir having a self-sustaining warm water fishery. Pages 444-452 *in* Reservoir Fishery Resources Symposium, South. Div. Am. Fish. Soc., Univ. Georgia Press, Athens.