J. Fish Biol. (1985) **27**, 1–12

Threadfin shad, *Dorosoma petenense* Günther, mortality: causes and ecological implications in a South-eastern United States reservoir

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(*Received 18 March 1982, Accepted 3 April 1984*)

Cold stress was identified as an important factor influencing both reservoir-wide mortality and impingement of threadfin shad, *Dorosoma petenense*, during the period October 1976 to April 1977 in Watts Bar Reservoir, Tennessee. Relative numbers and size frequency of impinged threadfin shad were similar to the relative numbers and size frequency of shad preyed upon by sauger, *Stizostedion canadense*, and skipjack herring, *Alosa chrysochloris*. This relationship implies that the factor mainly responsible for impingement, low temperature, also influences prey vulnerability. Threadfin shad made up 99% of the combined diet of sauger and skipjack herring from November until the threadfin shad disappeared in January. These predators did not readily switch to alternative prey in the short term, but by the next autumn 25–100% of the diet was alternative prey. Reappearance of threadfin shad the year following mass mortality and ability of the predators to vary their diet emphasize the resilient nature of some predator–prey systems.

I. INTRODUCTION

Threadfin shad, *Dorosoma petenense*, a fish native to the Gulf Coast from Florida to Guatemala and first found in the mainstream Tennessee impoundments in 1948, has in recent years been stocked in many states including Virginia, Georgia, Pennsylvania, California, Nevada, Arizona, Kansas, New Mexico, Hawaii (Minckley & Krumholz, 1960), and Tennessee. As a result of these introductions and subsequent proliferation, threadfin shad has become an important prey fish, but undergoes massive winter mortality in the northern part of its range. It also comprises 90% by number of all fish impinged at steam electric generating plants in nine south-eastern states in the U.S.A. (Loar *et al.*, 1978). Mortality of these fish may affect not only threadfin shad populations but predator populations as well.

This study sought to (1) identify physical and biological factors that contribute to the mortality and impingement of threadfin shad, (2) define effects of this threadfin shad mortality on threadfin shad population numbers, and (3) demonstrate effects of threadfin shad mortality on two threadfin shad predators.

Watts Bar Reservoir impounds about 13 000 ha of the Tennessee River Valley in middle east Tennessee, U.S.A. (Fig. 1). The upper portion of the reservoir is

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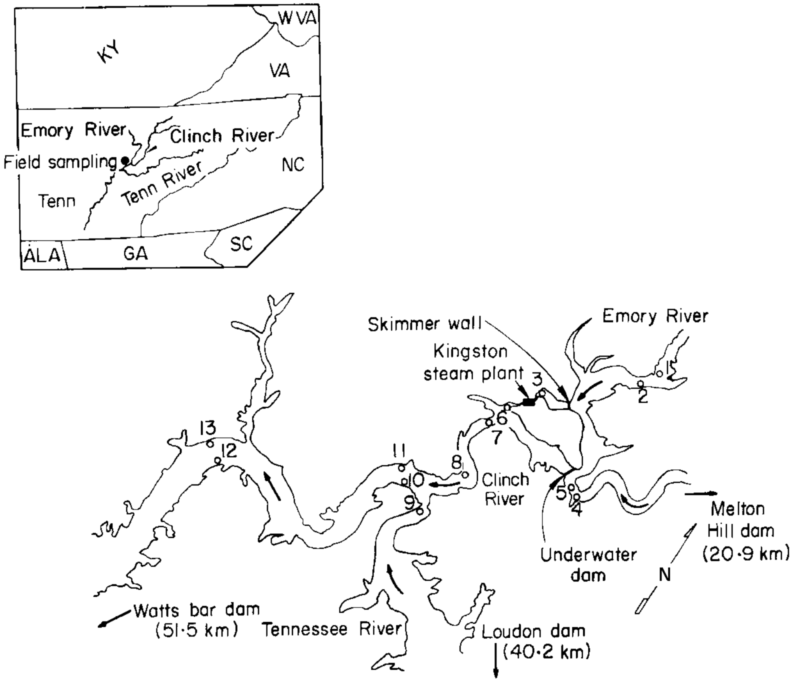

FIG. 1. Location of sampling stations and Kingston Steam Plant on Watts Bar Reservoir.

characterized by riverine reaches of the Emory, Clinch, and upper Tennessee rivers. The Emory flows unimpounded from the Cumberland Plateau, and the water is colder in winter than that of the Clinch and Tennessee which are fed by upstream storage reservoirs at lower elevations than the Plateau and which have large heat storage capacities.

The Tennessee Valley Authority's (TVA) Kingston Steam Plant, located on the Clinch River 48·3 km west of Knoxville, Tennessee (Fig. 1), is a fossil-fuel facility with a generating capacity of 1700 megawatts and cooling water requirements of 65 $m^3 s^{-1}$. Cooling water is withdrawn from either the Clinch or the Emory sources, depending on temperatures and flows and on reservoir levels. If the level of the Clinch and Tennessee is lower than that of the Emory, water from the Emory flows into the intake.

MORTALITY AND IMPINGEMENT

Mortality of threadfin shad in the autumn–winter period occurs as temperatures decrease (Parsons & Kimsey, 1954; Dryer & Benson, 1957). Death of fish in the reservoir coincides with the impingement and death of fish on the intake screens of the power plant. Impingement is believed to be a result of intake design, water temperature, and fish behaviour (Lifton & Storr, 1978; McLean *et al.*, 1982). In the south-eastern U.S.A. impingement of threadfin shad increases when temperatures drop below 10° C (Loar *et al.*, 1978). At 9° C, in the laboratory 9–14-cm threadfin shad acclimated at 15° C and subjected to a temperature drop of 1° C/72 h, show a decrease in feeding activity and school less compactly (Griffith, 1978). At lower temperatures they lose equilibrium, and none survive exposure to 4° C. Griffith & Tomlijanovich (1975) also showed that cold-induced (below 12° C) behavioural changes in threadfin shad result in decreased swimming and schooling abilities. Thus, an increase in impingement rate may also indicate an increase in the vulnerability of threadfin shad to predation. As temperatures continue to decrease below the lower lethal limit of threadfin, a decrease in impingement rate may indicate a decrease in prey availability. The objectives of this portion of the study are to use impingement to help document changes in both prey vulnerability and availability of predators.

PREDATION

In addition to impingement, cold-induced stress on threadfin shad probably causes an increased vulnerability of shad to predation by larger fishes that remain active during December–February when water temperatures decline below 12° C. Cool-water species such as the sauger, *Stizostedion canadense*, and walleye, *Stizostedion vitreum*, which occur near the south-eastern margin of their range in Tennessee, and the wide-ranging skipjack herring, *Alosa chrysochloris*, which occurs from the Gulf coastal states to as far north as Minnesota, may especially benefit from the increased availability of food at this time. In Norris Reservoir, Tennessee, adult sauger consume large quantities of gizzard shad, *Dorosoma cepedianum*, in the winter and have an abundance of visceral fat (Dendy, 1946). Walleye in Norris Reservoir also consume small shad, and their stomachs are generally well-filled in winter (Stroud, 1949). Little is known about the feeding habits of skipjack herring.

Since the introduction and subsequent proliferation of threadfin shad in the south-eastern U.S.A., this species has become a major component of the winter diet of piscivores such as sauger and walleye in Tennessee (Dryer & Benson, 1957; McGee *et al.*, 1977; Minton, 1981). The objectives of this portion of the study were to determine to what extent threadfin are utilized by predators at low temperatures and if the annual recurrence of winter impingement and mortality of threadfin shad reduces available forage.

II. METHODS

Impingement at the Kingston Steam Plant was monitored for three 24-h periods each week from mid-November 1976 to April 1977 and September 1977 to April 1978. Each of the 18 vertical travelling screens that were associated with operational pumps was rotated and washed at 0900 hours on Sunday, Tuesday and Thursday of each week. Twenty-four hours later, screens were rewashed and impinged fish were collected in a catch basket installed in the screen wash-water sluiceway. Fish were separated by species into 25-mm length classes (total length), counted and weighed. If samples were too large to be processed in several hours, a subsample was taken and extrapolated to the total number impinged.

To determine the relative abundance of threadfin shad at stations heated by the power plant discharge (Station 6, 7 and 8) compared with those unheated, bottom-set gillnets were used during the period of October 1976–April 1977 at 13 sites within 15 km of the steam plant (Fig. 1). Gillnets (bar mesh size 13–51 mm in 13 mm increments) were set for 24 h each week in the Clinch and Emory Rivers (Sites, 1, 2, 4, 5) and bi-weekly at the other sites. All data were normalized for a 24-h set of 8-m panel with 13, 25 or 38 mm bar mesh, which is defined as a standard gillnet unit. The Mann–Whitney *U* test was used to examine the difference in catch per unit effort between stations. Ice cover on the reservoir prevented gillnetting at sites 1 and 2 from mid-January through early February 1977 and

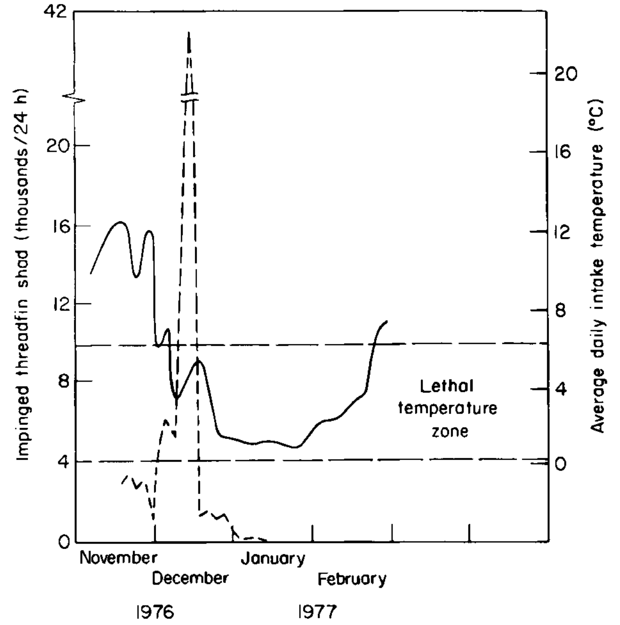

FIG. 2. Impingement rate (– – –) and upper and lower lethal temperatures (lethal temperature zone) of threadfin shad and intake water temperature (——) at the Kingston Steam Plant, Watts Bar Reservoir, Tennessee.

sites 4, 5 and 13 during early to mid-January. Temperature-depth profiles were taken at the time of each set, and continuous recordings of intake and discharge temperatures were obtained from the Hydraulic Data Branch of the Tennessee Valley Authority. Electrofishing was used in late January at sites 1, 2 and 4–7 to aid in determining the presence or absence of threadfin shad.

Predators were collected by gillnets from November 1976 through April 1977 and September through October 1977. Stomach contents were recorded for both sauger and skipjack for the entire period, and visceral fat weight was recorded for sauger collected during March, April, September and October.

III. RESULTS

An estimated 240 000 threadfin shad were impinged at the Kingston Steam Plant during the sampling period 1976–1977, representing 97% by number of fish of all species impinged. Increases in impingement of threadfin shad were strongly associated with the seasonal cooling of reservoir waters. Approximately 3000 individuals per day were impinged throughout the latter half of November (Fig. 2) when intake flows were being pulled from the Clinch River. When water temperatures decreased to 7° C, impingement increased to approximately 5000 threadfin shad per day. Peak daily impingement of approximately 42 000 occurred on 7–8 December when 4° C water from the Emory River displaced warmer Clinch River water at the intake. Fewer than 500 threadfin shad were impinged after 5 January.

The proportion of size classes impinged changed as the temperature decreased. From mid-November–mid-December, size classes smaller than 101 mm dominated (Table I). However, the larger size classes dominated the samples during the

Table I. Bi-weekly number and percentage by size class of threadfin shad, *Dorosoma petenense*, impinged at the Kingston Steam Plant between 14 November 1976 and 22 January 1977

Date	Size class (mm)												Total
	50–76		77–101		102–127		129–152		153–178		179–203		
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.
14–17 November	5518	28·2	12 380	63·4	1453	7·4	100	0·5	59	0·3	26	0·1	19 536
28 January–11 December	17 633	11·4	77 441	50·1	46 759	30·2	7743	5·0	4573	3·0	498	0·3	154 647
2–25 December	1390	3·3	13 374	32·0	17 247	41·3	6793	16·3	2796	6·2	154	0·4	41 754
26 December–8 January	459	13·8	1037	31·3	1279	38·4	336	10·1	206	10·1	12	0·4	3329
9–22 January	0	0·0	6	2·1	46	16·0	173	60·1	53	18·4	10	3·5	288
												Total	219 554

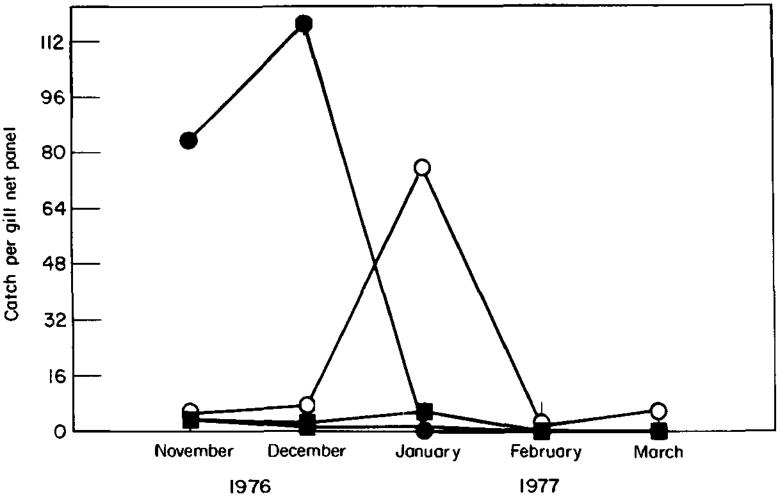

FIG. 3. Relative abundance of threadfin shad during November 1976 through February 1977 at three groups of sampling locations as determined by mean number of fish caught per standard gillnet unit. Intake is Station 3 (●), above plant stations are 1, 2, 4, 5 and below plant stations are 9–13 (■), and thermal stations (those receiving warm water) are 6–8 (○).

remainder of December through late January, after which the number of fish impinged dropped to near zero. Scale analysis indicated that the young-of-the-year threadfin shad ranged from 93 to 112 mm and those of age group I+ from 133 to 159 mm. During the 1977–1978 sampling period 560 000 threadfin shad were impinged comprising 99·5% young-of-the-year. Gillnetting data indicate that by January the distribution of threadfin shad in the reservoir began to change so that shad were found primarily at stations 6, 7 and 8 where the water was heated by the power plant discharge (Fig. 3). Gillnetting data were variable and primarily because of the zeros in the data the standard deviation is about twice the value of each point in Fig. 3 except for three points which are the intake (November = 83·5 ± 58·7, December = 117 ± 195) and thermal stations (March = 5·9 ± 23). During the period 23 December–25 January, when water temperatures of 5 to 7° C were approaching the lower lethal limits of threadfin shad (Griffith, 1978), significantly ($P < 0{\cdot}01$) more shad were caught at stations 6, 7 and 8 than were caught at these stations during the warmer period 29 October–21 December. A steady drop in temperature throughout the reservoir in January resulted in a reservoir-wide die-off of threadfin shad by February. During late January no fish were found by electrofishing and shad were observed dying in coves and making wind-rows of dead fish on the shore. No fish were detected in any areas monitored in February after that kill except for a remnant in the discharge area (Station 3, Fig. 3) that was receiving warm water. This dramatic decline in catch rate, while water temperatures remained below the lower lethal limit of threadfin shad, suggests that the population numbers had also dramatically declined.

Secchi disc readings in the intake indicate low suspended solids in the water during the months of heavy impingement. During December–February, the average reading in the intake was 163 cm compared with normal readings of 20 to 80 cm during summer and early fall. Reduced visibility, therefore, probably did not contribute to impingement.

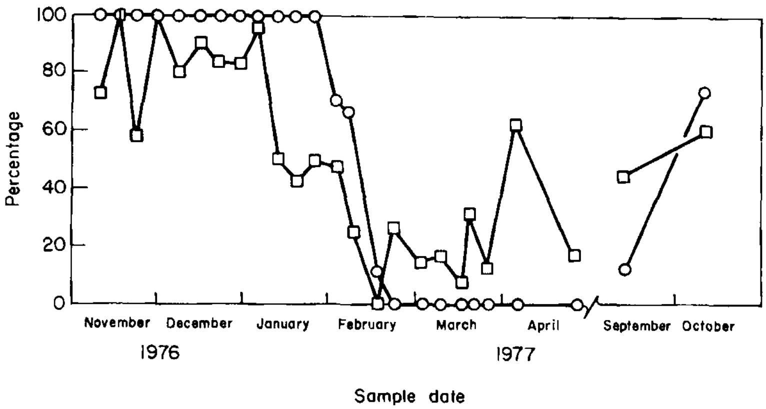

FIG. 4. Percentage of sauger stomachs containing prey (□——□) and percentage of those prey which were threadfin shad (O——O).

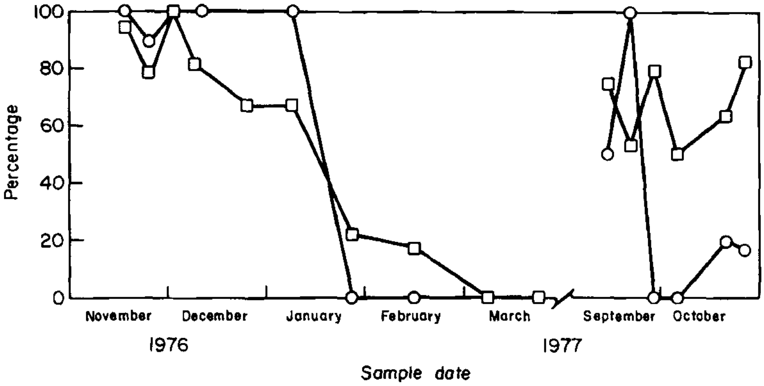

FIG. 5. Percentage of skipjack herring stomachs containing prey (□——□) and percentage of those prey which were threadfin shad (O——O).

STOMACH CONTENT ANALYSIS

Examination of stomach contents of 596 sauger and 259 skipjack herring revealed that food consumption and prey selection were similar during November–January but differed substantially in the remaining part of the sampling period. Food items identified to species made up 51–57% of the diets of sauger and skipjack herring respectively from November to January and threadfin shad made up 100% and 99% of these food items. Less than 25% of the population of either predator had an empty stomach during this period. During January–April, few threadfin were ingested and a high percentage of the predators had an empty stomach (Figs 4 & 5).

A comparison of the percentage occurrence on threadfin shad in sauger (Fig. 4) and skipjack herring stomachs (Fig. 5) and on the intake screens (Fig. 1) demonstrates that both the power plant and predatory fish are ‘preying’ on threadfin shad at the same time. The power plant ‘preyed’ on the same size shad as sauger and skipjack herring (Fig. 6), suggesting that low temperature made the threadfin shad susceptible both to impingement and to fish predation. The decline in sauger predation on threadfin shad lagged several weeks behind the decline in impingement rate, indicating shad were still available to the sauger in other areas of the reservoir which contained warmer water than the intake canal.

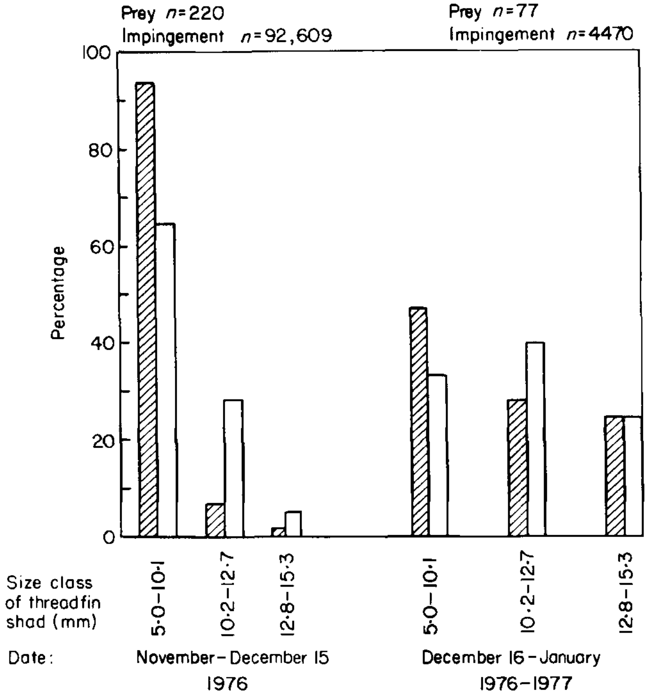

FIG. 6. Comparison of size classes of threadfin shad eaten by sauger and skipjack herring (▨) with those impinged (☐) at the Kingston Steam Plant, Watts Bar Reservoir (Tennessee).

During February, the percentage occurrence of threadfin shad in sauger stomachs progressively decreased, and the frequency of empty stomachs and the percent of alternative prey showed an increase (Fig. 4). During February and March, freshwater drum, *Aplodinotus grunniens*, log perch, *Percina caprodes*, bluegill, *Lepomis machrochirus*, and mayfly, *Hexagenia* sp., nymphs were found in sauger stomachs (McGee *et al.*, 1977), but skipjack herring did not switch to alternative prey except for one case of cannibalism. During these 2 months, 85% of the sauger and 94% of the skipjack herring stomachs were empty.

Sauger and skipjack herring captured in September and October 1977 were preying heavily on alternative prey although threadfin shad were a major part of the diet of skipjack herring in September (Fig. 5) and of sauger in October (Fig. 4). The alternative prey of both predators was primarily gizzard shad. Nine percent of the food items of sauger in October was a mixture of freshwater drum, centrarchids, and skipjack herring while 16% of the skipjack herring diet that month was young-of-the-year herring.

As the threadfin shad population declined, the two main size classes of sauger were affected differently. When the water temperature dropped below 7° C the larger sauger switched from 50–101 mm prey to larger prey, but the smaller sauger continued to only utilize the smaller prey (Fig. 7).

IV. DISCUSSION

THREADFIN SHAD MORTALITY AND IMPINGEMENT

The winter of 1976–77 was severe in East Tennessee. January, the coldest month of the year, was 49% colder than the 30-year average from 1941–1970

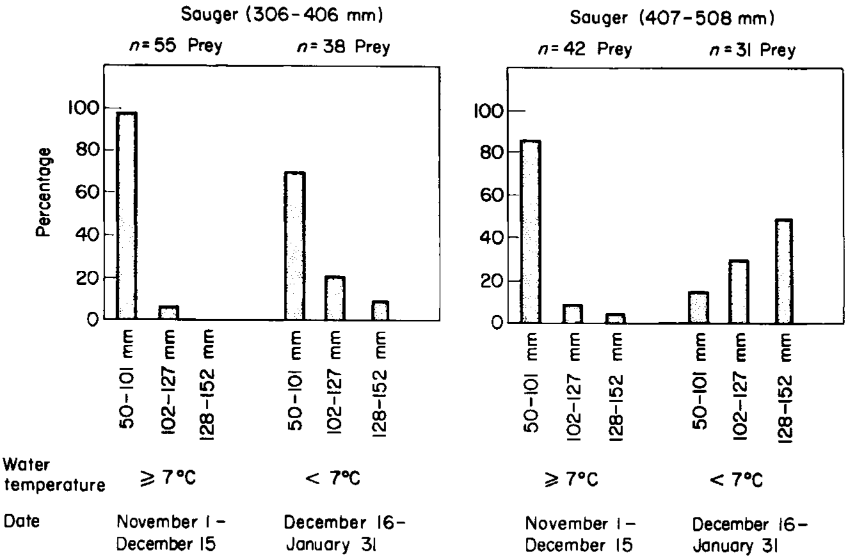

FIG. 7. Percentage occurrence by size class of threadfin shad, *Dorosoma petenense*, in stomachs of two size classes of sauger, *Stizostedion canadense*, in Watts Bar Reservoir (Tennessee).

(Atmospheric Transport and Diffusion Laboratory, Oak Ridge, pers. comm.). Low water temperatures were responsible for threadfin shad mortality. Mass mortality of shad in late December and January was evidenced by large numbers of fish on the shoreline, large decreases in the numbers caught in the gillnets, and large numbers on the intake screens of the power plant. This is thought to result from the effects of declining temperature on swimming and schooling ability.

Impingement of 240 000 threadfin shad at the Kingston Steam Plant was associated with low ambient temperatures, and fish behaviour. The general decline in water temperature in the reservoir November–January was a seasonal phenomenon due to cold air temperatures. However, in the intake canal of the power plant, the sudden temperature shock on 7–8 December was caused by a shift in intake water source from the Clinch to the Emory River.

Some threadfin shad may have survived to reproduce despite the cold water. Griffith (1978) showed that 9- to 14-cm threadfin shad acclimated at 8–12° C, subjected to $1°\,C\,h^{-1}$ decrease in water temperature until equilibrium was lost at about 3·5° C for 12, 30 and 90 min before being returned to warmer waters, experienced mortalities of 32, 79 and 94%, respectively. He also concluded that the final low temperature to which the fish were exposed, not the magnitude of the drop of temperature, was responsible for the deaths. Thus, some of the threadfin shad not in the intake canal may have been able to survive the rapid drop of temperature in the Clinch and Tennessee rivers if thermal refuges 3 to 4° C warmer than ambient were available. We found that refuges were available in the form of the power plant discharge and in a backwater cove near Station 11 (Fig. 1) where ground-water seepage was 9° C when ambient water was 5 to 6° C. Threadfin shad were found both in the discharge (Station 3, Fig. 3) and in the cove after fish had disappeared from most of the areas monitored that had no warm water input. The fact that threadfin shad did survive and reproduced somewhere in Watts Bar Reservoir or migrated in from an adjacent reservoir is evident by impingement counts the following year in which about 560 000 young-of-the-year threadfin shad were impinged. Migration assumes that adjacent reservoirs contain warmer water than Watts Bar and passage between reservoirs is possible. This assumption may not be valid since air temperatures are generally colder upstream (northeast) of Watts Bar and passage into Watts Bar from downstream reservoirs would have to be via the lock system. It is not known if threadfin shad frequent the locks, especially if the population numbers in the downstream reservoirs are also depleted.

PREDATOR RESPONSE

The importance of threadfin shad as prey is obvious when the feeding habits of the predators are examined. Stomach content analysis of sauger and skipjack herring showed that threadfin shad were the most important single food item during the study period. Most theadfin shad were consumed in November and December at a time when the shad were abundant and cold-stressed. Food consumption was reduced in late winter and spring after natural mass mortality of threadfin shad occurred. Sauger at this time switched to several alternative prey species but both predators had a high percentage of empty stomachs. Predators under 30 cm were perhaps most limited in food consumption because they consumed only the smallest prey. The maximum size of prey that was utilized by sauger and skipjack herring was 35% (McGee *et al.*, 1977) and 30%, respectively, of the predator's body length. When the water temperature dropped below 7° C, impingement counts indicated that large prey became cold-stressed and small prey became unavailable. Large sauger switched to larger prey (Fig. 7) while small sauger and small skipjack herring may have had a limited food supply.

Sauger depend on the increased vulnerability of prey due to cold stress in the winter months. Minton (1981) has shown that sauger store an excess of energy during only two periods of the year: the spawning period of threadfin and gizzard shad in June and the late fall–early winter period when shad are cold-stressed. During the summer, sauger may be spatially isolated from shad due to the ability of shad to withstand warmer temperatures, thus reducing energy intake. Walleye in Hoover Reservoir experienced decreased growth rates because of similar restraints (Momet *et al.*, 1977).

In contrast to sauger, skipjack herring do not appear to be limited by warm water since their range extends south to the Gulf of Mexico in the Mississippi River drainage system (Pflieger, 1975). These fish probably prey on shad during summer as well as winter and may not be as dependent on storing large amounts of energy in the fall–winter period as do sauger. Both skipjack herring and sauger, however, must have adequate energy for spawning in the spring. Sauger use almost four times more energy during the reproductive period than during the summer (Minton & McLean, 1982). Visceral fat storage by sauger probably supplies this needed energy. Skipjack herring probably store energy in the form of lipids; however, measurements of the timing and amount of energy storage have not been made.

In response to the loss of the principal forage, by January both predators eventually switched to alternative prey (Figs 4 & 5). Sauger, after a 1-month lag, began to eat freshwater drum and log perch. Although alternative prey was not evident in skipjack stomachs during the winter, the following fall over 50% of their prey were gizzard shad. Prey switching appears to be one mechanism predators use to survive in systems with a dynamic forage structure.

In conclusion, this study has shown that threadfin shad mortality and impingement increase at low temperature coincident with increased predation pressure from sauger and skipjack herring. However, adverse ecological effects are primarily short-term. During a severe winter, death occurs to all size classes and the majority of the population is probably killed, greatly reducing forage immediately available to sauger and skipjack herring. Small individuals of the predator population appear to experience loss of forage earlier in the year than larger individuals. In the long term, threadfin shad may be able to rebuild their population and predators compensate for loss of their principal prey by switching to alternative prey.

The authors thank J. W. Gooch and L. M. Stubbs for their effort in the field work and S. M. Adams, C. C. Coutant and W. Van Winkle for many helpful comments on the manuscript.

Research sponsored by the Office of Nuclear Regulatory Research, United States Nuclear Regulatory Commission, under Interagency Agreement DOE 40-550-75 with the United States Department of Energy under contract W-7405-eng-26 with Union Carbide Corporation.

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