# Experimental growth of four native Colorado River fishes at temperatures of 12, 18, and 24°C

*DRAFT FINAL REPORT*

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**Abstract**

Growth of four fish species native to the Colorado River drainage was examined at three temperatures, 12, 18, and 24°C. Species studied were humpback chub (*Gila cypha*), bonytail chub (*Gila elegans*), bluehead sucker (*Catostomus discobolus discobolus*) and razorback sucker (*Xyrauchen texanus*). These temperatures were selected to reflect a range of conditions found in the Colorado River and tributaries in Grand Canyon: 12 °C represents conditions in chronically cold tailwaters below Glen Canyon Dam, 18°C represents temperature likely to be achieved with proposed summer epilimnetic releases from Glen Canyon dam, and 24°C represents the summer temperature regime of the Little Colorado River. Growth (total length, weight) for groups of small, young-of-year fish were monitored at monthly intervals over a period of 238 days. Growth rates increased significantly with increased temperature. Humpback chub, bonytail chub, and razorback sucker exhibited little or no growth at 12°C while bluehead sucker showed some growth. All species exhibited substantial growth at warmer temperatures with the greatest growth occurring at the warmest 24°C treatment. All species were relatively lethargic at the 12°C treatment, spending most time hiding or resting on the bottom. All species showed increased activity (schooling and swimming in the water column) with increasing temperature. The lack of growth and reduced activity in fish at 12°C suggests that such cold temperatures contribute to increased mortality and reduced survivorship in small native fishes inhabiting the cold Colorado River mainstem in Grand Canyon. Our results suggest that temperatures in the mainstem need to reach at least 18°C for at least 60 days to realize significant growth in YOY humpback chub that disperse at a size of 65 mm TL from the Little Colorado River during late summer spates.

## Introduction

The construction of massive mainstem dams on the Colorado River has greatly altered the aquatic environment in this large southwestern river. The construction of dams has drastically altered water temperatures and natural hydrological patterns (Vanicek *et al.*, 1970; Holden and Stalnaker, 1975; Molles, 1980). Native fishes of the Colorado River are adapted to the seasonally fluctuating, warm, turbid, pre-impoundment conditions (Smith *et al.*, 1979). The clear, cold, seasonally stable but daily fluctuating flows resulting from hypolimnetic dam releases have had a negative impact on the status of endemic Colorado River fishes (Molles, 1980), and four species are now listed as endangered by the U.S. Fish and Wildlife Service: humpback chub (*Gila cypha*), bonytail chub (*Gila elegans*), razorback sucker (*Xyrauchen texanus*), and Colorado pikeminnow (*Ptychocheilus lucius*) (USFWS 1990). Current temperatures in the Colorado River below mainstem dams (8-12°C) are too low for embryonic development and hatching of these species (Hamman, 1982; Marsh, 1985). However, humpback chub and other native fishes successfully spawn in warm tributaries of the Colorado River in Grand Canyon (Allan 1993; Gorman 1994; Gorman and Stone 1999; Valdez and Ryel 1995, Otis 1994, Weis 1993) and many small young-of-year (YOY) fishes enter mainstem environments where recruitment is low (Valdez and Ryel 1995). In the Colorado River in Grand Canyon, Valdez and Ryel (1995) estimate that only 0.1% of juvenile humpback chub >150 mm TL reach adult size of 200 mm TL. In an experimental study of growth in YOY fish <50mm TL, Lupher and Clarkson (1994) found growth of humpback chub and Colorado pikeminnow was very small at 10°C. The introduction and proliferation of coldwater nonnative species into the Colorado River, particularly rainbow (*Onchorynchus mykiss*) and brown trout (*Salmo trutta*), is thought to have a detrimental effect on native species survival (Holden and Stalnaker, 1975; Molles,1980; Marsh and Douglas 1997).

Our objective was to investigate growth in YOY native fishes >50 mm TL of the Colorado River under a range of temperatures representative of conditions in tailwaters (12°C), in tailwaters with thermal warming from mixed epi- and hypolimnetic releases (18° C) and in warm tributaries that support successful reproduction and growth (24°C). Subject species included humpback chub, bonytail chub, bluehead sucker, and razorback sucker. Our study was intended to define the growth performance envelope for these species under idealized experimental conditions and compare our results with growth rates observed in natural populations. The results of our study should be invaluable in developing plans for temperature augmentation intended to increase growth and recruitment of YOY native fishes in tailwaters of mainstem dams.

## Methods

Growth experiments were conducted at a laboratory facility located at the Willow Beach National Fish Hatchery in Willow Beach, Arizona. Species studied were humpback chub (*Gila cypha*), bonytail chub (*Gila elegans*), bluehead sucker (*Catostomus discobolus),* and razorback sucker (*Xyrauchen texanus*). YOY humpback chub and bluehead sucker were collected in the Little Colorado River in the vicinity of Grand Canyon during late July 1998 and transported to the hatchery via helicopter. YOY razorback sucker were produced from Lake Mohave wildstock propagation at the hatchery in March 1998. YOY bonytail chub were produced in 1998 from captive broodstock maintained at Dexter National Fish Hatchery and shipped to the Willow Beach hatchery. From August to December 1998 all fish were segregated by species and maintained in a 40 *l* aquaria at densities of <25/tank. Water temperatures were allowed to freely fluctuate between 14 and 18°C. The growth experiment was initiated in early January 1999 for humpback chub, bonytail chub, and razorback sucker. Bluehead sucker were added to the experiment in March 1999. The experiment ended on 3 September 1999. Capture, transport, handling, rearing, disease prevention and control followed protocols established by a U.S. Fish and Wildlife Service advisory committee (Gorman 1998).

Experiments were conducted in a new laboratory facility constructed at the Willow Beach National Fish Hatchery. Each of the three temperature treatments consisted of a pod of 4 rearing tanks (circular fiberglass, 1.5m diameter, 1000 *l* capacity) and a common reservoir (2000 *l* capacity) using a recirculating system with a biological bead filter. Additional circulation/aeration was provided with airstones in each tank and reservoir. The large capacity of each pod (6000 *l*) facilitated maintenance of temperature, water quality, filtration, and administration of chemicals and drugs for disease prevention and control. Overhead flourescent lighting was set on a timer to provide a 12 h photoperiod. Temperature was regulated with electrical chillers and heaters installed in the common reservoir for each treatment pod. Minimal flow-through (~2 *l*/min)of treated lake water maintained water levels in the system for proper operation. All water used in the experimental treatments was taken from Lake Mohave, purified by passing through a Hayward sand filter and sterilized by a bank of UV light filters.

Temperature and dissolved oxygen levels were monitored for each treatment pod twice daily using a hand-held YSI model 85 dissolved oxygen meter. Nearly continuous temperature records for each treatment were obtained by using submersible Onset programmable temperature probes placed in each treatment reservoir. Total ammonia nitrogen, nitrites, pH, and total dissolved gas were measured twice weekly. Total ammonia and nitrite was measured with a Hach DR 2000 spectrophotometer, pH was measured with a PinPoint pH pen, and total dissolved gas was measured with a Weiss saturometer.

Fish were fed to saturation three times daily, morning, midday and early evening. Fish in each treatment were fed at a rate of 12% of their body weight daily, using a common diet of flaked krill, commercially prepared pelletized feed (Silvercup #2) and thawed frozen brine shrimp. All tanks were siphoned once daily to remove excess feed and waste using a ½" siphon tube.

Fish were observed at least twice daily to record general behavior/activity, feeding behavior, and anomalus behavior (e.g., rubbing, flashing, disorientation) as early indicators of disease or parasites. Behavioral observations were recorded in the following categories: general behavior (activity and position, e.g., hiding, resting on bottom, or swimming in water column ), feeding behavior (eating or ignored food), and health indicators/behaviors. For each tank and species general behavior/activity was scored on a scale of 1 to 7 to reflect a range of activity from hiding or resting on the bottom (1-2) to active swimming or schooling in the water column (6-8). Description of behaviors and activities and assigned scores are provided in Table 5.

Prior to the start of the experiment, the experimental treatment pods were operated for eight weeks to test the stability of temperature control and flow and filtration systems. On 8 January 1999 fish were distributed randomly among the 12, 18, 24° C temperature treatments as follows: 24 humpback chub were placed into each of two tanks for each treatment (144 total humpback chub); 24 bonytail chub were placed into one tank for each treatment (72 total bonytail chub); 24 razorback sucker were placed into one tank for each treatment (72 total razorback suckers). On 8 March 8 bluehead suckers were added to each treatment tank containing 24 razorback suckers (24 total bluehead suckers). Over the course of the study, 4 humpback chub, 14 bonytail chub, and 7 razorback suckers and 1 bluehead sucker suffered mortality; all losses were accounted for.

Growth was monitored by determining weight (to nearest 0.1 g) and total length (to nearest mm) for each fish on a monthly schedule. Growth measurements were taken in 9 times over the course of the 238-day experiment in 1999: 8 January (start), 8 February, 8 March, 8 April, 8 May, 3 June, 9 July, 10 August, and 3 September (end). Handling of fish for measurements followed established protocols (Gorman 1998). Fish were captured with nets and held in 19-*l* buckets. To reduce stress related to measurements, fish were fasted for 12 h prior to measurement and anesthetized with MS-222. Recovery was closely monitored and fish were released back into their experimental tanks. Following completion of measurements, each experimental pod was treated with 0.5% salt to prevent stress-related disease problems. Routine weekly treatments with 20 ppm formalin and 0.4 ppm malachite green were administered to prevent or eliminate disease.

To monitor overall growth response to temperature, means and variances for length, weight and condition factor were calculated for each species/treatment/measurement date. Differences between temperature treatments for each species and measurement was evaluated by ANOVA with Fisher's Least Significant Difference post hoc test. The experiment generally conformed to repeated measures design, using individual fish as experimental units within each temperature treatment. Thus, cumulative differences between monthly values for length and weight were evaluated with Repeated Measures ANOVA. The repeated measures model examines changes in the variables of interest (total length and weight) as effected by the treatment (temperature) and time (repeated measurements) and also determines interaction of time and treatment effect on the variables of interest. Assumption of the repeated measures model is re-measurement of the same experimental units. To accomplish this, unique identification by tagging or marking is required. In our study tagging of individual fish was not possible because of potential physical harm to small fish. To avoid gross violation of the repeated measures model, we attempted to match up individuals between months based on similarity of ranking by length and weight data. Ranking was accomplished by sorting data for a specific date, treatment, tank, and species by length and weight in ascending order. Error introduced by this approach will slightly reduce the variance within a date/treatment/tank/species. The entire data record for fish that suffer mortality in the course of the experiment are eliminated from the analysis. Regression models describing growth for each species and each temperature treatment were generated using length data. To assess the relative plumpness of fish between treatments and over time, condition factor for each fish was calculated using the formula $K=W/L^3x10^6$ where K represents Fulton's condition factor, W is fish weight (in grams), and L is fish length (in millimeters). Analysis of behavior for each fish species and treatment was performed using a Wilcoxon rank sum test with mean activity scores. Statistical analyses were conducted with Systat Version 8.0 software.

## Results

Over the course of 238 days, humpback chub, bonytail chub, and razorback sucker showed substantial growth in the 18 and 24°C treatments (Table1, Figs. 1-6). Compared to 12°C treatment, these species were significantly larger in both length and weight in the 24°C treatment after 90 days (4$^{th}$ measurement). Unlike the other species, bluehead sucker showed substantial growth in the 12°C treatment after 90 days. Increased temperature had a significant effect on growth rate relative to no growth (Table 2). In all species, grow rate increased with increased temperature.

By the end of the study, humpback chub showed an increase in length and weight, respectively, of 79.3% and 458.2% at 24°C compared to 39.6 and 189.3% at 18°C, and 10.6 and 43.3% at

12°C. Bonytail chub showed an increase in length and weight, respectively, of 66.2 and 334.6% at 24°C, compared to 25.6 and 93.0% at 18°C, and 8.4 and 50.3% at 12°C. Length and weight gains, respectively, for razorback sucker were an astounding 220.3 and 3125.4% in the 24°C treatment, compared to 95.3 and 502.2% at 18°C, and 22.4 and 114.5% at 12°C. Bluehead suckers showed a length and weight gain of 90.5 and 642.2%, respectively, at 24°C compared to 66.2 and 405.8% at 18°C and 43.1 and 209.1% at 12°C. All differences in growth between 12 and 24°C treatments were significant for all species (Table 1).

Temperatures in the 12°C treatment pod crept 2-3° above 12° in June 1999 because the chilling units were unable to maintain water temperatures when ambient air temperatures exceeded 35°C (Table 4, Figure 7). Concurrent with this temperature increase was increased growth for all species over the summer months in the 12°C treatment pod. To eliminate the effect of elevated summer temperatures in the 12°C pod, regression models for growth in the 12°C treatment included only data from measurements 1-6. Prior to June all species except for bluehead sucker showed slight or no growth in the 12°C pod but measurable growth afterwards (Table 2). Growth in the 12°C treatment from January through 3 June ($1^{st}$ -$6^{th}$ measurements, 146 days) were as follows: humpback chub showed a change in length and weight respectively of 1.0 and -0.3%, bonytail showed a change of -0.7 and 12.0%, razorback sucker showed a change of 8.2 and 31.3%. In comparison, change in length and weight in bluehead sucker from March-May (3rd-6th measurements, 88 days) was a substantial 16.7 and 88.5%, respectively.

Condition factor (plumpness) varied by species and temperature treatment over the course of the experiment but no consistent pattern was evident (Table 3). Overall, bluehead suckers in cold water were more plump than at warmer temperatures and humpback chub were only slightly more plump in cold water. However, bonytail chub and razorback suckers were slightly more plump at warmer temperatures.

Analysis of behavioral and activity level for humpback chub, bonytail chub, and razorback sucker showed significant differences among species and temperatures (Table 5). Humpback chub were relatively active, and spent more time swimming and schooling in the water column and activity level increased substantially with temperature. Bonytail chub spent most of their time hiding or staying near the bottom in all temperature treatments. Razorback sucker spent most of their time resting on the bottom at 12°C but were relatively active at 24°C where they spent most of their time swimming and schooling in the water column. Overall, fish were relatively inactive at 12°C spending most time resting, hiding, or swimming near the bottom of the tank. At 24°C, fish were relatively active, spending most time swimming and schooling in the water column.

## Discussion

Although the four species used in our experiment are native to the Colorado River, they showed substantial differences in their growth response to temperature. All species except for bluehead sucker showed none or relatively little growth at 12°C. Differences in activity level and growth response to temperature among the species suggest profound differences in their biology. Humpback chub and bonytail chub are judged to be very similar species, possibly sharing a common ancestry (Smith *etal.* 1979). In our experiments the two species were always readily discriminated by body color, relative eye size, body shape, and behavior. Bonytail chub were relatively skittish, and spent most of their time hiding or hovering near the bottom of the tank. Compared to humpback chub, bonytails were pearl-white in body color, showed well-defined lateral scales, had relatively shallow body depth, and moderate-sized eyes. Humpback chub displayed significantly more active behavior. They were inquisitive and spent most of their time swimming and schooling in the water column. Humpbacks had silvery sides with green dorsums, scales were not well defined, had moderate body depth, and relatively small eyes. Both species showed little growth at 12°C and rapid growth at 24°C. Growth at 18°C in both species was intermediate, though slightly higher in humpback chub.

Razorback sucker and bluehead sucker are not closely related species and showed sharp differences in response to temperature. The fastest growing species, razorback sucker, more than tripled in length and showed more than 30x increase in weight in the 24°C treatment. Substantial growth of bluehead sucker at 12°C contrasted with the other species. Like the minnows, activity level of razorback sucker increased with temperature and they were as active as humpback chub in the warmer water. Growth at 18°C was intermediate in razorback sucker, but in bluehead sucker was similar to that at 24°C. These findings suggest that YOY razorback sucker, humpback chub, and bonytail chub are adapted to warm (~24°C) temperatures under which they show rapid growth. YOY bluehead sucker, however, can grow rapidly at somewhat cooler (12-18°C) temperatures.

The lack of measurable growth in humpback chub, bonytail chub and razorback sucker in the 12°C treatment pod before temperatures in this pod increased in the summer months suggests that 12°C represents a lower physiological limit for growth in these warm-water adapted species. Slight but detectable growth observed when temperatures increased 2-3° above 12°C suggests that 14-15°C is the threshold temperature for growth in these species. The moderate growth rate in bluehead sucker at 12°C suggests that the threshold temperature for growth in this species is below 12°C.

Comparison of growth of humpback chub under experimental conditions with Grand Canyon field data should provide a coarse test of the applicability of experimental data to natural situations. Several factors affecting growth rates in the natural and experimental settings need to be considered. Growth in the experimental setting is idealized: survivorship is nearly 100% and food is not limiting. In the natural setting, the increase in the mean TL of the cohort is caused by size-dependent survivorship and real growth and assumes no emigration. Typically, the larger members of the cohort have disproportionate survivorship, which inflates the apparent increase in size of the surviving cohort. Estimations of growth in the Colorado mainstem may be compounded by emigration of YOY fish from the Little Colorado River. In the natural setting diet and food abundance may be quite different from the experimental setting. Finally, fish in the experimental setting are maintained in a disease and parasite free environment. While it may be difficult to resolve the relative effects of these different factors on growth in natural and experimental settings, growth values from the idealized experimental setting that are similar to values from natural settings suggest that temperature is the prime growth factor and growth observed in the experimental setting defines a growth performance envelope for the species.

In the Little Colorado River, the location of the largest reproducing population of humpback chub, temperatures typically exceed 20°C for at least 7 months per year (Gorman and Stone 1999). Analysis of the 1993 cohort from field studies conducted in the relatively warm Little Colorado River (Gorman 1994a, b) showed that humpback chub reached a modal size of ~32 mm TL by 12 June and ~52 mm TL by 16 July. Assuming a 7 mm TL hatch size (Muth 1990) and back extrapolating the observed 0.5 mm/day growth rate, the estimated hatch date is 23 April, a prediction consistent with spawning periods of humpback chub in the Little Colorado River (Robinson et al. 1996; Gorman and Stone 1999). By 14 August the modal size was 62 mm and by 18 September modal size was ~72 mm, representing a 0.28 mm/day growth rate for the previous 65 days. By April 1994 at one year of age, this cohort reached a modal size of ~90 mm TL, which represents an overwinter growth rate of 0.15 mm/day and an overall first-year growth rate of 0.23 mm /day. During the first summer of life, the rate of increase in TL declined with increasing size while temperatures remained near 24°C and declined over winter when temperatures dropped to the 12-20°C range. Similar patterns and growth rates were observed for the 1994 cohort of humpback chub (Gorman 1994a,b; Stone 1999). Other species showed similar patterns; calculated growth rates for 1993 cohort of bluehead sucker were nearly identical but higher for flannelmouth sucker. The June-July growth rate in flannelmouth sucker was estimated to be 0.8 mm/day and dropped to 0.5mm/day for July-September. By September YOY flannelmouth suckers were ~102 mm TL. These findings and inspection of length-frequency histograms of the 1993 and 1994 cohorts indicate YOY humpback chub grow during winter months and suggest that fish smaller than ~75 mm TL have lower overwinter survivorship in the Little Colorado River (Stone 1999). To achieve a size of 75 mm TL by October, an average growth rate of 0.38mm/day must be sustained for 180 days post hatch. A minimum size of 75 mm TL fits well with observations that prey species need to exceed 1/3 the length of the modal size of the most common predator, which is 200-250 mm TL humpback chub in the Little

Colorado River (Stone 1999). Overall, these findings suggest that our idealized 18° and 24°C experimental growth rates (0.14 and 0.28 mm/day, respectively) may provide acceptable benchmarks for growth in humpback chub >70 mm TL.

Experimental growth at 12°C for humpback chub and bonytail chub was essentially zero and very low for razorback sucker. Experimental growth at 18°C for humpback chub, bonytail chub and razorback sucker were intermediate between 12 and 24°C. Assuming a gross 18°C growth rate and an initial hatch size of 7 mm TL, humpback chub at 180 days (October) would be ~33 mm TL. This is much smaller than the size of spring yearlings in the Little Colorado River, suggesting that this growth rate is too low to ensure sufficient over-winter survivorship. It would take 593 days of constant growth at 18°C for these fish to reach 90 mm TL, the modal size of spring yearlings in the Little Colorado River.

In an experimental growth study of Colorado River fishes smaller than those studied by us, Lupher and Clarkson (1994) found that growth at cold temperatures (10°C) to be very small in humpback chub <50 mm TL (0.077 mm/day) and significantly elevated (0.35 mm/day) at warmer temperatures (20°C). Valdez and Ryel (1995) reported grow rates of 0.08-0.10 mm TL/day for juvenile humpback chub from the mainstem Colorado River and 0.34 mm TL/day for juveniles in the Little Colorado River. Data on survivorship of YOY humpback chub in the mainstem Colorado River from Gorman and Bramblett (1999) are scant but suggest that growth is not detectable and survivorship is low.

Our findings on growth of native fishes under experimental conditions may help in the formulation of management strategies to recover humpback chub in the mainstem Colorado River. Clearly, temperatures less than 12°C will not permit adequate growth of YOY fish nor allow successful spawning to take place. Also, small fish at this temperature are relatively inactive and may be unable to track changing habitat conditions under daily fluctuating river discharge. Small size, reduced activity, disorientation, and failure to seek adequate cover also makes small fish more susceptible to predation by trout. If we assume that YOY humpback chub disperse at a size of 65 mm TL from the Little Colorado River during late summer flood events into the mainstem Colorado River where temperatures have been elevated to 18°C, these small fish may be able to reach minimum pre-winter size. Assuming temperature, food supply, and adequate habitat and cover are available for at least 60 days, these fish might reach ~75 mm TL before winter. However, this size may be too small to avoid excessive over-winter loss to predation in the mainstem Colorado River where large rainbow trout are abundant (Gorman and Bramblett 1999). Thus, survivorship of small prey species in the mainstem may require a larger over-winter size than 75 mm TL.

Warm tributary confluences may offer oases of suitable habitat for growth of YOY humpback chub and other native fishes in the mainstem Colorado River corridor. Here temperatures are elevated and food resources more abundant relative to the mainstem, and YOY fish may be able to achieve minimum size before their first winter. However, daily fluctuating mainstem flows disrupt habitats of confluences and juxtaposition to the mainstem provides easy access for abundant predatory fish. Finally, the total area of confluences in the mainstem is relatively minuscule and would not be able to contribute significantly to native fish recovery without major improvement in mainstem habitat and reductions in predator abundance.

Our experimental study on growth in native fishes of the Colorado River raised additional questions that may warrant further study:

1. Conduct a growth experiment that starts with 50 mm TL or smaller fish. Because of delays in completion of the laboratory facility, our fish were ~75 mm TL at the start of our growth experiment. Our intention was to start with fish at ~50 mm TL which is where previous studies (Lupher and Clarkson 1994) left off.

2. Assess compensatory growth in fish moved from cold to warm temperatures. This experiment mimics conditions where fish in cold water move into warm tributaries or are exposed to warmer mainstem flows. The experiment addresses the question of how fast do fish assume a warm

temperature growth trajectory.

3. Conduct a growth study with fish held at a steady 12°C for 8 months. Because of a failure in our cooling system we were not able to achieve this in our growth experiment. Changes in our laboratory now permit maintaining steady temperatures over hot summer months.

4. Experimental growth studies could be conducted with larger fish, i.e., 120-150 mm TL. This could be achieved by continuing our growth experiment an additional 6 months.

5. Determine time and temperature required for native fish to reach sexual maturity. This question can be addressed by a 6 month extension mentioned previously.

6. Determine growth rates at other temperatures. 10°C is more typical of mainstem Colorado River temperatures and 28°C may approach the upper limit of the growth performance envelope.

7. Conduct a study of food consumption to determine the caloric intake required to maximize growth rates at different temperatures. This experiment is intended to demonstrate the need for sufficient food resources to achieve fast growth; temperature increases without increased food resources may not realize increased growth in natural populations.

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**Table 1.** Mean lengths and weights by species for humpback chub, bonytail chub, razorback sucker and bluehead sucker in 12, 18, and 24°C temperature treatments. Intervals represent initial and monthly measurements of length and weight. Significant effect (P<0.05) of temperature, time, and time x temperature for Repeated Measures ANOVA is denoted with a "*". Lines connecting treatment means indicates non-significant differences for Fisher's LSD post hoc ANOVA test. Bluehead suckers were added to the study at measurement interval 3, 59 days after the start of the experiment.

HUMPBACK CHUB

| interval | 12°C length / *weight* | | 18°C length / *weight* | | 24°C length / *weight* |
|---|---|---|---|---|---|
| 1 | 77.0 | ------------------------------ | 76.4 | ---------------------------- | 78.2 |
| | *3.7* | ------------------------------- | *3.5* | ------------------------------- | *3.9* |
| 2 | 76.6 | ------------------------------ | 75.9 | ________________________ | 80.1 |
| | *3.8* | ------------------------------- | *3.6* | ------------------------------- | *4.0* |
| 3* | 77.5 | ------------------------------ | 79.1 | | 93.5 |
| | *3.7* | ------------------------------- | *4.1* | | *6.6* |
| 4* | 76.7 | ------------------------------ | 80.7 | | 104.5 |
| | *3.7* | ------------------------------- | *4.1* | | *8.9* |
| 5* | 77.2 | | 85.0 | | 116.9 |
| | *3.6* | | *4.7* | | *12.3* |
| 6* | 77.8 | | 90.7 | | 123.8 |
| | *3.6* | | *5.7* | | *14.4* |
| 7* | 80.7 | | 98.6 | | 130.5 |
| | *3.8* | | *7.2* | | *17.0* |
| 8* | 81.5 | | 102.4 | | 134.1 |
| | *4.6* | | *8.4* | | *18.7* |
| 9* | 85.2 | | 106.7 | | 140.2 |
| | *5.3* | | *10.1* | | *21.7* |

**Table 1.** (continued)

BONYTAIL CHUB

| interval | 12°C length *weight* | 18°C length *weight* | 24°C length *weight* |
|---|---|---|---|
| 1 | 108.6 | 104.5 | 102.6 |
| | *7.5* | *7.5* | *8.0* |
| 2 | 105.8 | 98.9 | 105.7 |
| | *7.9* | *6.9* | *8.1* |
| 3 | 106.3 | 104.2 | 111.9 |
| | *7.7* | *7.9* | *9.8* |
| 4* | 105.9 | 109.6 | 124.4 |
| | *8.0* | *9.2* | *13.5* |
| 5* | 107.5 | 114.8 | 134.2 |
| | *8.1* | *10.9* | *18.0* |
| 6* | 107.8 | 118.6 | 143.1 |
| | *8.4* | *12.0* | *21.7* |
| 7* | 110.6 | 124.8 | 151.1 |
| | *8.7* | *13.4* | *26.1* |
| 8* | 112.5 | 125.6 | 158.8 |
| | *10.1* | *13.8* | *29.2* |
| 9* | 117.6 | 127.2 | 167.7 |
| | *11.3* | *14.1* | *35.0* |

**Table 1.** (continued)

RAZORBACK SUCKER

| interval | | 12°C | 18°C | 24°C |
|---|---|---|---|---|
| | | length / *weight* | length / *weight* | length / *weight* |
| 1 | length | 56.2 | 53.4 | 51.0 |
| | *weight* | *1.6* | *2.2* | *1.3* |
| 2 | length | 54.9 | 54.8 | 59.4 |
| | *weight* | *1.7* | *1.8* | *2.1* |
| 3* | length | 56.5 | 56.9 | 71.3 |
| | *weight* | *1.6* | *2.1* | *4.0* |
| 4* | length | 56.4 | 63.3 | 86.1 |
| | *weight* | *1.7* | *2.8* | *6.9* |
| 5* | length | 58.0 | 72.4 | 102.9 |
| | *weight* | *1.9* | *4.4* | *11.8* |
| 6* | length | 60.8 | 77.4 | 117.2 |
| | *weight* | *2.1* | *5.5* | *16.6* |
| 7* | length | 63.8 | 90.6 | 138.2 |
| | *weight* | *2.5* | *8.4* | *26.7* |
| 8* | length | 64.4 | 96.6 | 148.6 |
| | *weight* | *3.0* | *10.5* | *35.0* |
| 9* | length | 68.8 | 104.3 | 163.2 |
| | *weight* | *3.4* | *13.0* | *42.6* |

**Table 1** (continued).

BLUEHEAD SUCKER

| interval | 12°C length / *weight* | 18°C length / *weight* | 24°C length / *weight* |
| --- | --- | --- | --- |
| 3 | 65.7 --- | 68.1 --- | 63.7 |
| | *2.6* --- | *2.7* --- | *2.1* |
| 4 | 68.8 --- | 73.3 --- | 67.4 |
| | *2.9* --- | *2.9* --- | *2.3* |
| 5 | 74.2 --- | 81.9 --- | 84.5 |
| | *4.0* --- | *4.6* --- | *4.7* |
| 6* | 78.9 --- | 88.9 --- | 96.9 |
| | *4.9* --- | *5.8* --- | *7.4* |
| 7* | 86.9 | 102.6 --- | 111.6 |
| | *6.4* --- | *8.5* --- | *11.2* |
| 8* | 92.4 | 111.3 --- | 120.0 |
| | *7.7* | *11.5* --- | *14.2* |
| 9* | 98.3 | 120.3 --- | 128.1 |
| | *9.0* | *14.8* --- | *17.3* |

**Table 2.** Regression models for growth in each fish species for each temperature treatment. Temperature in treatment 12°C after 150 days (after 3 June 1999 measurement) was elevated by 2-3°C (Table 3, Figure 9).

| Treatment | Model | $R^2$ | Significance |
|---|---|---|---|
| | humpback chub | | |
| 12°C (<150d) | Y = 76.757 + 0.005 mm/day | 0.001 | 0.645 |
| 12°C (>150d) | Y = 66.147 + 0.077 mm/day | 0.029 | 0.040 |
| 18°C | Y = 72.003 + 0.139mm/day | 0.506 | 0.000 |
| 24°C | Y = 77.946 + 0.278mm/day | 0.669 | 0.000 |
| | bonytail chub | | |
| 12°C(<150d) | Y = 106.921 + 0.001 mm/day | 0.024 | 0.968 |
| 12°C (>150d) | Y = 88.400 + 0.119 mm/day | 0.071 | 0.028 |
| 18°C | Y = 98.370 + 0.129 mm/day | 0.353 | 0.000 |
| 24°C | Y = 99.703 + 0.281 mm/day | 0.609 | 0.000 |
| | razorback sucker | | |
| 12°C(<150d) | Y = 54.847 + 0.030 mm/day | 0.035 | 0.028 |
| 12°C (>150d) | Y = 47.896 + 0.084 mm/day | 0.047 | 0.082 |
| 18°C | Y = 46.892 + 0.229 mm/day | 0.497 | 0.000 |
| 24°C | Y = 45.921 + 0.486 mm/day | 0.929 | 0.000 |
| | bluehead sucker | | |
| 12°C(<150d) | Y = 65.030 + 0.154 mm/day | 0.220 | 0.006 |
| 12°C (>150d) | Y = 57.713 + 0.223 mm/day | 0.155 | 0.057 |
| 18°C | Y = 63.048 + 0.319mm/day | 0.740 | 0.000 |
| 24°C | Y = 61.444 + 0.389mm/day | 0.813 | 0.000 |

**Table 3**. Mean condition factor [ $K=(W/L^3) \times 10^6$ ] for each species, temperature treatment, and measurement interval.

| interval | treatment 12°C | 18°C | 24°C |
|---|---|---|---|
| | | **humpback chub** | |
| 1 | 8.1 | 7.8 | 8.1 |
| 2 | 8.3 | 8.1 | 7.6 |
| 3 | 7.8 | 8.1 | 7.2 |
| 4 | 7.9 | 7.6 | 7.4 |
| 5 | 7.6 | 8.5 | 7.4 |
| 6 | 7.4 | 7.3 | 7.2 |
| 7 | 7.0 | 7.2 | 7.2 |
| 8 | 8.2 | 7.6 | 7.4 |
| 9 | 8.6 | 8.3 | 7.9 |
| *grand means* | *7.9* | *7.8* | *7.5* |
| | | **bonytail chub** | |
| 1 | 5.8 | 6.6 | 7.4 |
| 2 | 6.6 | 6.8 | 6.6 |
| 3 | 6.3 | 6.7 | 6.7 |
| 4 | 6.6 | 6.6 | 6.8 |
| 5 | 6.4 | 6.9 | 7.2 |
| 6 | 6.6 | 6.9 | 6.9 |
| 7 | 6.3 | 6.7 | 7.3 |
| 8 | 6.9 | 6.8 | 6.9 |
| 9 | 6.9 | 6.9 | 7.4 |
| *grand means* | *6.5* | *6.8* | *7.0* |
| | | **razorback sucker** | |
| 1 | 9.0 | 10.0 | 9.8 |
| 2 | 9.8 | 9.7 | 9.9 |
| 3 | 8.3 | 10.0 | 10.0 |
| 4 | 9.3 | 9.6 | 10.0 |
| 5 | 9.3 | 9.5 | 10.0 |
| 6 | 8.7 | 9.9 | 10.0 |
| 7 | 9.1 | 9.6 | 9.9 |
| 8 | 11.0 | 10.0 | 10.0 |
| 9 | 10.4 | 11.6 | 9.8 |
| *grand means* | *9.4* | *10.0* | *9.9* |

**Table 3.** (continued).

| interval | 12°C | treatment 18°C | 24°C |
|---|---|---|---|
| | | **bluehead sucker** | |
| 3 | 9.2 | 8.5 | 8.1 |
| 4 | 8.4 | 7.2 | 7.1 |
| 5 | 9.4 | 7.8 | 7.4 |
| 6 | 9.6 | 7.6 | 7.9 |
| 7 | 9.4 | 7.6 | 7.8 |
| 8 | 9.4 | 8.1 | 8.1 |
| 9 | 9.5 | 8.5 | 8.2 |
| *grand means* | *9.3* | *7.9* | *7.8* |

**Table 4.** Mean temperature readings by month for cold, medium and warm water regimes. Temperatures during January-March did not vary more than 0.2°C. Dates for measurement of lengths and weights were: 8 January (start), 8 February, 8 March, 8 April, 8 May, 3 June, 9 July, 10 August, and 3 September (end).

| | Treatment | | |
|---|---|---|---|
| week | 12°C | 18 | 24°C |
| 3/12/99-3/18/99 | 12.6 | 18.1 | 24.4 |
| 3/19/99-3/25/99 | 12.6 | 18.1 | 24.5 |
| 3/26/99-4/2/99 | 12.8 | 18.0 | 24.5 |
| 4/3/99-4/9/99 | 12.2 | 17.8 | 24.5 |
| 4/10/99-4/16/99 | 12.6 | 18.2 | 24.5 |
| 4/17/99-4/23/99 | 13.0 | 18.2 | 24.6 |
| 4/24/99-4/30/99 | 12.4 | 18.1 | 24.5 |
| 5/1/99-5/7/99 | 12.8 | 18.2 | 24.6 |
| 5/8/99-5/15/99 | 13.3 | 17.8 | 24.6 |
| 5/16/99-5/22/99 | 13.5 | 17.8 | 24.5 |
| 5/23/99-5/29/99 | 13.7 | 18.0 | 24.4 |
| 5/30/99-6/5/99 | 13.4 | 17.9 | 24.2 |
| 6/6/99-6/12/99 | 13.6 | 17.8 | 24.2 |
| 6/13/99-6/19/99 | 13.6 | 17.7 | 24.2 |
| 6/20/99-6/26/99 | 14.2 | 17.8 | 24.2 |
| 6/27/99-7/3/99 | 14.9 | 18.1 | 24.2 |
| 7/4/99-7/10/99 | 15.0 | 18.1 | 24.2 |
| 7/11/99-7/17/99 | 14.6 | 18.1 | 24.3 |
| 7/18/99-7/24/99 | 14.5 | 17.9 | 24.5 |
| 7/25/99-7/31/99 | 14.7 | 17.8 | 24.4 |
| 8/1/99-8/7/99 | 14.8 | 17.9 | 24.2 |
| 8/8/99-8/14/99 | 14.4 | 17.9 | 24.1 |
| 8/15/99-8/21/99 | 14.9 | 17.9 | 24.2 |
| 8/22/99-8/28/99 | 15.2 | 18.1 | 24.2 |
| 8/29/99-9/3/99 | 15.3 | 17.9 | 24.2 |

**Table 5.** Behavior analysis of activity level for each fish species. Significant differences ($P<0.05$) for multiple group comparisons using the Wilcoxon rank sum test are denoted with "*". Species codes are: humpback chub, HBC; bonytail chub, BTC; razorback sucker, RBS.

| Tank | Species | Individual Groupings<br>Mean† | Rank Sum |
|---|---|---|---|
| | | 12°C treatment | |
| 1 | HBC | 2.29 | 1008216.0 |
| 2 | RBS | 1.85 | 818438.0 |
| 3 | HBC | 2.16 | 974202.0 |
| 4 | BTC | 1.07 | 353177.5 |
| | | 18°C treatment | |
| 5 | HBC | 3.07 | 1411663.5 |
| 6 | RBS | 3.59 | 1667906.0 |
| 7 | HBC | 2.41 | 1067935.5 |
| 8 | BTC | 1.14 | 386857.5 |
| | | 24°C treatment | |
| 9 | HBC | 4.19 | 1782851.0 |
| 10 | RBS | 3.70 | 1658241.5 |
| 11 | HBC | 3.67 | 1617289.5 |
| 12 | BTC | 2.09 | 942750.0 |

| Test | Multiple Group Comparisons<br>Mean | Rank Sum |
|---|---|---|
| | Species Differences | |
| HBC | 2.96 | 7862157.5* |
| RBS | 3.05 | 4144585.5* |
| BTC | 1.43 | 1682785.0* |
| | Temperature Differences | |
| Cold | 1.84 | 3154033.5* |
| Medium | 2.55 | 4534362.5* |
| Warm | 3.41 | 6001132.0* |

†Means are based upon values for specific type of activity/behavior:

1=hiding
2=resting at bottom of tank
3=moving at bottom of tank
4=schooling at bottom of tank
5=suspended in water column
6=swimming in water column
7=schooling in water column

**Figure 1. Humpback chub length with standard error bars**

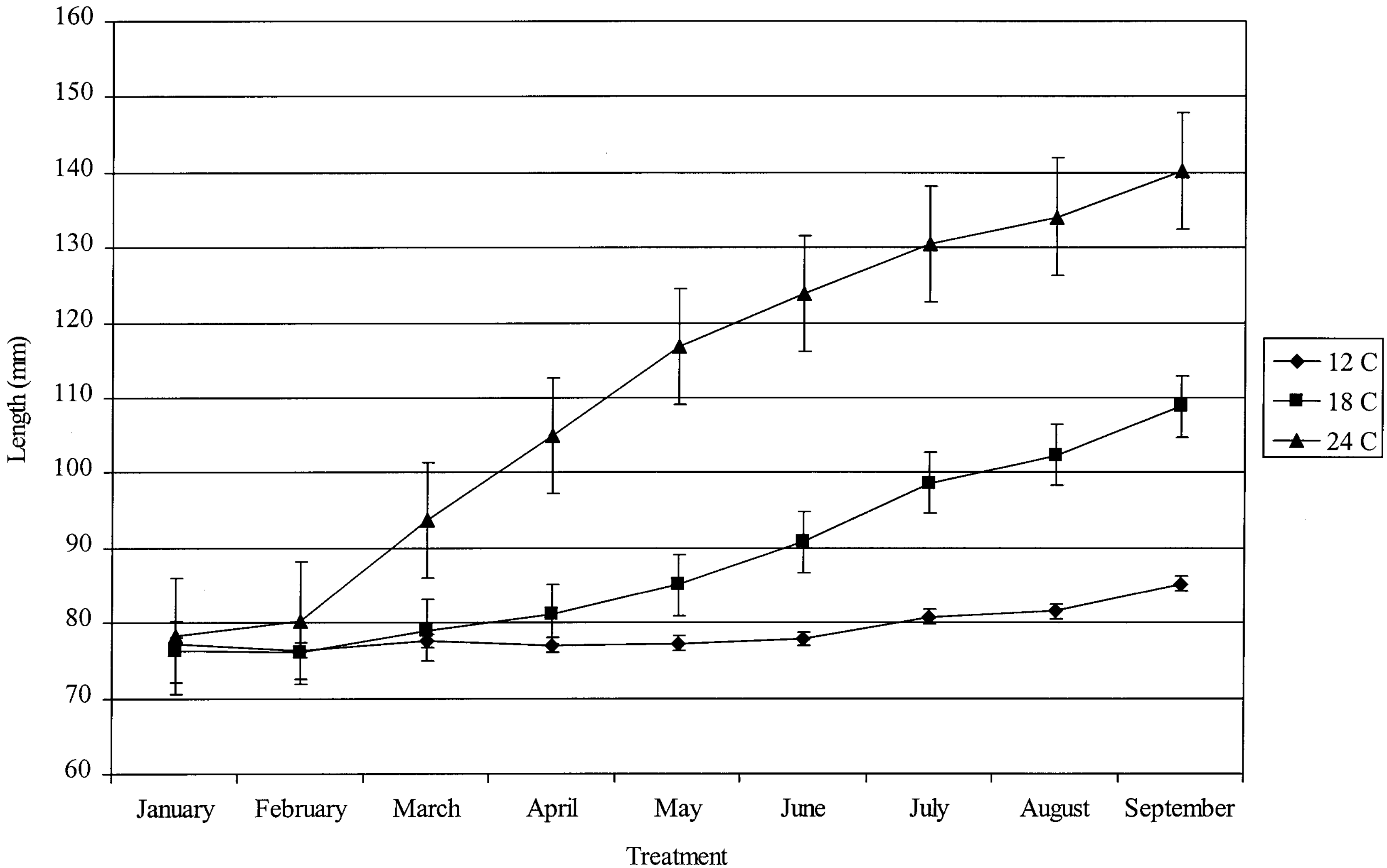

**Figure 2. Humpback chub weight with standard error bars**

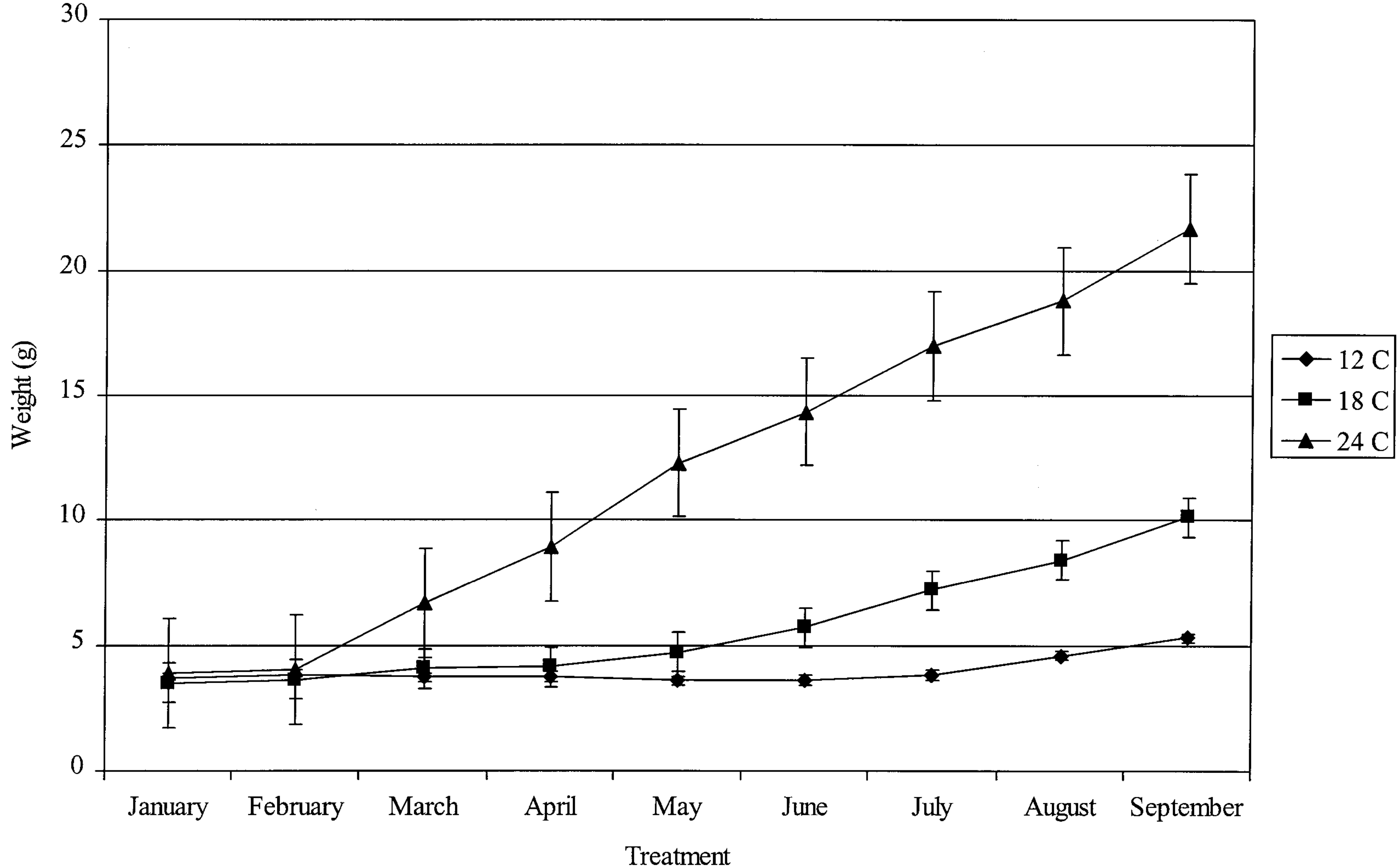

**Figure 3. Bonytail chub length with standard errorbars**

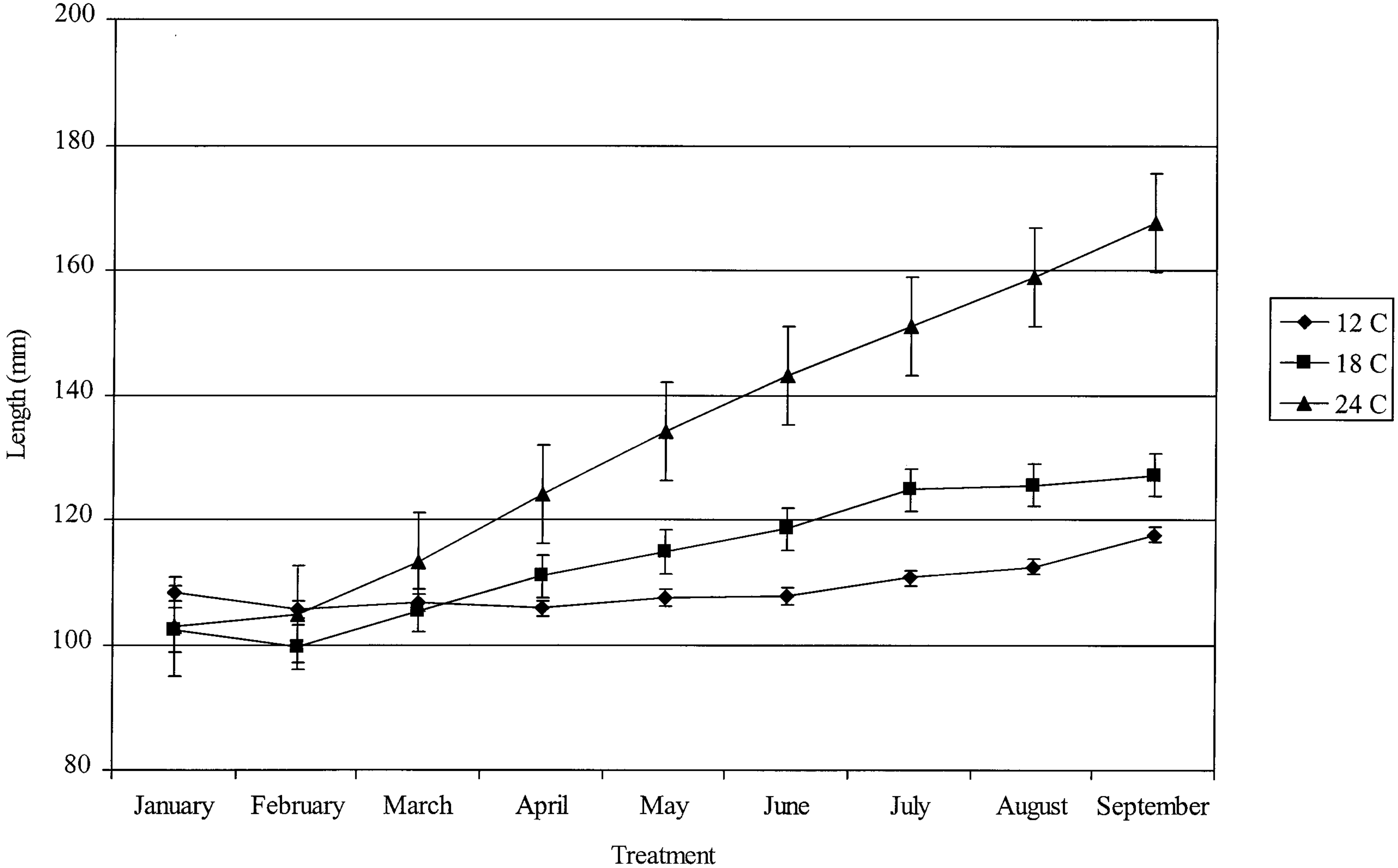

**Figure 4. Bonytail chub weight with standard error bars**

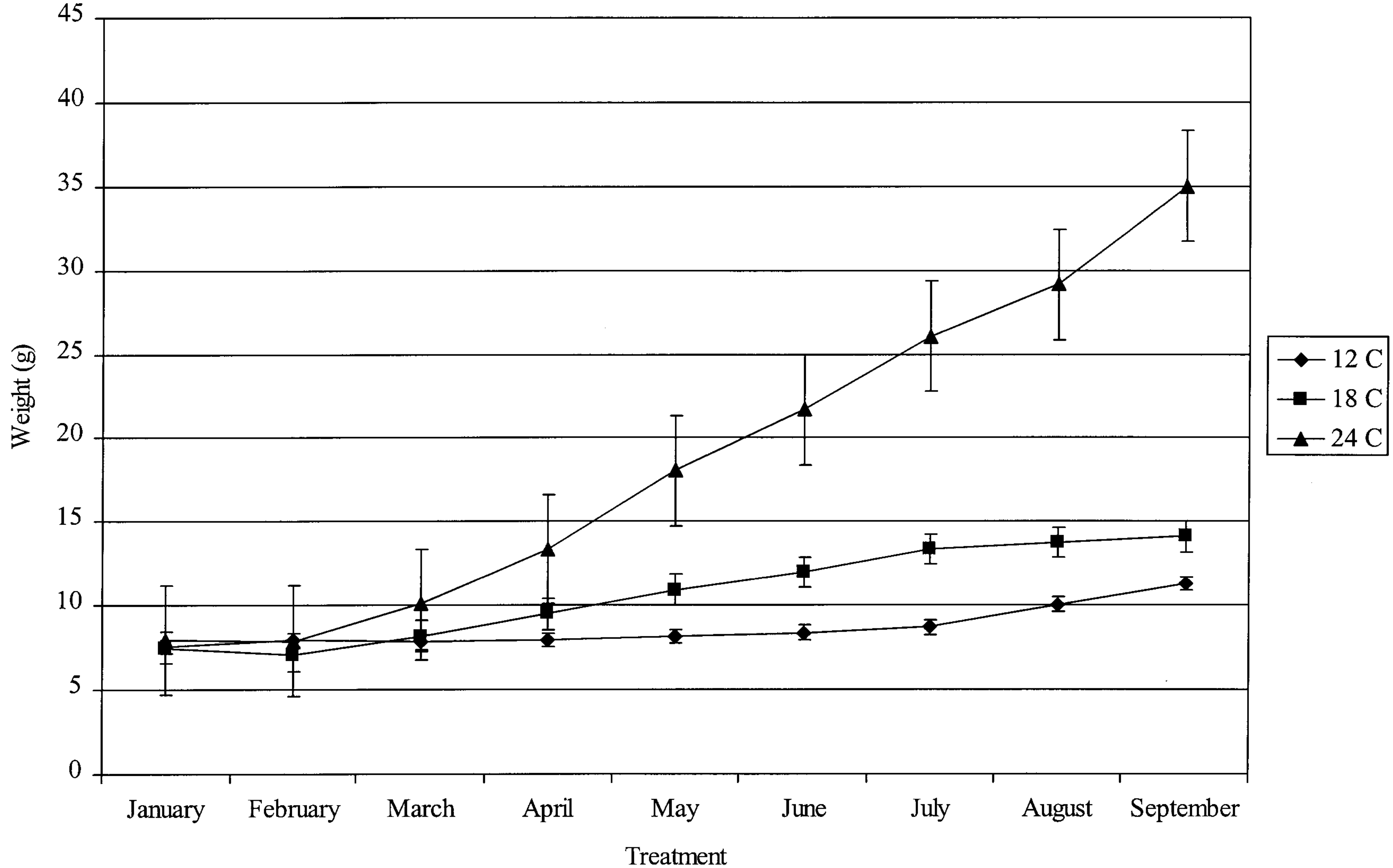

**Figure 5. Razorback sucker length with standard error bars**

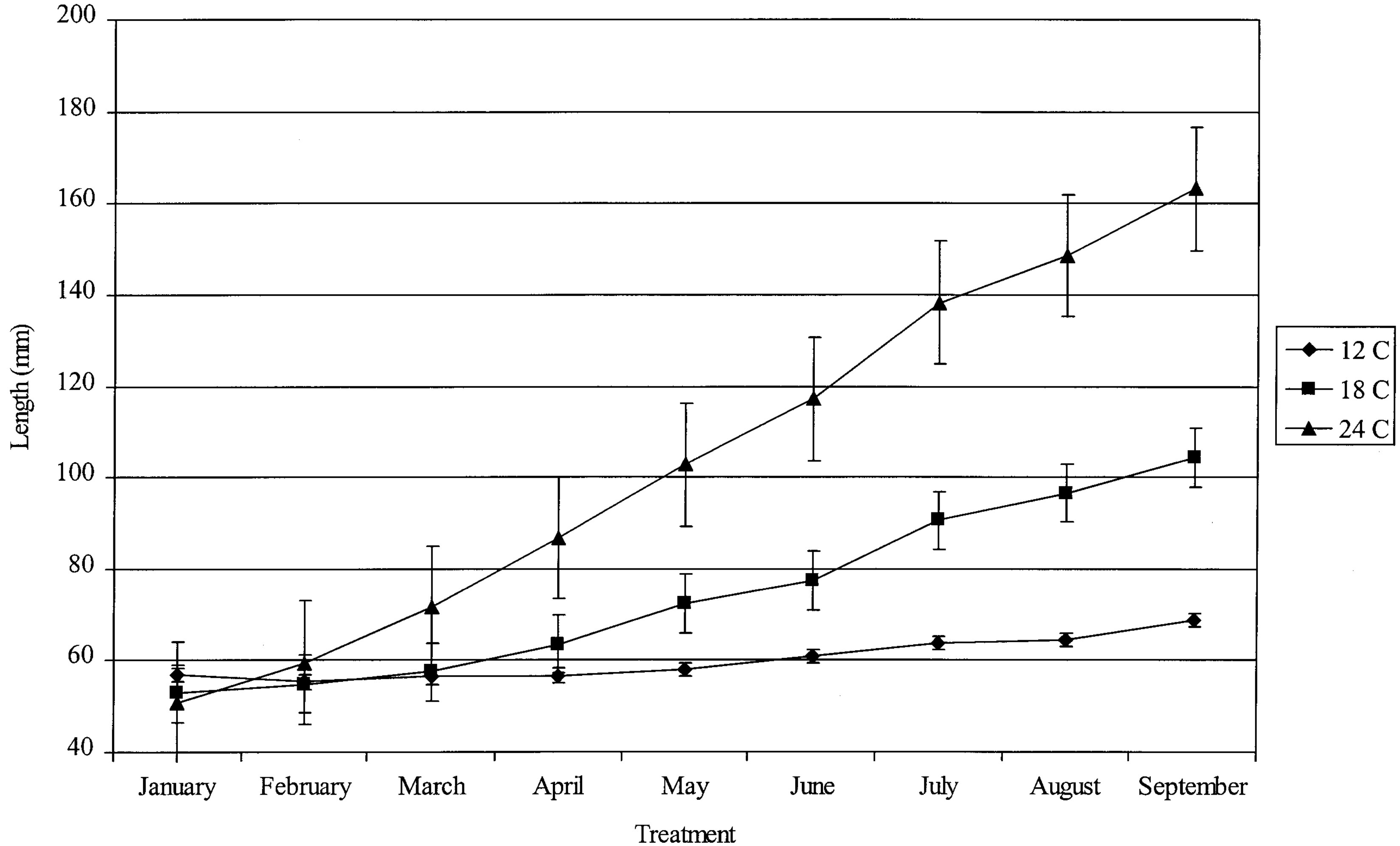

**Figure 6. Razorback sucker weight with standard error bars**

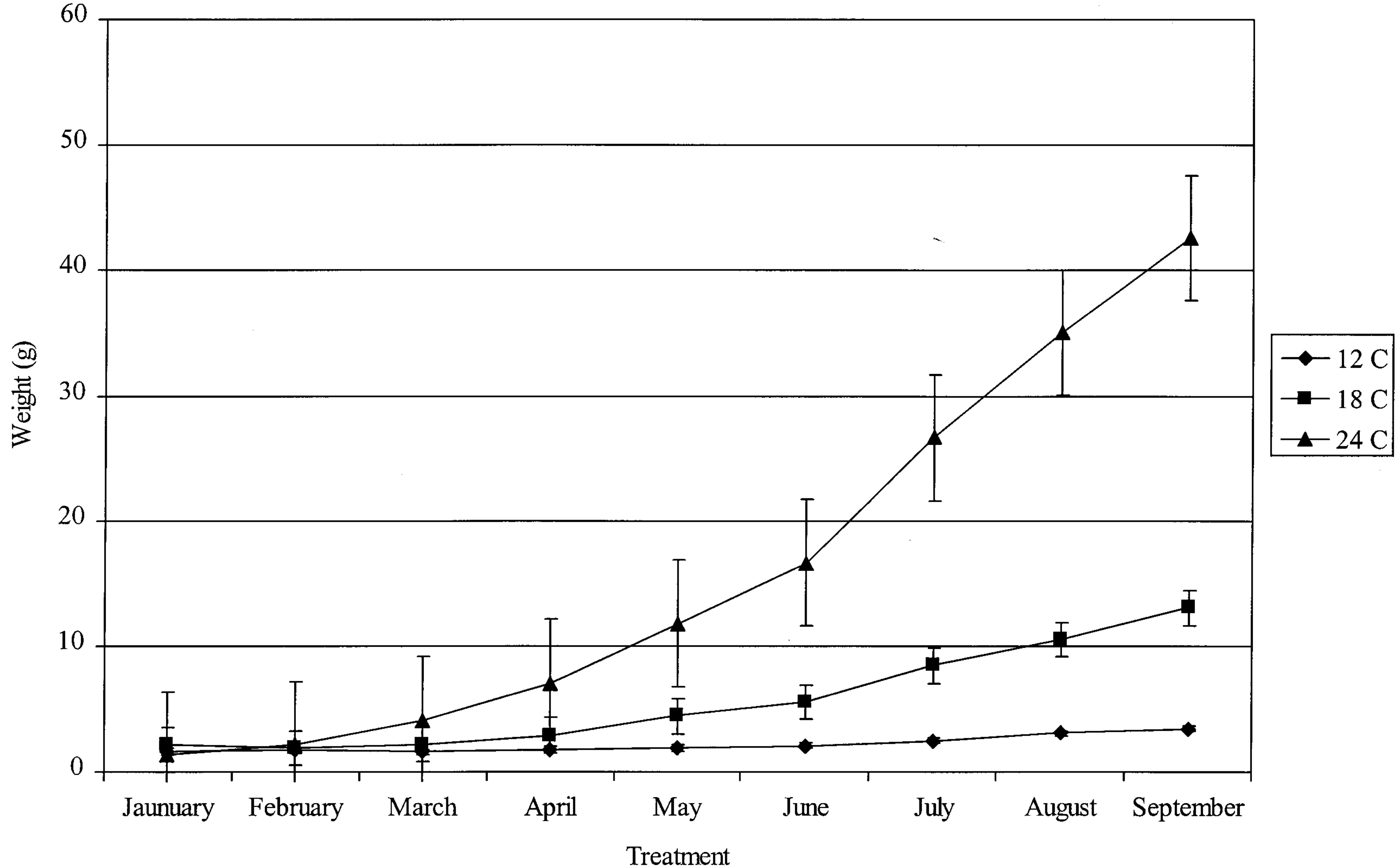

**Figure 7. Bluehead sucker length with standard error bars**

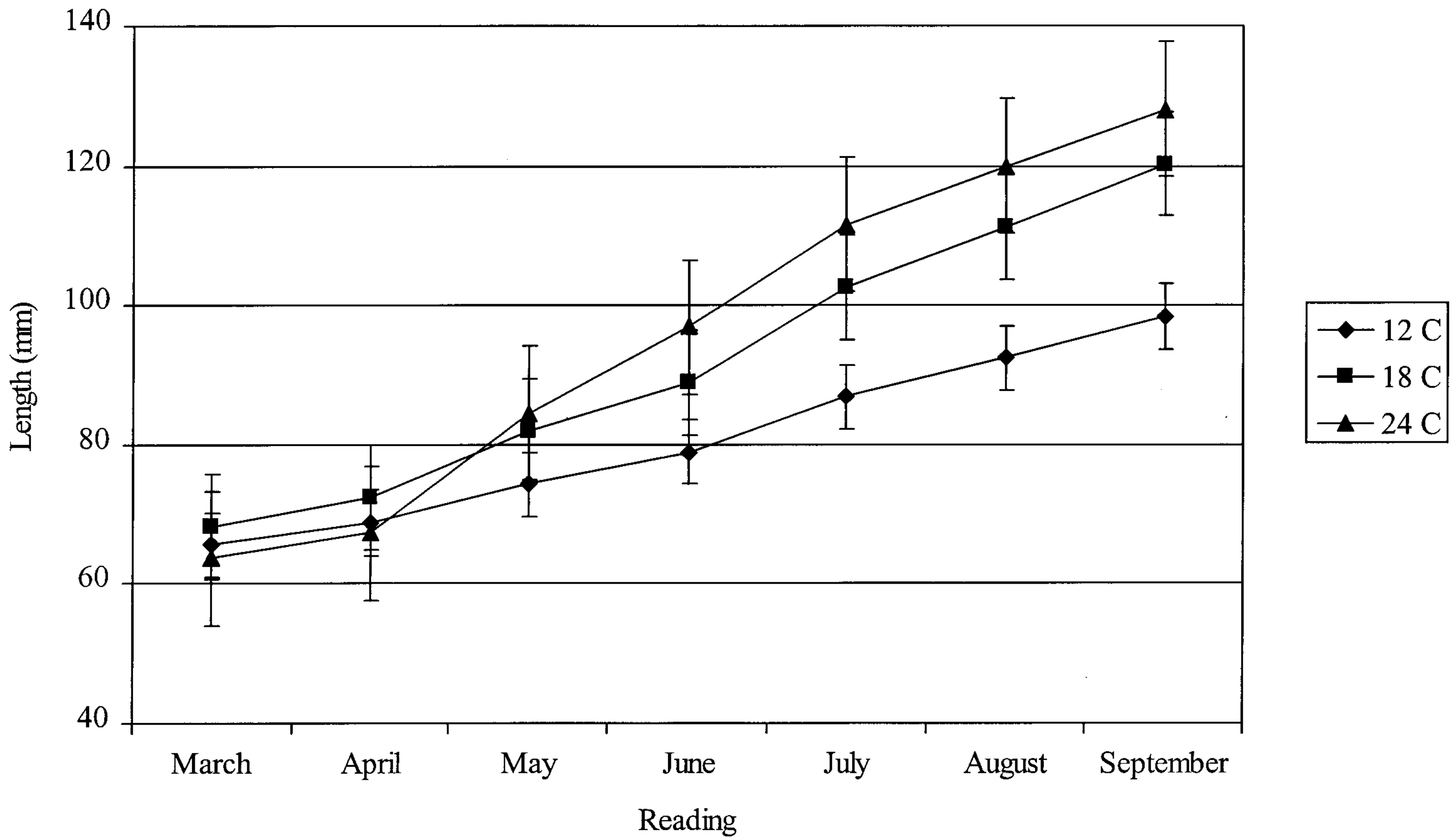

**Figure 8. Bluehead sucker weights with standard error bars**

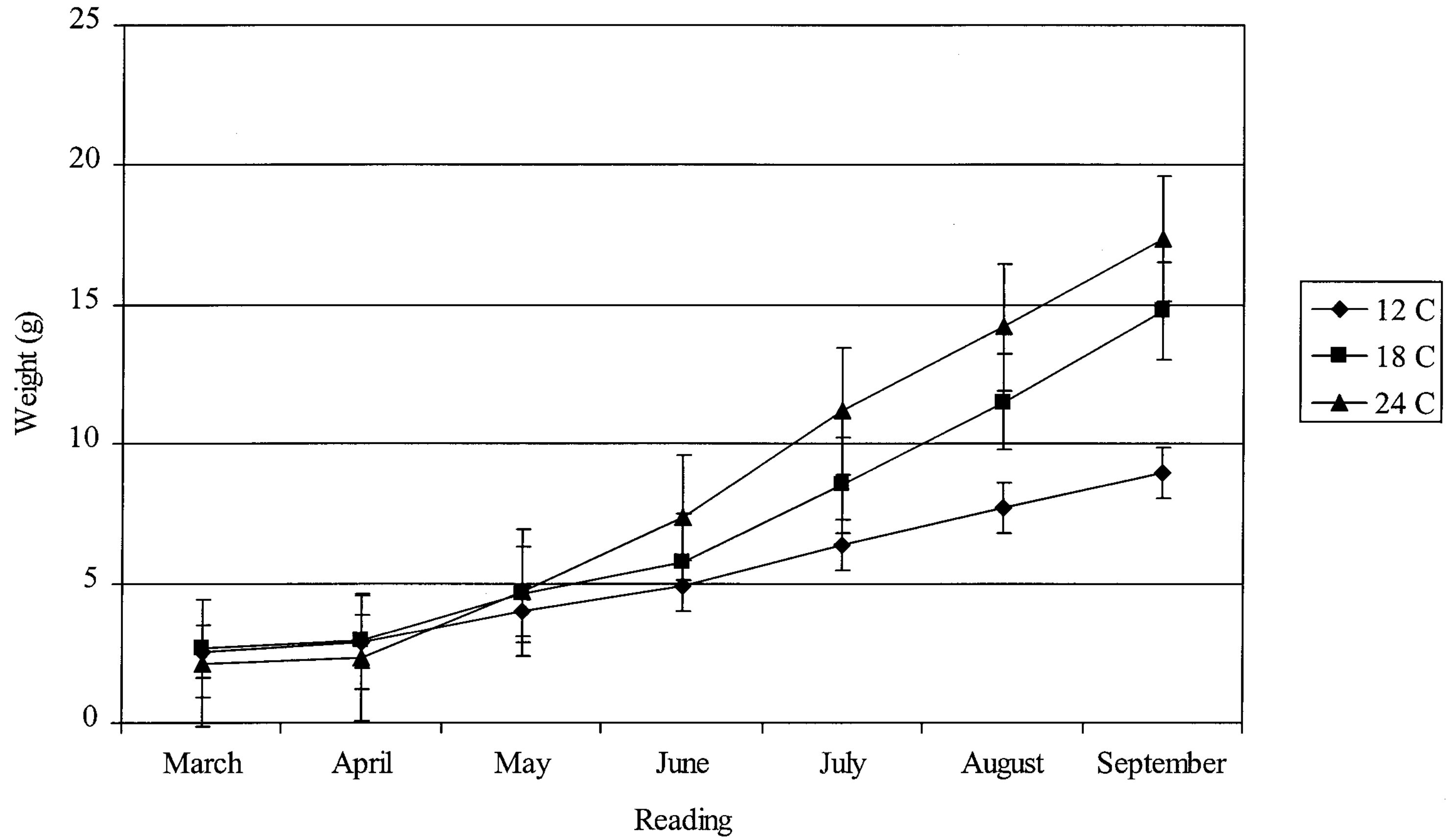

**Figure 9. Temperatures in recirculating systems**