

REPORT NO. 5

TOLERANCE AND PREFERENCES OF COLORADO RIVER
ENDANGERED FISHES TO SELECTED HABITAT PARAMETERS

by

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INTRODUCTION

The Colorado River drainage contains several species of endangered and threatened fishes. Very little information is available on the habitat requirements of these fishes to assist water development agencies in assessing and thereby minimizing the effect of their project(s) on species protected by state and federal endangered species regulations. Habitat factors most likely to be altered by development projects include water temperature and velocity and concentrations of total dissolved solids.

Objectives of our study were to (1) determine temperature and total dissolved solids preferences of juvenile and adult Colorado squawfish (Ptychocheilus lucius), humpback chub (Gila cypha), bonytail chub (Gila elegans), and razorback sucker (Xyrauchen texanus), (2) determine base-line hematological parameters for each species, (3) determine swimming stamina for each species at various water velocities and temperatures, and (4) determine effects of swimming and transport stress on certain blood parameters.

METHODS

Fish History

Razorback suckers (Xyrauchen texanus) used in all experiments were from a single female spawned in 1974 at the Willow Beach National Fish Hatchery (WBNFH). The progeny were reared in concrete outdoor raceways where they were fed commercial trout feed. Approximately 100 of the largest specimens (30-40 cm in length) were shipped to California in the spring, 1980. Remaining fish (n = 700, 15-30 cm in length) were transported to the Utah Water Research Laboratory (UWRL), Logan, Utah, on June 17, 1980. Fish were held in circular 833-liter tanks under controlled photoperiod (14L x 10D) and acclimated to 8°, 14°, 20°, 26° ± 1° C. Fish were fed Silver Cup trout chow (3 mm pellets) ad libitum once per day. Terramycin was added to the feed (4-10 mg/L) for two 7-day periods to control columnaris infection. Diseased fish were not subjected to testing of any kind during treatment or for 7 days thereafter.

Juvenile Colorado squawfish (Ptychocheilus lucius) that were used in temperature preference, blood analysis, and swimming stamina studies were hatched on July 1, 1979, from hatchery-reared adults at the WBNFH. The progeny were held in concrete outdoor raceways and fed commercial trout feed. The fish were transported to the Fisheries Experiment Station (FES), Logan, Utah, in February 1980, and then on July 17, 1980, they were moved to the UWRL facility. At UWRL, they were held in circular 225-liter tanks, fed Silver Cup commercial trout food (#3 crumbles) ad libitum twice per day, kept on a 14L x 10D photoperiod, and were acclimated to 14°, 20°, 26° ± 1° C. The fish ranged in length from 7.5 to 10 cm (n = 1000) when received and appeared to grow best at 20° C

(after 1 year, 20° C fish were 4X larger than 14° C fish and 2X larger than 26° C fish). We experienced no difficulty in holding the squawfish; no diseases or signs of stress were noticed.

Adult Colorado squawfish used in temperature preference, blood analysis, and swimming stamina studies were hatched at WBNFH in 1974. They were held in concrete outdoor raceways and fed commercial trout pellets. The fish were transported (n = 120, 30-50 cm in length) to the FES in February of 1980. They were held in concrete outdoor ponds and fed Silver Cup trout pellets (6 mm) and fingerling rainbow trout (*Salmo gairdneri*) ad libitum. In December 1980, 25 of the squawfish were transferred to UWRL and were held in 833-liter circular tanks at 20° + 1° C. The photoperiod was 14L x 10D and they were fed in the same manner as at FES. Within 2 weeks of transfer, the fish contracted a columnaris infection. They were treated with abdominal injections of Terramycin (250 mg/kg) and the following day with a nitrofurazone dip (10 mg/L for 1 hr). Tank temperature was lowered from 20° C to 14° C (1° C per day). Nine fish were lost to the disease; the remaining fish had no further problems. In August 1981, 35 additional adult squawfish (40-55 cm in length) were transferred from FES. These fish were acclimated to 14°, 20°, 26° + 1° C, kept on a 14L x 10D photoperiod, and fed fingerling rainbow trout ad libitum.

Juvenile Colorado squawfish used in total dissolved solids (TDS) experiments were hatched at WBNFH in July 1980, held in concrete outdoor, recirculating raceways, and fed commercial trout feed. They were transported to FES in April 1981, and held in the same manner as at WBNFH. They were transferred by 14-liter covered plastic garbage cans to UWRL on the morning of each TDS experiment (experiments started in June 1981) and placed directly into the experimental apparatus. The fish were held at UWRL after the experiments in 450-liter circular tanks, on Logan River water and at ambient temperatures and photoperiod.

Humpback chubs (*Gila cypha*) used in all experiments were hatched at WBNFH in June 1980, from wild fish caught at Black Rocks, Colorado. They were held in concrete outdoor recirculating raceways and fed commercial trout feed. They were transported to the University of Idaho, Moscow, in September 1980, where they were held in 225-liter rectangular tanks and fed Biodiet trout feed. They were transferred to UWRL (n = 300, 8-12 cm in length) in February 1981, where they were held in 833-liter circular tanks and fed Silver Cup trout pellets (#3 crumbles) ad libitum twice per day. They were acclimated to 14°, 20°, 26° + 1° C and kept on a 14L x 10D photoperiod.

Bonytail chubs (*Gila elegans*) used in temperature and TDS preference experiments were hatched at WBNFH in May 1981, held in concrete outdoor recirculating raceways, and fed commercial trout feed. They were transported to UWRL (n = 800, 2.5-5 cm length) on August 7, 1981. A second group of bonytails (n = 300, 8.5-12 cm in length) was transferred to UWRL on August 27, 1981, for blood analysis and swimming stamina experiments. These fish were from the same group hatched at WBNFH in May 1981, but were held at Dexter National Fish Hatchery (DNFH) in earthen ponds and on natural food supplemented with commercial trout feed. Both groups of bonytail chubs were held together in 225-liter circular tanks

and fed Silver Cup trout feed (#3 crumbles) ad libitum twice per day. They were acclimated to 14°, 20°, 26° + 1° C and kept on a 14L x 10D photoperiod.

Hybrid chubs (bonytail x humpback) used in temperature preference experiments were hatched at WBNFH in May 1980, and sent to DNFH where they were reared in outdoor earthen ponds and fed natural food supplemented with commercial trout feed. They were transported (n = 31, 12 cm in length) to UWRL in November 1980, where they were held in 833-liter circular tanks at 20° + 1° C, fed Silver Cup trout pellets (3 mm) ad libitum twice per day, and kept on a 14L x 10D photoperiod.

All fish held at UWRL were kept in flow-through systems of heated dechlorinated city water with supersaturation removed from the water before it entered the tanks. Dissolved oxygen was maintained in the tanks at 90-100 percent of saturation, ammonia was kept below 0.2 ppm (direct Nesslerization method, Hach Kit), and pH was kept at 8.0. All fish were acclimated to the various water temperatures in accordance with procedures outlined by Richards et al. (1977).

Temperature Preference

The final temperature preferendum is defined by Fry (1947) as that temperature toward which a fish will finally gravitate regardless of previous thermal history and at which acclimation and preference temperature are equal. Final preferendum has been generally assumed to be an innate and species-specific measure of thermal behavior (Reynolds and Casterlin 1976, Magnuson and Beiting 1978). Final preferendum for razorback suckers acclimated to four temperatures (8°, 14°, 20°, 26° C) was determined using an electronic shuttle box adapted from Neil et al. (1972). This device is basically a plexiglass chamber in which individual fish were allowed to regulate water temperatures by triggering photocells controlling warm and cold water flow (Figure 1). The shuttle box was filled with water from tanks in which the fish were being held and an individual fish was placed in the device. After a 1-hour acclimation period, the photocells were activated and water temperature was recorded (Honeywell Thermographs) for the next 47 hours. The final preferendum during light and dark hours was determined with data from 15-minute intervals of the last 24 hours of testing for 20-23 specimens. The mode, instead of the mean or median, was used to describe the final preferendum of individual fish because it best corresponds to the definition of (modal) preferendum as that temperature occupied most frequently by a fish (Plitt et al. 1976, Richards et al. 1977). In addition to individual modes, a mean of the individual modes, a pooled mode and mean, and Pearson's coefficient of skewness were calculated for day and night for fish of each acclimation temperature. Data were collected in degrees Fahrenheit but were not converted to degrees Centigrade for statistical analysis.

Because of their small size, humpback, bonytail, and hybrid chubs were unable to operate the shuttle box and no final preferendum could be directly determined. Acute preferendum (measured in the first 3 hours and affected by prior thermal history) was measured for humpback and bonytail chubs acclimated to 14°, 20°, 26° C and hybrid acclimated

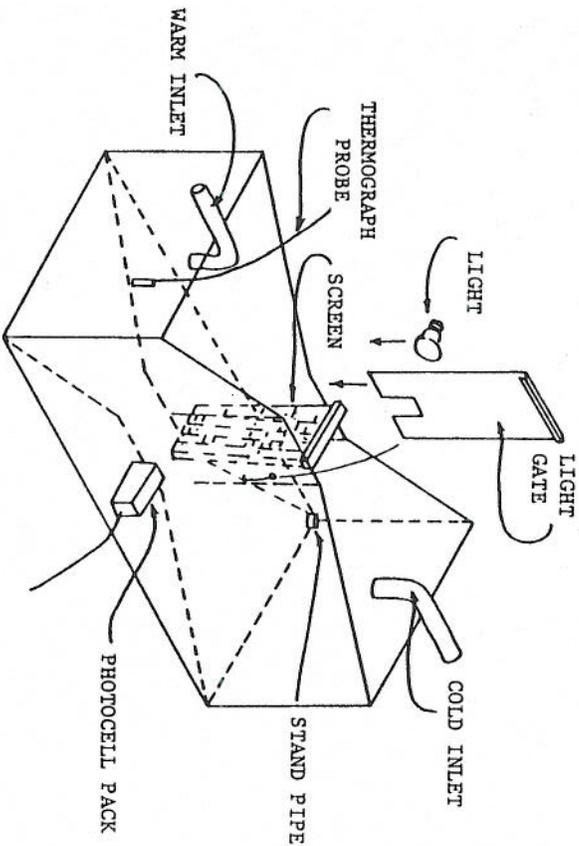


Figure 1

Electronic shuttlexbox for thermal preference studies
(after Neill et al. 1972)

to 20° C using a horizontal gradient trough (234 cm x 33 cm). The range of temperature in the gradient was ca. 14-34° C but varied slightly with each fish. The range was maintained by adjusting the flow of hot and cold water at opposite ends of the trough. Temperature probes (YSI tele-thermometer) recorded temperatures in degrees Fahrenheit at 26-cm intervals along the trough bottom. The device was supplied with aeration by five air stones 40 cm apart and was enclosed by a curtain. Fish were observed through a small aperture in the side of the curtain. A fish was placed in the gradient device at a position that approximated its acclimation temperature and was allowed to explore the trough for 1-hour before observations began. Temperature and location of the fish were observed at 1-minute intervals for 2 hours. During the second hour hot water was turned off to alter the gradient and check for positional effects (Staufier et al. 1975). An additional test for positional effects (i.e. as a control) was done by placing a fish in the trough with a uniform temperature (14° C) and observing it in the same manner as above. Twenty to 30 fish for each acclimation temperature were tested and 10 additional fish, acclimated to 14° C, were tested in the control experiment. All temperature data were converted to degrees centigrade before statistical analysis. Data were analyzed similarly to that recorded for the razorback sucker.

Preliminary tests were conducted for juvenile squawfish. At least 10 fish from three acclimation temperatures (14°, 20°, and 26° C) were tested in the horizontal thermal gradient (234 cm x 33 cm) used for humpback chubs to determine acute temperature preference. Several squawfish were left in the gradient overnight to estimate final temperature preference.

Additional juvenile squawfish (10-18 cm in length) were tested in a horizontal trough, 5 m x 25 cm with variable depth (5-10 cm). Seven air stones and 13 thermistor probes were attached at uniform intervals along the bottom of the trough. Air stones used to prevent gas supersaturation and vertical temperature stratification helped to maintain an even temperature gradient. The thermistor probes were attached to a tele-thermometer on the observation platform. Uniform, low-level lighting (1 lux) was provided, and the area surrounding the trough was covered in black plastic with a small opening for observation.

Twenty squawfish from each acclimation temperature (14°, 20°, and 26° C) were tested in the larger gradient trough. Range of temperatures in the gradient was varied according to the acclimation temperature of the fish; 13-33° C for 14° C fish, 16-35° C for 20° C fish, and 14-34° C for 26° C fish. A single fish was placed in the trough at a point where the temperature corresponded to the fish's acclimation temperature (Richards and Ibara 1978, Hall et al. 1979). Observations of fish position and temperature at that position were recorded at 1-minute intervals for 3 hours, beginning as soon as the fish was placed in the trough. Only the last hour was used in the analysis of temperature preference. At the end of 3 hours, either the hot or cold water was turned off to shift the gradient. The fish was observed in a similar manner for 30 minutes to see if it remained in a particular preferred area of the trough (e.g., corner or end), or if it followed its selected temperature down the trough (Richards and Ibara 1978, Erlich et al. 1979, Hesthagen 1979).

Frequently the gradient did not shift significantly, particularly near the end of the trough where the water remained on, therefore additional criteria were used to determine if those fish were actually selecting temperature over other physical factors of the trough. Five fish from each acclimation temperature were individually tested in the trough with the water held at a uniform temperature equal to their respective acclimation temperature (Richards and Ibara 1978, Hesthagen 1979). Fish position was recorded at 1-minute intervals for 3 hours; only the last hour was used in data analysis.

Testing procedures of adult squawfish were essentially identical to those of the juveniles, though an even larger gradient trough (5.3 m long x 61 cm wide x 13 cm deep) was constructed after testing 10 of the smaller adults (38-42 cm in length). The large gradient provided ample room for the larger adults (42-50 cm in length). Two air stones were added and slightly higher flows were required; otherwise conditions were the same. Ten adults per acclimation temperature (14°, 20°, and 26° C) were tested with a thermal gradient. Fish acclimated to 20° C and 26° C were offered a range of 16-32° C, those acclimated to 14° C were offered 13-26° C. Five fish per acclimation temperature were tested at a uniform temperature equal to their acclimation temperature. The 10 smaller adults were tested in April 1981, the remaining adults were tested in April 1981, the remaining adults were tested in August and early September 1981.

Individual modes, a mean of individual modes, a pooled mean and mode, and Pearson's coefficient of skewness were calculated for juvenile and adult squawfish at each acclimation temperature. Effects of acclimation temperature and age on selected temperature were tested by analysis of variance. If differences were significant, means were further compared with Fisher's (protected) least significant difference test (Steel and Torrie 1960).

Egg Temperature Tolerance

Eggs were initially held at the water temperature of spawning or if shipped, at the water temperature of the water in which they arrived. They were gradually tempered to test temperatures. Eggs were placed in water in plastic cups supported by styrofoam, ten eggs per cup and three or four replicates per temperature. The eggs were initially checked with a dissecting scope to see if they were viable and if in the same stage of development (usually four-celled). They were then checked for viability every 24 hour.

Total Dissolved Solids Preference

The preference of Colorado squawfish, humpback chub, and bonytail chub to various levels of total dissolved solids (TDS) was tested in an enlarged version of a salinity gradient device designed by Staaland (1960). The apparatus was designed to test marine snails and later modified by Reynolds and Thomson (1974) for use with fish. The device consisted of a long trough (243 cm x 30 cm x 45 cm) with series of staggered partitions 20-cm high that enable the establishment of a

salinity gradient by using the difference in densities of water at different levels of TDS to keep them from mixing (Figure 2). Chamber 1 contained dechlorinated Logan city water to which the fish were acclimated and chamber 2 contained the major ions found in the Colorado River at Moab, Utah, (U.S. Geological Survey 1978, mean of 1978 water year August-March). Chambers 3-8 contained the same ions as chamber 2 except levels of mg^{++} , Na^+ , SO_4^{--} were raised a combined total of 1 g/L/chamber (Table 1). These three ions are considered to be the major constituents of the saline input from oil shale processing (Wagenet et al. 1980). A group of fish (30 squawfish, 20 humpbacks, or 40 bonytails) were placed in chamber 1 at the start of the experiment and allowed to migrate throughout the trough for 24 hours. Positions were recorded every 0.5 hours for the first 7-hours (to insure that all chambers were sampled by the fish) and again at 24 hours for the distribution used as data. TDS was measured (YSI conductivity meter) before and after the experiment because the concentration in each chamber would slowly change over time, but only the last measurement was used for data (see Table 1 for conversion of TDS to conductivity). Three treatments and three controls (all chambers filled with city water) were performed for each species. Because of the schooling tendency of these fish, independence could not be assumed for their distributions and no statistics could be performed. Pooled distributions, however, were made for comparisons between controls and treatments, and between species.

Black plastic was used to shield the apparatus from light and to minimize external disturbance. Photoperiod was maintained at ambient (14L x 10D). Temperature of the gradient was 16-18° C. Water was changed after each experiment. Dissolved oxygen and NH_3 (first controls only) were measured before and after each experiment and were never found to be a problem ($\text{D.O.} > 7.2 \text{ mg/L}$, $\text{NH}_3 < 0.2 \text{ mg/L}$).

Baseline Hematology and Stress

Hematological analysis for glucose, chloride, hematocrit, red and white blood cell counts, and white blood cell differentials were determined using methods of Wedemeyer and Yasutake (1977). Instruments routinely used by aquaculturists to monitor fish health were used to determine total protein (refractometer) and hemoglobin (hemoglobinometer). Razorback sucker were sampled for baseline data on June 14-16, 1980, while held at WBNFH. They were moved to the UWRL on June 17. Other species were sampled for blood analysis after being held for 1 month at 14° C at the UWRL. Comparison between sex (razorbacks), age (squawfish), and fish length (all species) was conducted by analysis of variance.

The effect of transporting the razorback suckers from WBNFH to Logan was examined by analysis of blood chloride and glucose levels. About 700 razorback suckers (15-30 cm in length) were transported in a 1,000-liter hauling tank. Density was not determined exactly but was less than 65 g/L. Fish were transported in hatchery water with aeration. Temperatures were controlled by adding ice to maintain $12^\circ + 2^\circ \text{ C}$. No salt or anesthetic was added; 5 mg/L Furacin (4.59 percent active ingredient) was added to prevent bacterial infection. Total hauling time was 15 hours. Fish were loaded and unloaded by netting. Fish resided in

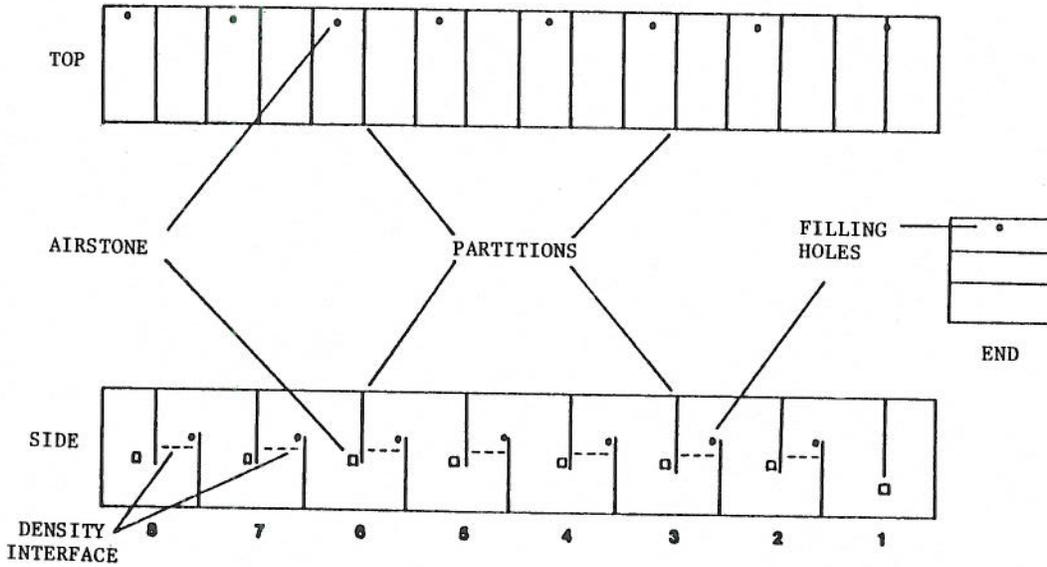


Figure 2

The TDS gradient device with positions of density/TDS interfaces and location of airstones. Length = 2.4 m, width = 45.7 cm, height = 30.5 cm.

Table 1
Initial concentrations of ions in each compartment of TDS preference chamber

Compartment	Ionic concentration (mg/l)							
	1/	2/2	3	4	5	6	7	8
Ca ⁺⁺	47	160	160	160	160	160	160	160
Mg ⁺⁺	16	82	170	250	330	420	500	580
Na ⁺	1.0	170	360	550	740	930	1,100	1,300
K ⁺	0.0	6	6	6	6	6	6	6
Cl ⁻	4.0	220	220	220	220	220	220	220
SO ₄ ⁼	6.2	590	1,300	1,200	2,800	3,500	4,200	4,900
HCO ₃ ⁻	200	210	210	210	210	210	210	210
	274	3/1,438	2,426	3,396	4,466	5,446	6,396	7,376

1/ Logan city water.
2/ Approximate composition of Colorado River water at Moab, Utah (U.S. Geological Survey 1978).
3/ mmhos of conductivity = 0.618 + 0.00068 mg/l TDS; r² = 0.91.

Table 2
Water quality of Willow Beach National Fish Hatchery and Utah Water Research Laboratory

Parameter	Willow Beach National Fish Hatchery ^{1/}	Utah Water Research Laboratory ^{2/}
Dissolved oxygen (mg/l)	7.5-9.0	9.0-9.3
Ammonia	0.1 mg/l	0.05 mg/l
Carbon dioxide (mg/l)	2.0-4.0	---
pH	7.5-8.0	8.2
Alkalinity (mg/l as CaCO ₃)	127.0	138.0
Calcium (mg/l)	92.0	47.0
Magnesium (mg/l)	31.0	14.0
Total hardness (mg/l as CaCO ₃)	358.0	174.0
Total dissolved solids (mg/l)	730.0	164.0
Sulfate (mg/l)	317.0	4.0
Nitrate (mg/l)	1.0	0.2
Fluoride (mg/l)	0.45	0.02
Chloride (mg/l)	104.0	1.0
Iron (ug/l)	0.07	76.0

1/ Ground water well at Willow Beach National Fish Hatchery.
2/ Utah Water Research Laboratory, city water after charcoal filtration. Only trace amounts (less than 1 ug/l) of arsenic, cadmium, chromium, copper, and lead were found; 131 ug/l zinc was found.

water of somewhat similar quality to that of the hatchery (Table 2) at the UWRL for 17-21 hours. Blood was then collected to determine effects of hauling stress. The effect of stress on the suckers was determined for each sex and for fish of various lengths by analysis of variance.

Swimming Ability

Swimming ability was determined in a stamina tunnel (Thomas et al. 1964). Fish were tested at temperatures of 14°, 20°, and 26° C, at various water velocities. A standard testing protocol was used. Fish were acclimated for at least 1 week to the temperature at which they were tested. Acclimated fish were netted and introduced in pairs into the stamina tunnel. Fish were allowed to swim for 5 minutes in a water velocity of 0.15 m/sec, and were then immediately subjected to the test velocity. Swimming fish which retreated to the rear of the tunnel were subjected to mild electric shock (5-10 volts). Time of fatigue was defined as the time at which a fish could no longer avoid the electric field. Fatigued fish were removed from the tunnel, measured for length, and returned to holding tanks for post-test observation. Data were analyzed by analysis of variance with temperature and velocity as main effects, and fish length as a covariate.

RESULTS

Temperature Preference

Razorback suckers acclimated to 8° C had considerable trouble in working the shuttlexes. Of 20 fish tested, only 4 could regulate the shuttlex correctly (10 raised their temperature so fast they died, the rest just sat in one chamber or the other). Fish acclimated to 14° C had similar problems in regulating their temperature as did 8° C fish, but to a lesser degree (10 out of 21 fish tested were able to operate the shuttlex). Beltlinger (1974) had a similar problem with bluegill sunfish (*Lepomis macrochirus*) unless maximum temperature was limited to 19° C for the first 24 hours. This limitation essentially allowed bluegill acclimation rate to catch up with their thermal preference (Beltlinger and Magnuson 1976). Mean of the individual razorback modes and pooled modes were similar both day and night for fish acclimated to 8° C (x modes = 25.4° C D, 25.6° C N; pooled mode = 26° C D, 26° C N) whereas razorbacks acclimated to 14°, 20°, 26° C had higher night pooled modes than day (Table 3, Figure 3).

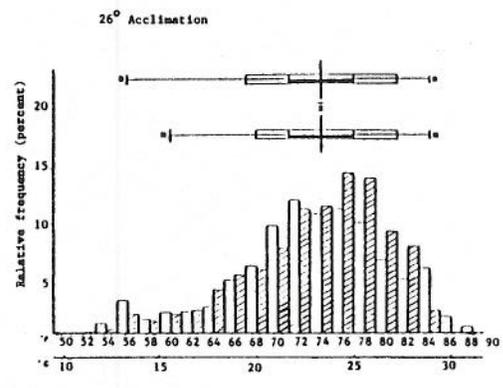
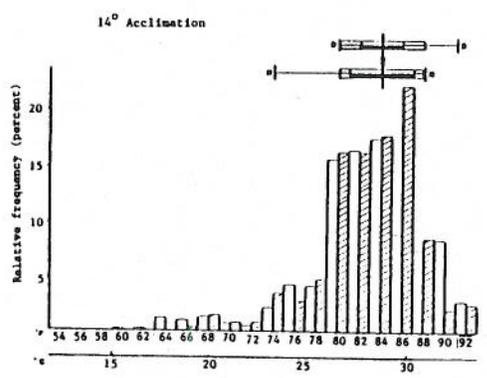
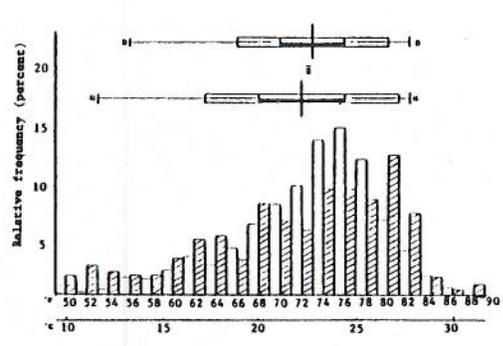
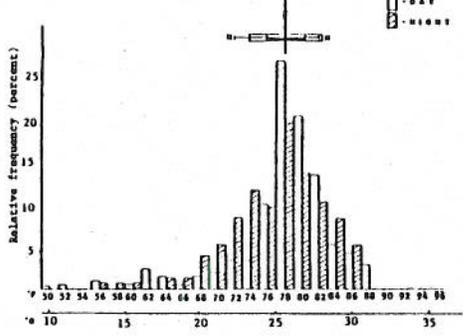
The means of individual modes for 14° C fish were similar for day and night (28.9° C D, 28.8° C N, Table 3), whereas pooled modes showed a slightly higher night temperature (29° C D, 30° C N, Figure 3). This same trend of higher night-time selected temperature was noted for razorbacks acclimated to 20° C (x modes = 22.9° C D, 22.2° C N; pooled mode = 24° C D, 27° C N, Table 3, Figure 3) and to 26° C (x modes 23.3° C D, 23.3° C N; pooled mode = 22° C D, 24° C N, Table 3, Figure 3). Reynolds and Casterlin (1976) found that mean values did not describe differences in day and night temperature preference of bluegill sunfish, smallmouth bass (*Micropterus dolomieu*), or largemouth bass (*M. salmoides*), whereas

Table 3
Temperature distribution statistics for razorback suckers,
comparison of day and night values

Acclimation temperature °C	Razorback suckers	Day/night	Range of individual modes	Mean of modes ^{1/}	Pooled data			
					Mode	Mean	Standard deviation	Skewness ^{2/}
8	4	D	24 - 26	25.4 ± 0.35	26	24.7	4.2	-0.3
		N	22 - 28	25.6 ± 1.39	26	25.1	1.9	-0.5
14	10	D	27 - 32	28.9 ± 0.64	29	28.2	2.8	-0.3
		N	23 - 31	28.8 ± 0.75	30	28.4	1.9	-0.8
20	20	D	13 - 28	22.9 ± 0.89	24	22.7	3.0	-0.4
		N	12 - 28	22.2 ± 1.12	27	22.3	2.1	-2.2
26	20	D	13 - 29	23.3 ± 0.90	22	22.8	2.9	0.3
		N	16 - 29	23.3 ± 0.73	24	23.3	2.1	-0.3

^{1/} ± standard error of the mean.

^{2/} Pearson's skewness coefficient = (mean-mode)/standard deviation. A negative value indicates a longer tail on the low temperature side of the distribution curve.



Relative frequency distribution of temperatures selected by razorback suckers. Pooled 15-minute data during second day and night for fish acclimated to 8, 14, 20, and 26°C. Figures above vertical bars provide day (D) and night (N) range of individual modes, mean of individual modes \pm 2 standard errors (darkened box) and \pm 1 standard deviation (clear box).

pooled frequency distributions indicated differences. They believed that the skewness in their distributions accounted for the lack of agreement. Our data were also skewed for razorbacks acclimated to 14°, 20°, 26° C (Table 3) but in the opposite direction (i.e. warmer temperature selected at night) than the data of Reynolds and Gasterlin. This difference may be a reflection of the differences in biological requirements of centrarchids and catostomids. The small lamp used to trigger the photocells may also have lowered sensitivity of razorbacks to day and night changes.

Final preferenda for razorbacks acclimated to different temperatures were compared using analysis of variance on the combined night and day individual modes. Difference in preferenda were significant ($P > 0.005$), and analysis with Fisher's LSD test (Steele and Torrie 1960) showed that 14° C fish selected significantly higher temperatures than did 20° C or 26° C fish (Table 4). There is some evidence that cold-acclimated fish (15° C) may initially overshoot their final preferendum, but by the third or fourth day of testing their preferenda equal those of warm-acclimated fish (Beitinger and Magnuson 1976, Reynolds 1978). Final preferendum of 8° C suckers was also higher than those of 20° C and 26° C fish (Table 4), but the difference was not significant perhaps due to the small sample size of the 8° C fish.

Data from 8° C and 14° C acclimated razorback suckers were not used to estimate final preferendum because of small sample size (8° C fish) and possible overshoot as mentioned above. Data from 20° C and 26° C acclimated razorbacks, however, agreed well with Fry's (1947) definition of final preferendum as that temperature where fish will finally gravitate regardless of previous thermal history. Use of average day and night x modes and pooled modes for 20° C and 26° C acclimated fish (Table 3 and 4) indicated that the best estimate of razorback suckers final preferendum was 23-24° C. The geometric mean (24.9° C) of the means of individual modes for all four acclimation temperatures (8°, 14°, 20°, 26° C) as an indication of central tendency agreed closely with the estimated final preferendum of 23-24° C by the above method even with the small sample size of the 8° C and 14° C fish.

Testing thermal preference in a horizontal gradient device tends to produce more variable data than that obtained from the shuttlebox but gives comparable results (Magnuson and Beitinger 1978, Huggins 1978). There is also the problem of fish selecting for a particular position in the trough rather than the temperature associated with that position. Ten 14° C acclimated humpback chubs were tested in the horizontal gradient with a uniform temperature (14° + 1° C) to detect preferred positions (Figure 4). (Future horizontal gradients should be constructed long enough to insure thermal avoidance temperatures at each end of the gradient to eliminate this problem.) As an additional test for positional effects, hot water was shut off to the gradient during the second hour of observation. This change allowed the gradient to shift and eventually be eliminated (Stauffer et al. 1975, Cherry et al. 1975, Richards et al. 1977). Use of these two tests effectively screened fish for positional effects and allowed us to eliminate those fish that were influenced by the chamber. Data of fish were rejected for analysis if location modes of an individual were the same during the first and the second hour of observation, or if their location mode during the first

Table 4
Temperature selection of four Colorado River fishes

Species	Acclimation temperature °C	Number	Range of individual modes	Mean of modes ^{1/} (\bar{x} modes)	Mode	Mean	Standard deviation	Skewness ^{2/}
Razorback sucker	8	4	22 - 27	25.0 ± 0.96	26	24.8	3.42	-0.4
	14	10	27 - 31	29.0 ± 0.52	28	28.3	2.47	0.1
	20	20	12 - 28	22.7 ± 1.07	24	22.5	2.67	-0.6
	26	20	13 - 29	23.1 ± 0.90	26	23.0	2.60	-1.2
Humpback chub	14	9	17 - 26	21.0 ± 1.26	18	20.3	3.88	0.6
	20	8	21 - 31	24.4 ± 1.20	23	23.1	3.78	0.03
	26	7	21 - 27	23.5 ± 1.72	17	21.3	4.37	1.0
Bonytails	14	6	15 - 21	17.9 ± 0.92	17	17.9	3.31	0.3
	20	8	15 - 30	22.5 ± 1.94	27	22.5	4.81	-0.9
	26	8	21 - 31	25.1 ± 1.71	24	25.1	4.67	0.2
Hybrid Squawfish	20	8	18 - 28	23.8 ± 1.48	26	22.3	4.26	-0.8
Juveniles	14	18	17 - 27	21.9 ± 0.74	21	22.1	2.97	0.4
Adults	14	4	14 - 27	21.5 ± 3.07	26	20.9	5.28	-1.0
Juveniles	20	20	24 - 32	27.6 ± 0.44	28	27.4	2.46	-0.3
Adults	20	2	20 - 25	22.5 ± 2.50	20	22.1	3.68	0.6
Juveniles	26	19	21 - 31	23.7 ± 0.64	23	24.1	3.46	0.3
Adults	26	6	24 - 27	25.7 ± 0.50	27	24.7	3.53	-0.7

1/ ± standard error of mean.

2/ Pearson's skewness coefficient = (mean-mode)/standard deviation. A negative value indicates a longer tail on the low temperature side of the distribution curve.

RELATIVE FREQUENCY (%)

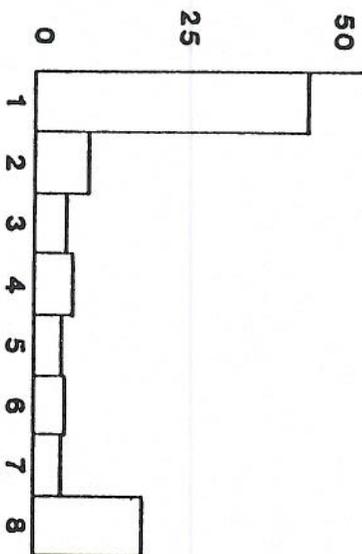


Figure 4

Humpback chub relative frequency distribution in 8 locations within a horizontal thermal gradient chamber. (Fish were acclimated to 14°C and placed in chamber with a uniform water temperature of 14°C). Data on 10 fish pooled for first hour, one observation/minute.

hour was at one end of the gradient and at the other end during the second hour. Humpback chubs acclimated to 20° C selected higher temperatures (x modes = 24.4° C) than did chubs acclimated to 14° C (x modes = 21° C) (Table 4). Chubs acclimated to 26° C, however, selected temperatures lower (x modes = 23.5° C) than those of 20° C chubs and much lower than would be predicted from data of other researchers (Stauffer et al. 1975, Mathur et al. 1981). Similar results were also seen in spotfin shiner, (*Notropis spilopterus*), (Stauffer et al. 1975) and in bluegill sunfish (Beltlinger 1974). Differences in temperatures selected by humpbacks acclimated to the three temperatures were not statistically significant, however.

Further testing of humpbacks is needed to determine if our lack of relation of acclimation temperature to acute preference was the result of a negative energy balance. Energy intake from food must at least equal energy expended in metabolism, or fish seek lower temperature to balance their energy budget. Stuntz and Magnuson (1976) found that insufficient energy stores in bluegills acclimated to high temperatures caused them to select a lower than expected temperature. Another possibility is that photoperiod should have reflected time of year when low and high temperatures were found in the field (Cherry et al. 1975).

It is interesting to note that pooled distributions of humpbacks were skewed in the opposite direction from those of razorback suckers (Table 4, Figure 5) and that the distribution for 26° C humpback chubs was bimodal. The 17° C peak in Figure 5 is the mode by definition, but with the mean of the individual modes and the pooled mean (Table 4) line up with the peak on the right (23° C). Perhaps this bimodality is an artifact of the shuttling behavior of fishes described by Reynolds (1978). Reynolds noted that fish tend to "shuttle back and forth within a range of temperatures above and below the preferendum" rather than staying at the preferred temperature.

The electronic shuttlexboxes used with razorback suckers provided a direct measure of final preferendum. Estimation of final preferendum from acute preferendum data collected from horizontal gradients, however, must be done indirectly by extrapolating data to the point where acclimation temperature equals preferred temperature (Fry 1947). By use of the graphical method recommended by Richards et al. (1977), preferred temperature (x modes) was plotted against acclimation temperature and a line was drawn connecting the points. The final preferendum for the humpback chubs (24° C) was the point of intersection with the 45 degree line (i.e. the line of acclimation temperature = preferred temperature). Linear regression of the individual modes (Stauffer et al. 1975) gave similar results.

Bonytail chubs acclimated to 14°, 20°, and 26° C were also tested in the horizontal gradient and screened in the same manner as the humpback chubs. They showed a trend of increasing preferred temperature with increasing acclimation temperature which was similar to data of other researchers (Stauffer et al. 1975, Mathur et al. 1981). Fish acclimated to 14° C had a thermal preference of 17.9° C (x mode) whereas 20° C fish preferred 22.5° C and 26° C fish preferred 25.1° C (Table 4). Pooled distributions, however, showed the same pattern as that of the humpback chubs. The pooled mode for 20° C acclimated fish (27° C) was higher than

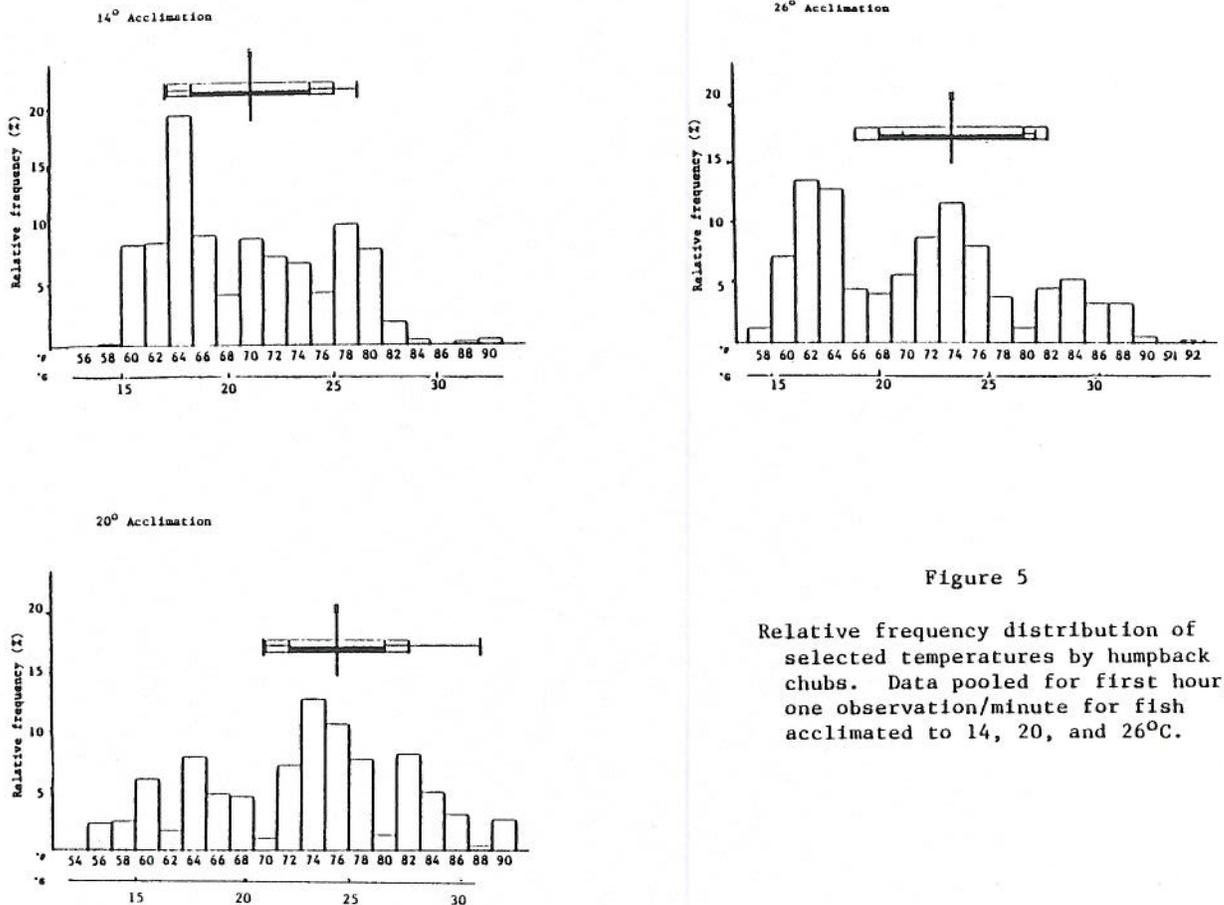


Figure 5
Relative frequency distribution of selected temperatures by humpback chubs. Data pooled for first hour, one observation/minute for fish acclimated to 14, 20, and 26°C.

the pooled mode for the 26° C fish (24° C) (Figure 6). The final preferendum was estimated for the bonytail chubs in same manner as for the humpback chubs. The point of intersection with the 45 degree line was 24.2° C.

Hybrid chubs (humpback x bonytail) acclimated to 20° C were tested in the horizontal gradient and screened in the same manner as were the humpback and bonytail chubs. The mean of the individual modes (23.8° C) was intermediate to that of the 20° C acclimated humpbacks (24.4° C) and bonytails (22.5° C) (Table 4). The pooled distribution showed a higher mode (26° C vs. 23° C) than that of the humpbacks but was similar to that of the bonytails (27° C) (Figure 7). The distribution was also bimodal as with the 26° C humpback chubs.

Behavior of juvenile squawfish differed greatly from that of adults during temperature preference testing. The majority of the juveniles appeared to select temperature over position in the gradient trough. Application of criteria for reflection of data similar to that used for humpback and hybrid chubs rejected only 3 of 60 juvenile fish. The majority of the adults either swam randomly or remained at one end of the gradient chamber; data from 18 of 30 adult fish were rejected.

Juveniles acclimated to 14° C were the least precise of the three groups of juveniles tested. Six 14° C-acclimated fish swam to the 30° C region and lost equilibrium within the first few minutes after introduction to the gradient; two subsequently died. The only other indication of a lethal temperature occurred during preliminary testing when one 20° C-acclimated fish lost equilibrium at 35° C.

The pooled mode is often accepted as the statistic that best describes the preferred temperature (Table 4) (Reynolds and Casterlin 1976, Richards et al. 1977, Hesthagen 1979). However, the mean of the individual modes is less sensitive to skewness which can be caused by one or two fish remaining in the same spot (particularly towards one end of the gradient). Use of the mean of the modes as the statistic to describe the preferred temperature also gives each fish equal weight in data computation. When there is little skewness, as in squawfish juveniles (Table 4, Figure 8), all measures of central tendency agree closely. For adult squawfish the pooled mode did not agree with other measures because the data were significantly skewed (-1.0 to 0.6) (Table 4). Means of individual modes for 14°, 20°, and 26° C-acclimated juvenile squawfish were 21.9°, 27.6°, and 23.7° C respectively. For 14°, 20°, and 26° C-acclimated adults, means of individual modes were 21.5°, 22.5°, and 25.7° C (Figure 9).

Acute preferenda of juveniles and adults acclimated to different temperatures was compared by analysis of variance on the individual modes. Acute preferenda of juveniles were significantly different ($P = 0.01$); whereas, those of the adults alone were not (Table 5). Preferenda of juveniles at different acclimation temperatures were further analyzed with Fisher's LSD test (Table 6). Preferenda of each acclimation temperature was significantly different from the others; 20° C-acclimated fish selected the highest temperature (27.6° C), followed by 26° C-acclimated fish (23.7° C) and 14° C-acclimated fish (21.9° C).

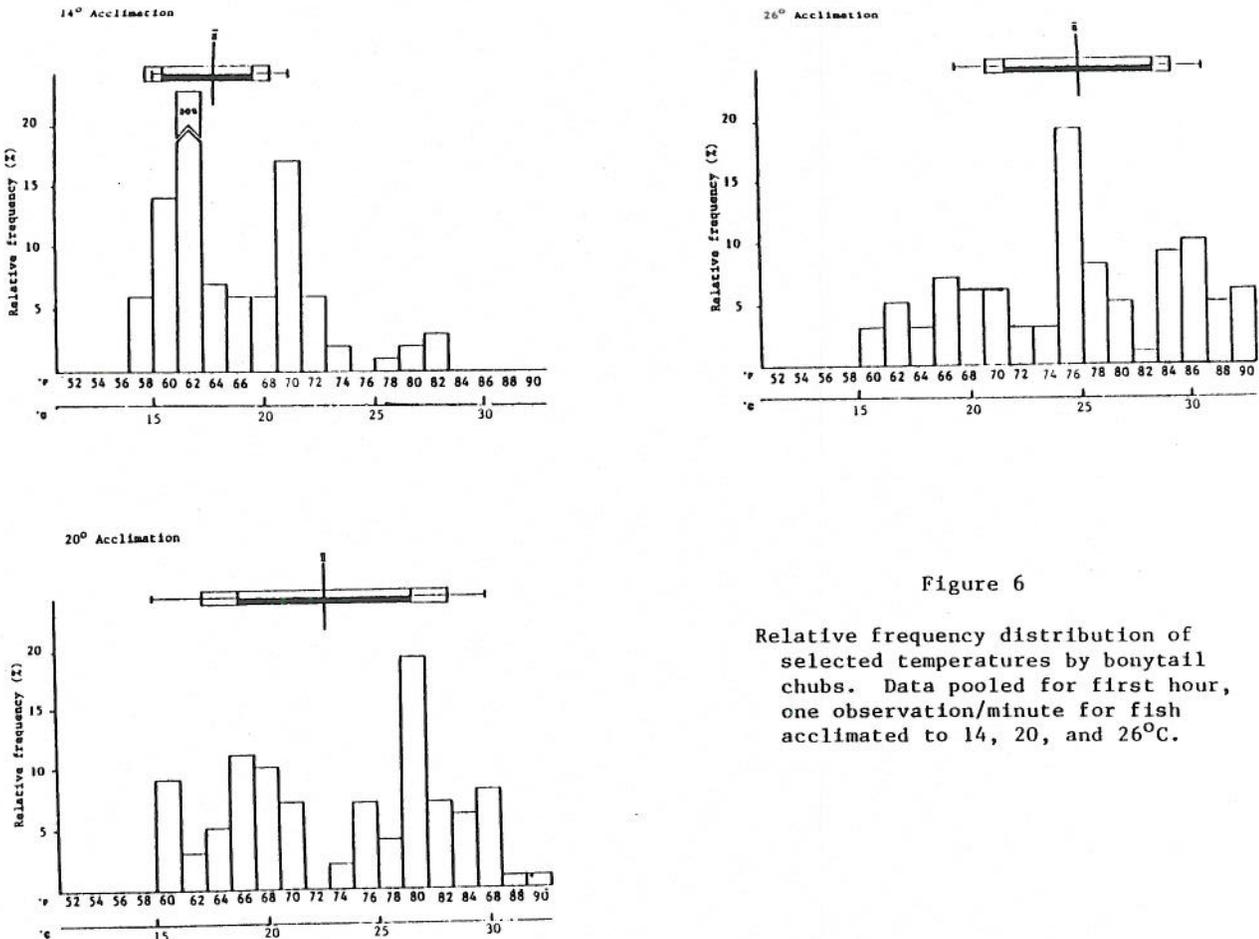
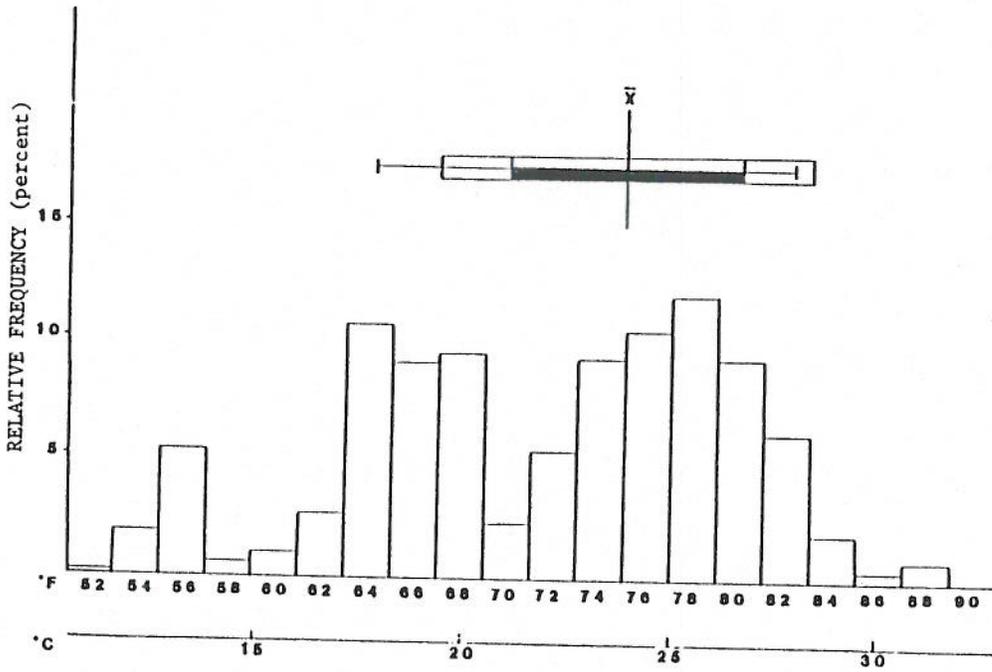


Figure 6
Relative frequency distribution of selected temperatures by bonytail chubs. Data pooled for first hour, one observation/minute for fish acclimated to 14, 20, and 26°C.

Figure 7



Relative frequency distribution of selected temperatures by hybrid humpback-roundtail chubs acclimated to 20°C. Data pooled for first hour, one observation/minute.

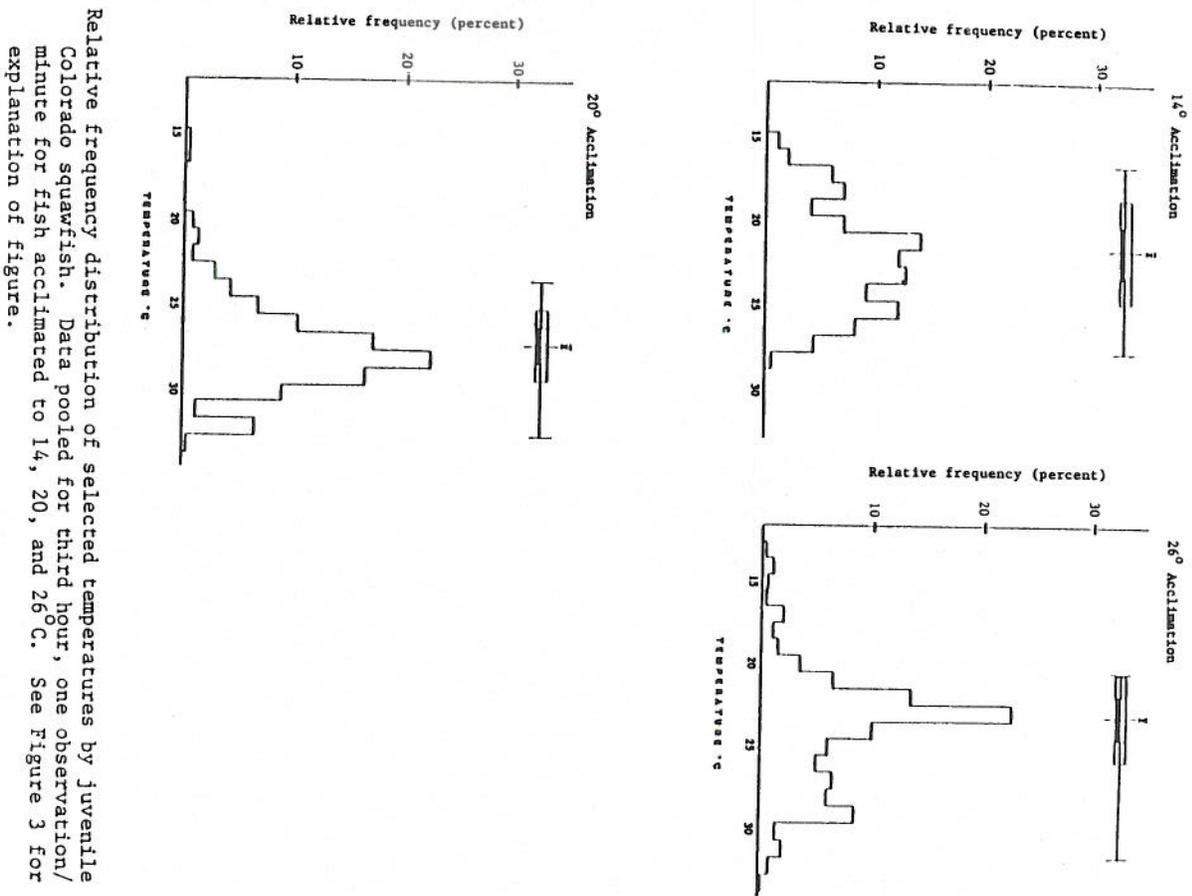
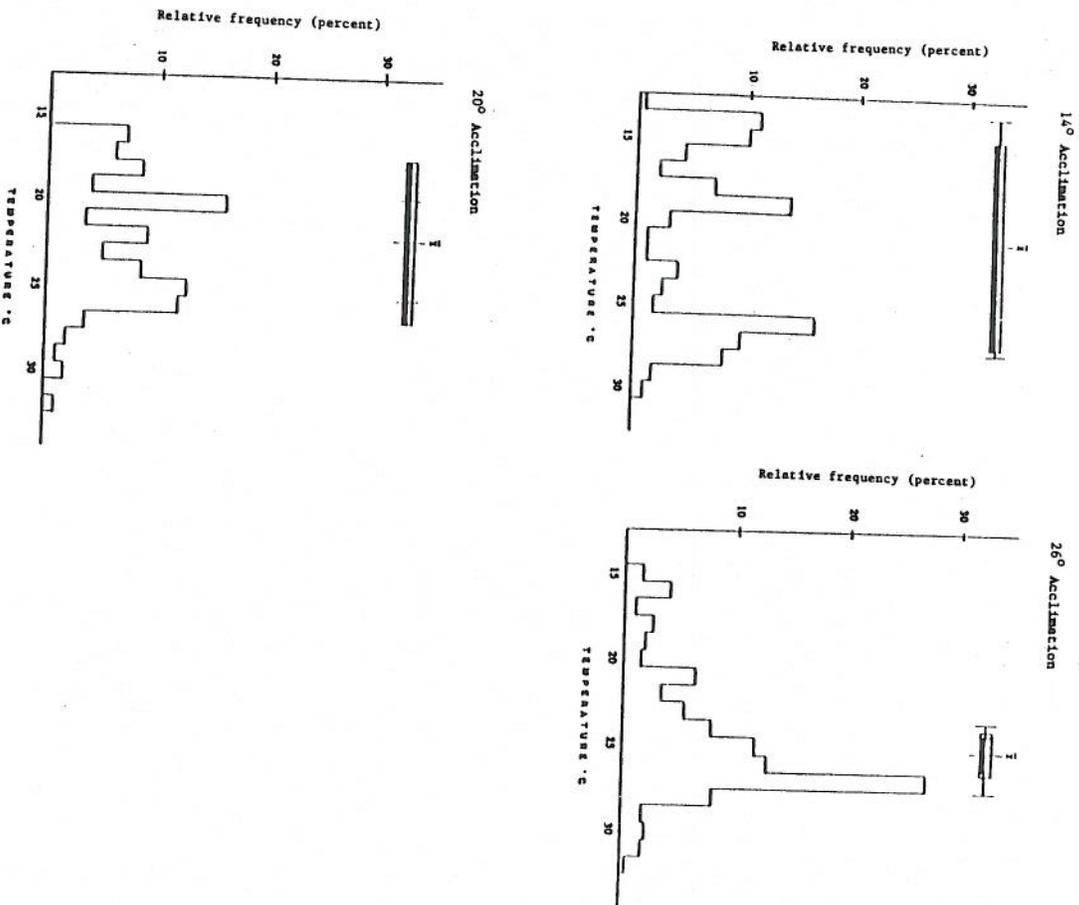


Figure 8

Relative frequency distribution of selected temperatures by juvenile Colorado squawfish. Data pooled for third hour, one observation/minute for fish acclimated to 14, 20, and 26°C. See Figure 3 for explanation of figure.

Figure 9



Relative frequency distribution of selected temperatures for adult Colorado squawfish. Data pooled for third hour one observation/minute for fish acclimated to 14, 20, and 26°C.

Table 5
Analysis of variance of acute thermal preference of Colorado squawfish

	Degrees of freedom	Sum of squares	Mean square	F
Juvenile squawfish				
Source of variation				
Among temperatures	2	319.8	159.9	1/22.7
Within temperatures	54	379.9	7.0	
Total	56	699.7		
Adult squawfish				
Source of variation				
Among temperatures	2	45.4	22.7	1.5
Within temperatures	9	133.3	14.8	
Total	11	178.7		
Juvéniles vs. adults				
Source of variation				
Treatment (between ages)	1	5.5	5.5	0.6
Block (among temperatures)	2	306.9		
Error (within temperatures)	65	571.6	8.8	
Total	68	884.0		

1/ Significant at the 0.01 probability level.

Table 6
Fisher's (protected) least significant difference of juvenile squawfish at different acclimation temperatures

Comparison	Least significant difference (0.05)		Least significant difference (0.01)		Significance
	$ \bar{Y}_1 - \bar{Y}_2 $				
14° vs 20°C	5.66	1.78	2.39	2/	2/
14° vs 26°C	1.85	1.8	2.42	1/	1/
20° vs 26°C	3.81	1.75	2.35	2/	2/

1/ Significant at the 0.05 probability level.
2/ Significant at the 0.01 probability level.

These results were similar to those found in the preliminary tests of young juveniles. Fish acclimated to 20° C selected 30.3° C, those acclimated to 26° C selected 21.8° C, and those at 14° C selected 21.1° C. In data not reported here but mentioned earlier, growth of juveniles held at 20° C during the testing period was much faster than that of fish held at either 14° or 26° C. In the preliminary tests it appeared that the 26° C-acclimated fish selected a lower temperature because they were on a negative energy budget. Feeding frequency was increased from once or twice daily in the preliminary test to three times daily for all lots of fish in the final test. Differences between the preliminary and final testing of 26° C fish tended to substantiate our impression of a negative energy budget in the preliminary test fish. Mean of individual modes for the first 26° C lot of fish was 21.8° C and in the second 26° C lot was 23.7° C.

Final preferendum of juvenile squawfish were best estimated from a plot of preferred temperatures against acclimation temperature (Figure 10). The final preferendum, that point at which the preferred temperature equals the acclimation temperature (Fry 1947) for juveniles was estimated as 24.6° C. Linear regression of individual modes vs. acclimation temperature provided a very similar estimate of final preferendum (25.5° C).

Acute preferenda of adult squawfish were not analyzed with Fisher's LSD test because differences were not significant. The acute preferenda increased with increasing acclimation temperature but were not significantly different, probably due to small sample sizes and higher variability within each acclimation temperature. The range of acute preferenda of adults acclimated to different temperatures was 21.5° to 25.7° C. Best estimate of adult final preferendum was 25.4° C (Figure 10). A linear regression of individual modes vs. acclimation temperature provided an estimate of 25.3° C for the adult final thermal preferendum.

Acute preferenda of adult and juvenile squawfish were not significantly different (Table 4) even though age has been found to be an important non-thermal factor influencing temperature preference in other species of fish (Bacon et al 1967, McCauley and Read 1973, Reynolds and Casterlin 1978, and Kwain and McCauley 1978). Young fishes select higher temperatures than do the older conspecifics; and in nature are found in the shallower, warmer water (McCauley and Huggins 1979). Squawfish distributions in nature are consistent with this pattern. Adults have been found in greatest abundance in water with mean summer temperatures of 11.1-21.1° C (Vanicek and Kramer 1969). Juveniles were primarily collected in waters ranging from 12-28° C (Holden 1977). The range of acute preferenda of juveniles (21.9-27° 6° C) agrees well with field data, the range for the adults (21.5-25.7° C) does not. Further testing of adults is necessary to determine if their temperature preference is significantly lower than that of juveniles; estimates of final preferenda suggest that adults and juveniles prefer similar temperatures. Hence, factors other than temperature may affect their distribution in the wild.

Other researchers have found close agreement between temperature preferences in the laboratory and temperatures actually occupied by fish in the field (Neill and Magnuson 1974, Stauffer et al. 1975, Magnuson et

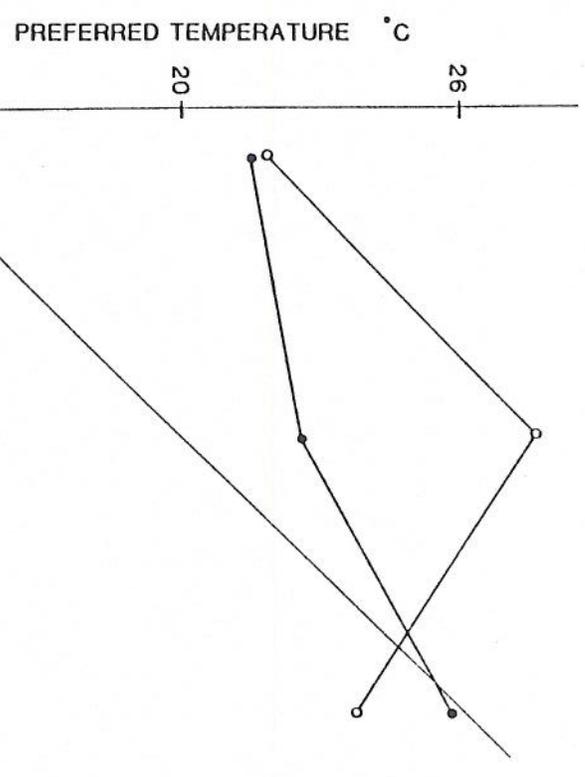


Figure 10

Relationship of preferred temperature (mean of individual modes) to acclimation temperature for Colorado squawfish. Final preferendum is the point of intersection with the 45° line (i.e. that point where selected temperature = acclimation temperature). Open circles represent juvenile fish; solid circles represent adult fish.

al. 1979). This agreement appears to hold for the species we have studied as well. Of the native Colorado fishes tested, acute preferred temperatures have ranged from 18-29° C (x modes) which is in good agreement with the historical summer temperatures of the Colorado River drainage.

Razorback suckers, humpback chubs, and bonytail chubs had almost identical final preferenda (23-24° C vs. 24° C vs. 24.2° C). Final preferendum for hybrid chubs could not be determined, but their acute preferendum of 23.8° C when acclimated to 20° C was very close to the final preferendum of razorbacks, humpbacks, and bonytails. Final preferendum of both juvenile and adult squawfish was only one degree higher from that of the other species. Considering the amount of variation in the estimates, all four species had essentially the same final preferendum.

Stauffer et al. (1975) found that they could predict the distribution of different species of fish in a heated powerplant effluent based on laboratory thermal preference of the fish. Conversely, razorback suckers, humpback chubs, bonytail chubs, and Colorado squawfish based on their laboratory preferences would avoid cold tailwaters of a reservoir. This avoidance probably explains at least in part the disappearance of native species from the Green River below Flaming Gorge Reservoir. For years after construction of the reservoir, native Colorado River fishes have not been found from the dam downstream to the confluence of the warmer Yampa River (McAda and Wydoski 1980, Holden 1978).

Egg Temperature Tolerance

Two lots of Colorado squawfish eggs received from the Fisheries Experiment Station of the Utah Division of Wildlife Resources, Logan, Utah, did not develop. A third lot developed only at 20° C (test incubation temperatures ranged from 5-35° C) with a 50 percent normal hatch and a 5-day incubation time. A fourth lot was incubated at test temperatures of 5°, 19°, 14°, 20°, and 26° C in the holding tanks, and 16°, 18°, 22°, and 26° C in the gradient trough. Water temperatures in the trough varied and increased as much as 3° C throughout the duration of the experiment. The only group that had a hatch higher than 50 percent was those held at 20° C. They had a 60 percent normal hatch and a 10-day incubation time. No hatching occurred among eggs held at 5°, 10°, or 14° C.

One lot of bonytail chub eggs were received on May 8, 1981, more than 24 hours after fertilization. Eggs were incubated at 5°, 10°, 14°, 20°, 26°, 31°, and 37° C, with four replicates per temperature. No eggs hatched at 5°, 10°, 31°, or 37° C. The percent normal hatch at 14° C ranged from 50-70 percent with a 10-day incubation time; at 20° C, 40-100 percent normal hatch with a 6-day incubation time and at 26° C, 70-90 percent normal hatch in two of the replicates with a 3-day incubation time eggs in the other two replicates died before hatching due to fungus infection.

One lot of humpback chub eggs was received on June 4, 1981, approximately 30 hours after fertilization. They were incubated at 5°, 10°, 14°, 20°, and 26° C with four replications per temperature. There was no hatch at 5° C, 30 percent at 10° C (after 19 days); 50 percent hatch at 14° C with a 16-day incubation time; 100 percent hatch into replicates at 20° C with a 4-day incubation time, and 90-100-percent hatch in two replicates at 26° C with a 3-day incubation time.

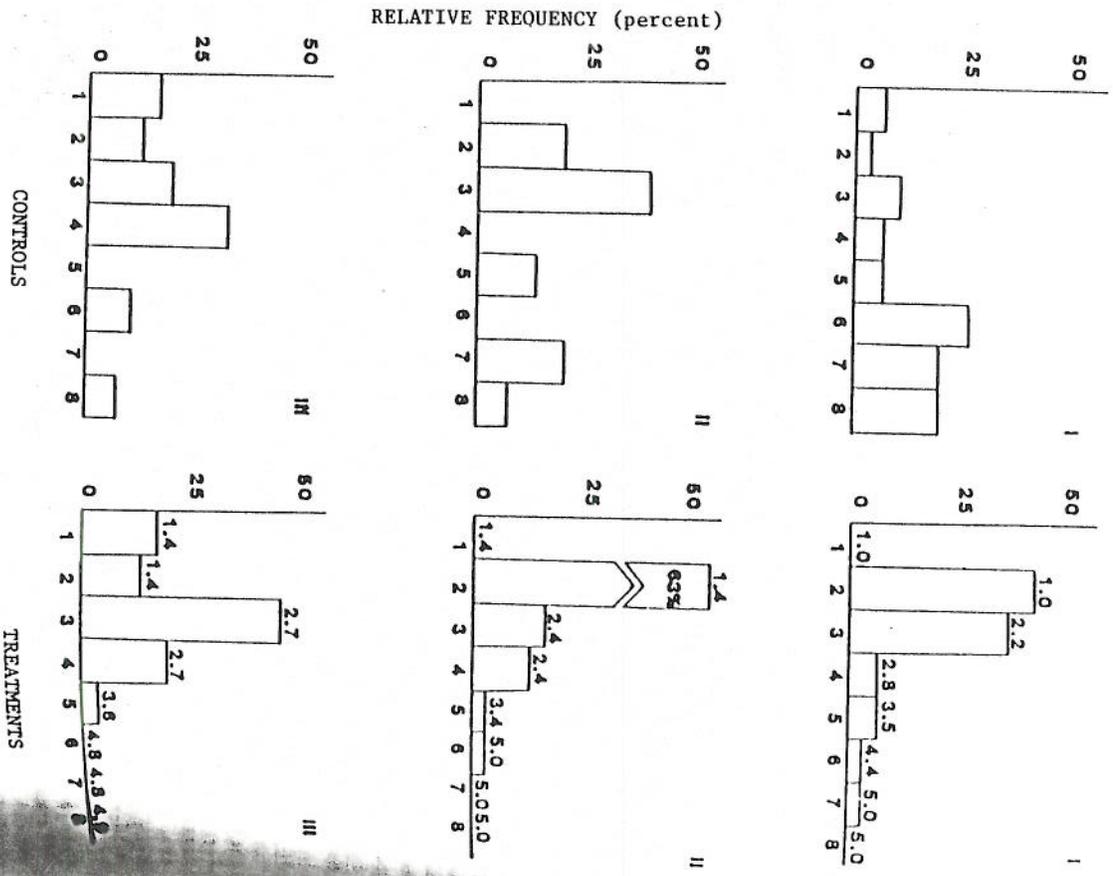
Total Dissolved Solids Preference

Colorado River fishes tested in the TDS gradient device showed varying degrees of schooling behavior, therefore, no independence could be assumed for their distributions and no analyses were performed. Pooled distributions, however, were made for comparisons between controls and treatments, and between species.

Colorado squawfish were the most mobile species in the gradient of the species tested evidentially because of their tendency to swim in the upper level of the water column and because of their relatively loose schooling behavior. Comparison of the control histograms showed that while the distributions were not uniform, the compartment modes were random between replicates (Figure 11). Conversely, the distributions of the treatments appeared to have very consistent modes with a range of 1.0-2.7 mmhos of conductivity. The pooled control distribution with an replicates indicated a fairly uniform control distribution with an unexplainable peak at compartment 3 (Figure 13). The treatments, however, indicated a definite preference for lower TDS (mode = 1.0-1.4 mmhos, Figure 13); 97 percent of the 90 fish tested avoided TDS >3.6 mmhos. Note that because the water was changed with each replicate, no two gradients were identical, and the concentrations of TDS for pooled distributions are given as the range of TDS in that compartment over the three replicates. Note also that the gradients had the same conductivity in more than one compartment (Figure 11). This condition was the result of a "gradient drift," i.e. the gradient started out with a different and discrete increment of TDS concentration in each compartment, but during the 24-hour period of the test some mixing caused by aeration and the fish swimming through the density interface occurred. This shift in gradient may explain why fish were not found in adjacent compartments even though they had equal conductivity (i.e. compartments diffused to same conductivity after the fish had made their final compartment selection).

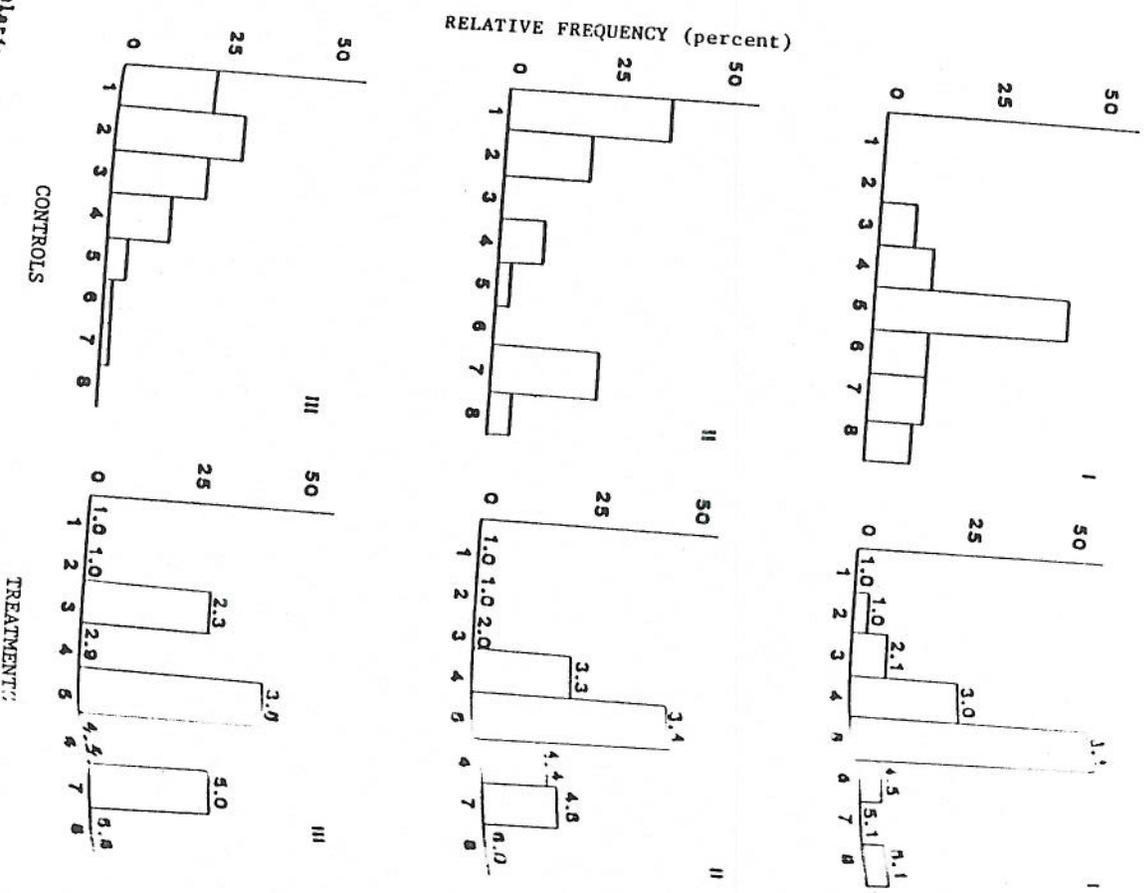
Bonytail chubs were also relatively weak schoolers (intermediate to squawfish and humpbacks) but were more bottom oriented than were the squawfish. Because the bonytails were the smallest of the species tested (2.5-5.0 cm in length), 40 fish/replicate could be used (n = 30/replicate for squawfish, n = 20 or 40/replicate for humpbacks). Comparison of the control histograms (Figure 12) indicated that the distributions were nonuniform, but compartment modes were random between replicates as were those of the squawfish (Figure 11). The treatments, however, had very consistent modes in compartment 5 with a range of 3.4-3.8 mmhos of conductivity and indicated that TDS avoidance levels are above 5.1 mmhos.

Figure 11



Relative frequency distribution of juvenile Colorado squawfish compartments of TDS gradient device (Figure 2) with and without gradient established. Numbers I, II, and III are replicates controls and treatments. Number over vertical bar is conductivity in mmhos. Data on location and conductivity are values after start of experiment.

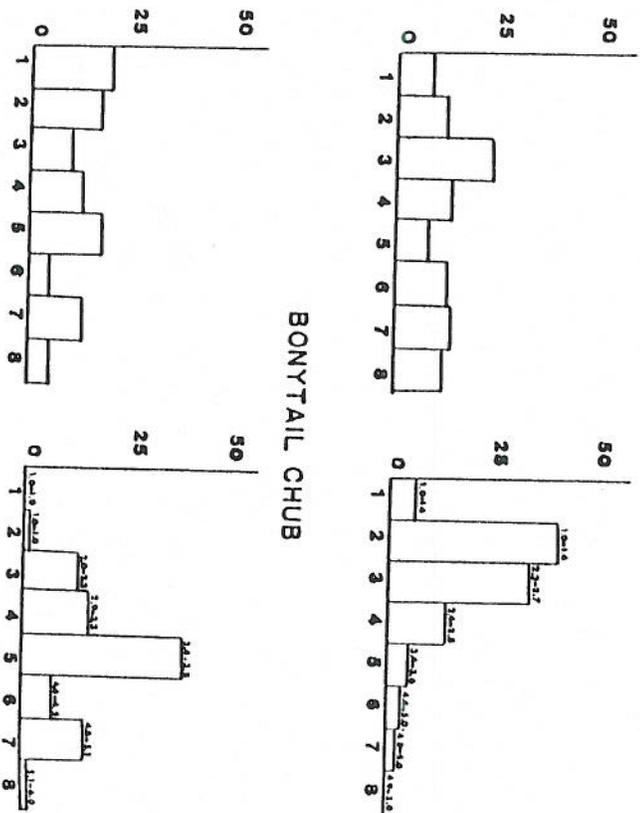
Figure 12



Relative frequency distribution of juvenile bonytail chub compartments of TDS gradient device (Figure 2) with and without gradient established. Numbers I, II, and III are replicates controls and treatments. Number over vertical bar is conductivity in mmhos. Data on location and conductivity are values after start of experiment.

COLORADO SQUAWFISH

Figure 13



Relative frequency distribution in 8 compartments of the TDS gradient device for pooled data from three treatments and three controls for each species. Numbers above vertical bar are the range of conductivity (mmhos) for that compartment over the three treatments (Figures 11 and 12).

pooled controls histograms indicated a relatively uniform distribution while the pooled treatment histogram had a strong peak in compartment 5 which had a TDS of 3.4-3.8 mmhos of conductivity (Figure 13).

Humpback chubs had the strongest schooling tendency of the fish tested and were bottom oriented like the bonytail chubs. Because of their larger size (8-12 cm), only 20 fish/replicate could be tested in the gradient. An initial two test replicates suggested that distribution of the fish was affected by the schooling tendency of this species so that fish tended to be either abundant or absent in a compartment (Figure 14, Table 1). Fish also appeared to be selecting the highest TDS concentration in the gradient. Hence, concentrations in each compartment except compartment 1 (Logan city water) were doubled so that conductivity up to 9.8 mmhos was present. Distribution of fish in three treatment replicates at these higher concentrations was just as random as for the controls (Figure 15). The mode of treatment 1 was in compartment 5 (6.8 mmhos); treatment 2 was bimodal (compartment 1 = 2.4 mmhos, compartment 7 = 8.5 mmhos); mode of treatment 3 was in compartment 2 (3.0 mmhos). Hence, it did not appear that humpbacks were consistently selecting a particular concentration of TDS within the available range.

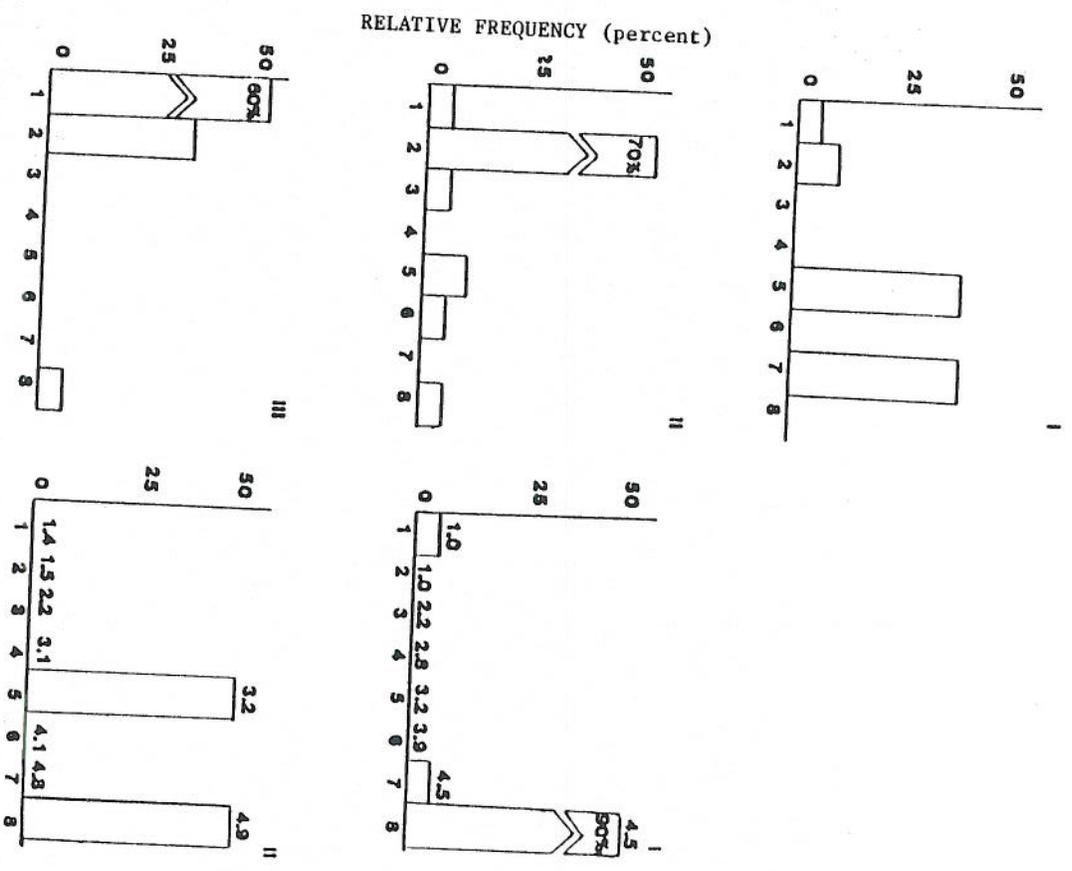
Part of the apparent random distribution of humpback chubs in the TDS gradient was attributed to the small sample size per replicate. A sample of 20 fish 8-12 cm in length was the maximum that could be held in the chamber and maintain dissolved oxygen levels over the 24-hour period. Fish from a later spawning and of sublarval length (ca. 4.0 cm) to test 40 individuals/replicate were eventually obtained. Water temperature which could not be controlled in the gradient had decreased, however, from the 16-18° C level used in all previous tests to 12° C. Temperature is a factor that must be considered in TDS preference determinations because low temperature hinders osmoregulation and thus influences tolerance to salinity (Davis and Simco 1976).

Controls and three test replicates were run with the smaller fish, cooler water temperature, and the original TDS concentrations used for the other species (Table 1). Fish in the first control run with the new conditions were rather uniformly distributed over the gradient (Figure 16). Succeeding control runs were less uniform, but distribution was more widespread than when 20 fish/replicate were used. In contrast, fish in test runs were consistently more abundant in compartment 3 where conductivity was either 1.3 or 2.3 mmhos. Conductivity in specific compartments is not constant during replicates because of gradient drift described earlier.

Pooled treatment results from humpbacks of both body sizes tested at 12° and 18° C indicated that most fish selected water with a conductivity of 1.3 to 3.0 mmhos (Figure 17). About 60 percent of the 220 fish tested were found after 24 hours in this conductivity range. No fish selected water with TDS above 9.4 mmhos, and only 5 percent was found in conductivity of 8.5-9.4 mmhos.

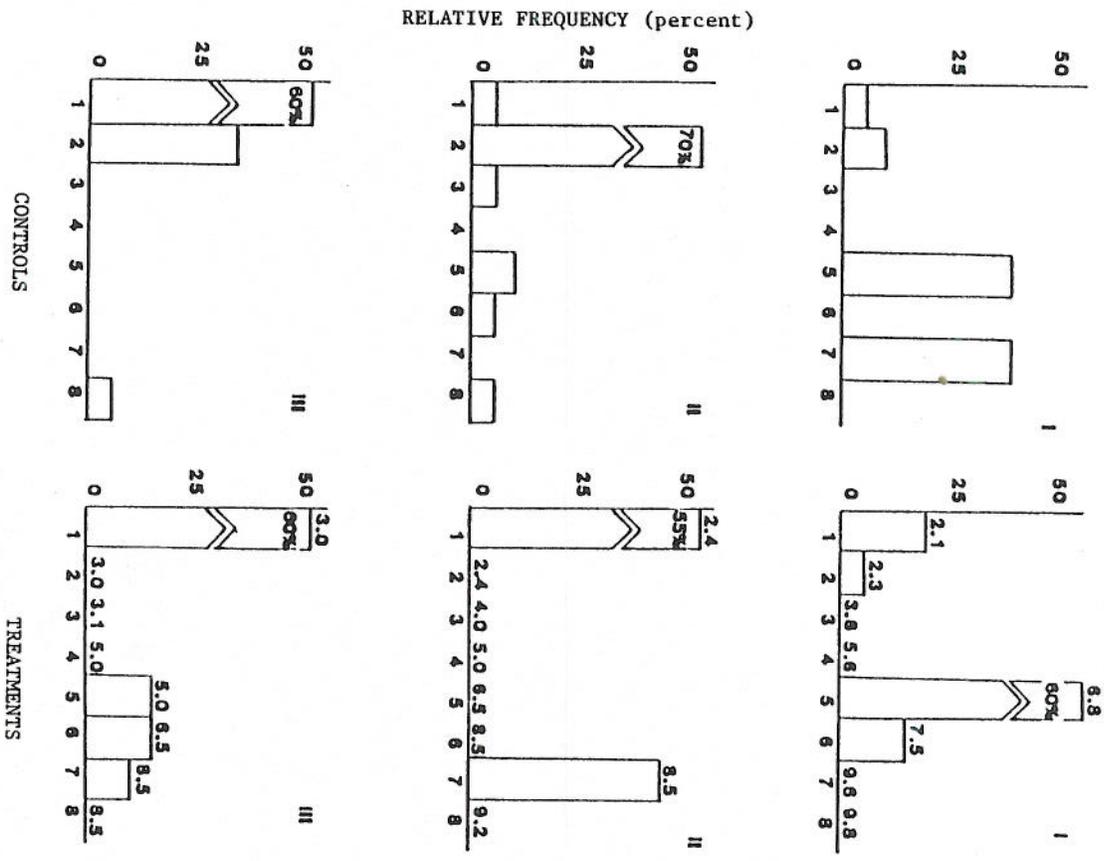
Pooled distribution of Colorado squawfish, bonytail chubs, and small humpback chubs agreed well in overall shape with those of the Gulf of California grunion (*Leuresthes sardina*) (Reynolds and Thomson 1974),

Figure 14



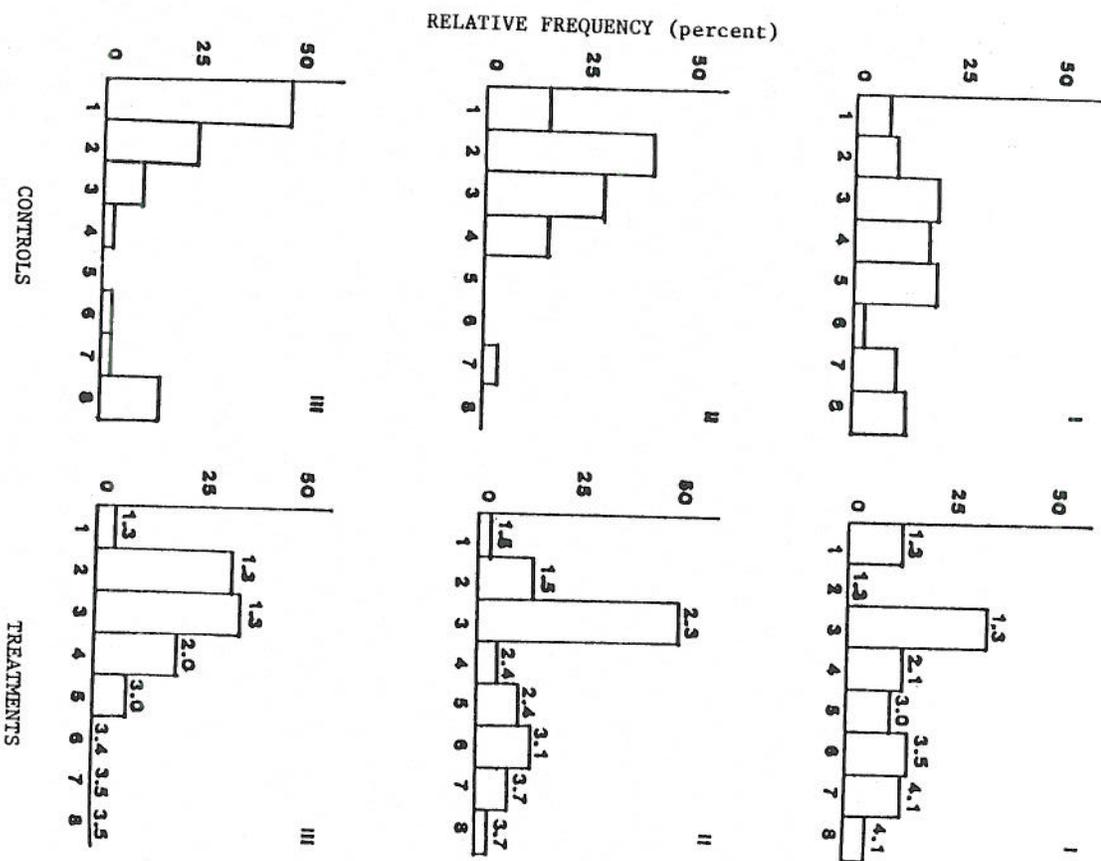
Relative frequency distribution of juvenile humpback chubs in 8 compartments to TDS Gradient device (Figure 2) with and without gradient treatments. Numbers I, II, and III are replicates for controls and on location and conductivity in mmhos. Data on location and conductivity are values 24 hours after start of experiment. N = 20 8-12-cm fish/replicate.

Figure 15



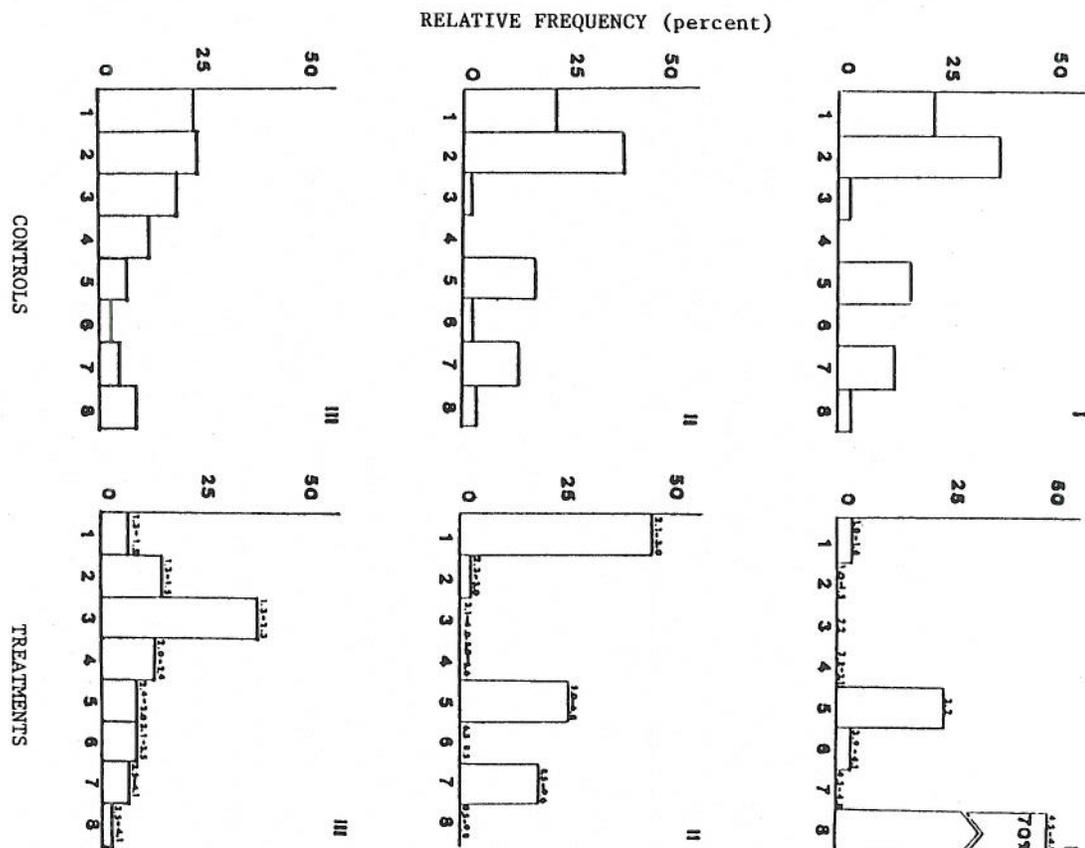
Relative frequency distribution of juvenile humpback chubs in 8 compartments to TDS Gradient device (Figure 2) with and without gradient established. Numbers I, II, and III are replicates for controls and treatments. Number over vertical bar is conductivity in mmhos. Data on location and conductivity are values 24 hours after start of experiment. N = 20 8-12-cm fish/replicate. Concentrations were double those of previous test.

Figure 16



Relative frequency distribution of juvenile humpback chubs in 8 compartments to TDS gradient device (Figure 2) with and without gradient established. Numbers I, II, and III are replicates for controls and treatments. Number over vertical bar is conductivity for controls and on location and conductivity are values 24 hours after start of the experiment. N = 40 4-cm fish/replicate tested at 120°C.

Figure 17



Relative frequency distribution in 8 compartments of the TDS gradient device for pooled data for 8-12 cm humpback chubs tested at 180°C (I, II) and 4-cm chubs tested at 120°C (III). Numbers above vertical bars are the range of conductivity (mmhos) for that compartment for 2 or 3 replicates (Figures 13, 14, and 15).

and the common welk (*Buccinum undatum*) (Staaland 1969), while distribution of the larger humpback did not. Both Reynolds and Thomson, and Staaland found good agreement with salinity preference in laboratory and salinities occupied in the field. McInerney (1964) also found good agreement between laboratory and field salinity preferences for five species of juvenile Pacific salmon, using a different type of preference chamber. Comparison of our experiments indicated that the Colorado squawfish has the lowest TDS preference (1.0-1.4 mmhos = 0.6-1.1 mg/ml) that of the bonytail chub (ca. 5.1 mmhos). TDS preference of the Colorado fish is similar to TDS levels found in the Green and Upper Colorado Rivers today but the bonytail chub preference (3.4-3.8 mmhos = 4.1-4.7 mg/ml) is much higher. Humpback chub TDS preference (1.3-3.0 mmhos = 1.0-3.5 mg/ml) appears to be intermediate to squawfish and bonytails, however, their TDS avoidance level (>8.5 mmhos) may be much higher. From the results of these experiments, one would predict that of the species tested, the Colorado squawfish would be the most affected by increases in TDS caused from evaporative loss in reservoirs and any salt release from oil shale development. TDS preference of the bonytail and humpback chubs is also low enough that habitat could be lost to them by TDS increases.

Hematology

No differences were found between sex or with length (15-30 cm) in the blood constituents of 60 (30 male, 30 female) juvenile razorback suckers. Consequently, blood data for sexes were pooled and averaged (Table 7). Hematocrit averaged 33 percent, hemoglobin average 7.5 mg/100 ml, and erythrocytes totaled 1.32 x 10⁶/mm³. These parameters are correlated and respond rapidly to changes in environmental oxygen levels. Leucocytes totaled 26.9 x 10³/mm³ and were 60.4 percent lymphocytes, 33.7 percent thrombocytes, and 5.4 percent granulocytes. We classified 1.9 percent of the granulocytes as eosinophils based on recommendations of Lester and Daniels (1976). The remainder of the granulocytes were identified as neutrophils. An analysis of the white cell portion of fish blood has been commonly employed to determine the effects of injury or infectious diseases (Pickford et al. 1971). Glucose (blood sugar), a parameter frequently employed to monitor general stress (Hartingh 1977) averaged 52.7 + 13.8 mg/100 ml whole blood. Blood chloride averaged 108 mg/l. Chloride and other blood electrolytes can be indicative of the osmoregulatory state of a fish (Mazeaud et al. 1977).

Hematocrit of juvenile squawfish (n = 31) averaged 38 percent, hemoglobin averaged 7.5 mg/100 ml, and the red blood cells numbered 1.59 x 10⁶/mm³. White blood cells numbered 77.5 x 10³/mm³ and, as in the razorback sucker, lymphocytes were the most abundant cell (69.8 percent). Thrombocytes and granulocytes made up 25 percent and 3.66 percent of the remaining white blood cells respectively. We could obtain only 50-150 ul of whole blood from the squawfish examined and therefore had an insufficient volume to determine chloride and glucose levels. However, mean chloride (99.1 mg/l) and glucose (107.1 mg/100 ml) were determined for large squawfish (Table 7). Large squawfish had significantly less total plasma protein levels than small squawfish. Otherwise, the hematological profiles of juveniles and adults were similar.

Table 7
Hematological characteristics of four Colorado River fishes

Parameter	Razorback suckers		Squawfish		Humpback chub	Bonytail chub
	(56)	Juvenile (30)	Adult (19)	(30)	(30)	(31)
Length (millimeters)	240.6	108.3	414	92.3	98.33	98.33
Range	146-327	98-120	375-497	82-111	87-116	87-116
Weight (grams)	151.3	8.0	---	5.7	8.97	8.97
Range	30-328	6.2-11.9	---	3.3-10.2	5.7-14.0	5.7-14.0
Hematocrit (percent)	33.5	38.7	38.0	30.2	34.5	34.5
Standard deviation	4.5	7.0	38.0	7.8	5.8	5.8
Total protein (g/200 ml)	4.9	10.9	1/5.57	6.1	8.8	8.8
Standard deviation	0.7	1.7	0.8	1.3	1.1	1.1
Red blood cells (10 ⁶ /mm ³)	1.32	1.59	2.085	1.92	2.22	2.22
Standard deviation	0.27	0.41	0.49	0.33	0.48	0.48
White blood cells (10 ³ /mm ³)	27.1	72.0	90.4	52.5	91.6	91.6
Standard deviation	8.7	27.2	25.3	13.4	21.4	21.4
Hemoglobin (g/100 ml)	7.5	7.5	9.4	7.2	7.1	7.1
Standard deviation	1.0	1.1	1.5	0.9	1.1	1.1
Glucose (mg/100 ml)	52.7	2/	107.1	2/	2/	2/
Standard deviation	13.8	108.0	99.1	2/	2/	2/
Chloride (mEq/l)	9.2	2/	20.8	33.4	63.0	63.0
Standard deviation	60.6	69.8	62.4	10.0	8.7	8.7
Lymphocyte (percent)	16.0	11.3	9.1	62.5	34.3	34.3
Standard deviation	33.9	25.3	31.4	10.5	9.7	9.7
Thrombocytes (percent)	14.6	11.0	7.7	0.8	0.6	0.6
Standard deviation	3.5	0.3	1/2.0	1.1	0.9	0.9
Neutrophils (percent)	4.4	0.5	2.5	2.7	1.7	1.7
Standard deviation	1.9	3.36	3.8	2.4	1.3	1.3
Eosinophils (percent)	2.5	0.9	4.5	0.6	0.0	0.0
Standard deviation	0.0	0.9	1/0.5	1.1	---	---
Other leucocytes (percent)	---	1.5	0.6	---	---	---
Standard deviation	---	1.5	0.6	---	---	---

1/ Juvenile and adults significantly different, t-test, p=0.05.
2/ Insufficient sample volume for individual determinations.

Hematocrit of juvenile humpback chub averaged 30 percent, hemoglobin averaged 7.2 g/100 ml, and red blood cells numbered $1.92 \times 10^6/\text{mm}^3$. Leucocytes numbered $52.5 \times 10^3/\text{mm}^3$ but, unlike the other two species examined, thrombocytes were the most abundant cell (62.4 percent), followed by lymphocytes (33.4 percent) and granulocytes (3.5 percent). Less than 1 percent of the white blood cells were identified as either hemoblasts or macrophages according to descriptions presented by Grizzle and Rogers (1979) for channel catfish (*Ictalurus punctatus*).

Hematocrit of juvenile bonytail chubs averaged 34.5 percent, hemoglobin averaged 7.1 g/100 ml, and red blood cells numbered $2.22 \times 10^6/\text{mm}^3$. Leucocytes numbered $91.6 \times 10^3/\text{mm}^3$. Like the razorback and juvenile squawfish, lymphocytes of the bonytail were the most abundant (63 percent) white blood cell, followed by the thrombocytes (34.3 percent), and granulocytes (2.5 percent). Total protein levels averaged 8.8 g/100 ml. Overall, the hematocrit of the bonytail was similar to that of the other juvenile rare species.

Certain similarities were apparent when comparing the hematological profiles of the three Colorado River species (Table 7) with those of three commonly cultured species (Table 8). The white blood cell types found in the Colorado River fish were similar in appearance and occurrence to those of other species. The hematocrit, hemoglobin, and total protein values were in the same order of magnitude among species and similar to the range described as normal for teleost fishes (Stachell 1971). The number of blood cells was the most variable parameter among species.

These hematological data may be useful to fish culturists for assessing the effects of culture and stocking practices on fish health. Recovery plans for the rare fish now or, may in the future, suggest the use of artificial propagation as a means of protecting the species. Clinical tests have been useful to the fish culturist for monitoring fish health and diagnosing disease, diet, and water quality problems (Blaxhall 1972, Wedemeyer and Yasutake 1977). For example, elevated total protein and blood chloride levels may indicate impaired water balance due to osmoregulatory dysfunction. Decreased erythrocyte counts, hematocrit and hemoglobin levels may indicate diet-induced anemias. Leukopenia may indicate acute stress. The hematological characteristics presented here may not represent those of fish reared on other diets and at other water temperatures. Therefore, we recommend that a normal hematological profile be established for each hatchery and compared with our values. Because most fish will be reared only the fingerling stage, our data may be more comparable than if variables such as sex, degree of maturity, and season were involved.

Two methods are commonly used to determine hemoglobin and total protein levels in fish. Colorimetric methods using a bench-top meter (e.g., Bausch and Lomb Spectronic 70 spectrophotometer) are considered more accurate than refractometric methods using a hand-held meter (e.g., American Optical Brix-Goldberg refractometer for total protein or an American Optical Hb-Meter for hemoglobin) (Wedemeyer and Yasutake 1977). Hand-held meters are portable and most suited for field or hatchery work. A comparison was made between the two methods for determining

Table 8
Baseline hematology of three species of commonly cultured fish^{1/}

Parameter	Goldfish	Channel catfish	Rainbow trout
Hematocrit (percent)	37	24	24-43
Hemoglobin (g/100 ml)	3.8	6.6	5.4-9.3
Total protein (g/100 ml)	10.6	5.4	2-6
Glucose (mg/100 ml)	28.5	29	41-151
Chloride (meq/l)		114	84-132
Erythrocytes ($10^3/\text{mm}^3$)	1.24	2.44	0.77-20.9
Leucocytes ($10^3/\text{mm}^3$)	21.9	164	7.8-20.9
Leucocytes differential			
Lymphocyte (percent)	77	54	89-98
Thrombocyte	8	41	1-6
Granulocyte (percent)	11.5	3	1-9
Other (percent)	3.5	1.0	0

^{1/} Data from Watson et al. 1963, Weirreb and Weirreb 1969, Humm et al. 1968; Smith et al. 1952; Chavln and Young 1970; Wedemeyer and Yasutake 1977.

hemoglobin and total protein levels of the Colorado squawfish and the razorback sucker. Blood was obtained using routine methods, and individual samples were then analyzed using both techniques (Table 9). The refractometric method recorded higher values for both parameters than did the spectrometric method. While the accuracy of the spectrophotometer was probably greater, the precision (as indicated by the magnitude of the standard deviations) of the methods was similar. The hand-held meter would, therefore, be a useful tool for monitoring trends or comparing one group of fish to another.

Medemeyer and Yasutake (1977) developed a graph useful in determining the sample size needed to be 95 percent certain of determining a 10, 15, 20, or 50 percent difference in blood chemistry between experimental and control groups. The sample size depended on the coefficient of variation for each clinical test (Table 8). Sample sizes needed to detect a 20 percent difference in hemoglobin and total protein for the squawfish would be 15 and 12 individuals, respectively, for the refractometer, and 30 and 19 individuals, respectively, for the photometer. Sample sizes needed to detect a 20 percent difference in hemoglobin and total protein for the razorback would be 22 and 21, respectively, for the refractometer and 30 and 8, respectively, for the spectrophotometer.

We evaluated transportation stress in 40 (20 male, 20 female) razorback suckers using blood chloride and glucose levels. Blood glucose increased from 54 mg/100 ml at Willow Beach Hatchery to 144 mg/100 ml after hauling to Logan, Utah. A hypochloremic trend was found in the transported fish but the decrease in blood chloride from 108 mEq/l at the hatchery to 99 mEq/l after hauling was not a statistically significant change. No mortalities due to hauling were observed either during the trip or during the 1 week post-hauling period. There was no difference between sexes in chloride or glucose levels before or after hauling. Our finding suggests that salt might be used to advantage during transport. Many studies have shown that the use of salt (0.1-3.0 percent, depending on species) in hauling tanks can be effective in reducing osmoregulatory stress (Hartingh et al. 1975).

Swimming Ability

Swimming speeds of fish are usually defined as (1) burst speed (darting for a few seconds at 8-12 body lengths/sec), (2) sustained speed (swimming for several minutes at 4-7 body lengths/sec), and (3) cruising speed (swimming for hours at 2-4 body lengths/sec). Great variability exists in swimming data collected in the artificial conditions of a stamnia tunnel (Bell 1973, Hettler 1977). We also noted such variability especially at water velocities between the extremes tested at a temperature. For example, one fish in a pair would occasionally fire in a few minutes while the remaining fish swam for 2 hours. We compared the swimming ability of fish tested singly and in pairs and found no difference. We felt, therefore, that the behavior of the fish that we tested probably represented different levels of motivation and ability within each species.

Table 9
Comparison of refractometric and colorometric methods for determining hemoglobin and total protein levels in the Colorado squawfish and razorback sucker^{1/}

Species	Hemoglobin (g/100 ml)				Total protein (g/100 ml)			
	Number	Refracto- meter	Number	Spectro- photometer	Number	Refracto- meter	Number	Spectro- photometer
Squawfish								
Mean	19	2/9.35	15	7.74	18	5.57	17	2/4.99
Standard deviation		1.49		1.95		0.76		0.91
Coefficient variation		15.9		25.9		13.6		18.2
Razorback								
Mean	13	5.94	13	5.28	13	3.84	13	3.55
Standard deviation		1.15		1.30		0.72		0.38
Coefficient variation		19.4		24.6		18.8		10.7

^{1/} A t-test was employed to compare means obtained by the two methods.
^{2/} Significant at 0.01 probability level.

Several cursory studies were conducted to determine testing protocol. Fish conditioned to the tunnel for 10 minutes at no current and for 5 and 20 minutes at 0.15 m/sec. did not perform differently when tested at 0.45 m/sec. Retesting individual fish four times at 48-hour intervals did not affect performance. Occasionally a fish did not learn to swim in the tunnel in the 5-minute conditioning time, and was not tested further.

Razorbacks could cruise for about 2 hours in water velocities ranging from 0.15-0.3 m/sec. (Table 10). However, fish could only swim for about 1 minute in a water velocity of about 0.6 m/sec. Larger fish performed significantly ($p = 0.05$) better than did smaller fish (Table 11). Water temperature did not significantly affect swimming ability. Most fish tested at 0.15 m/sec. exhibited reotrophic behavior but swam very little since they could maintain position in the tunnel by positioning the pectoral fins against the bottom.

Juvenile squawfish were able to swim for 1 hour or more in velocities of about 0.39 m/sec. Ability rapidly dropped at higher velocities, and no fish could swim for more than a minute at velocities of 0.57 m/sec (Table 12). Juvenile squawfish tested at 20° and 26° C had significantly greater swimming ability than those tested at 14° C (Table 11). Within a length group of 77-142 mm, no significant difference in swimming ability of juvenile squawfish due to length could be detected. However, fish length was an important factor in determining swimming ability of adult squawfish (375-697 mm in length). Adult fish had greater endurance than the juveniles (Table 13). Large squawfish were able to swim for 1 hour or more in velocities of about 0.91 m/sec—about twice the stamina of smaller juveniles. Stamina rapidly decreased as velocity increased, and fish could swim for only a few minutes at 1.09 m/sec. Neither fish length (within the large fish group) nor temperature significantly affected the time to fatigue of large squawfish (Table 11).

Juvenile bonytail chubs had time-to-fatigue levels which were similar to those of other juvenile fish tested. Sustained swimming was observed at 0.45 m/sec at 14° C, 0.56 m/sec at 20° C, and 0.63 m/sec at 26° C. Above these water velocity levels, swimming ability rapidly declined (Table 14). Bonytail performance was significantly affected by water temperature (Table 11). For example, fish could swim for less than 1 minute at 0.57 m/sec at 14° C, but at 20° C, they could swim for over an hour at this velocity. The size range of fish tested (73-120 mm in length) was apparently insufficient to detect size related differences in swimming ability (Table 11).

Humpback chub swimming stamina was similar to that of the squawfish and razorback. Humpbacks could swim for about 2 hours at 0.32 m/sec but only for a few minutes at 0.78 m/sec (Table 15). Their ability was positively and significantly related to temperature. Larger fish (134 mm maximum length) performed significantly ($p < 0.05$) better than did smaller fish (73 mm minimum length).

The results of our studies compare well (considering differences in test conditions) with data collected for similar-sized fish of other species (Table 16). The fish used in our work were reared under culture conditions in low velocity waters since hatching. Lack of conditioning

Table 10
Swimming performance (minutes to fatigue) of razorback suckers (15-30 cm in length)
at different water temperatures and velocities
(A test was discontinued when a fish swam for 120 minutes)

Velocity (m/sec)	12°C			20°C			26°C		
	Number	Mean	Standard deviation	Number	Mean	Standard deviation	Number	Mean	Standard deviation
0.15	5	120	0	5	120	0	-	---	---
0.30	12	82.12	56.1	10	105.37	31.1	6	100.5	47.8
0.375	9	42.23	58.4	3	80.4	68.6	5	111.0	20.1
0.45	10	13.92	37.3	8	17.27	41.5	8	30.43	55.3
0.60	10	1.32	0.5	10	1.75	1.25	10	0.45	0.72

1/ ns = not significant at 0.05 probability level.
 2/ Significant at 0.01 probability level.
 3/ Significant at 0.05 probability level.

Table 11
 Analysis of variance of the effects of water velocity (main effect), temperature (main effect), and fish length (covariate) on swimming-time-to-fatigue of four Colorado River fishes

Species	Source of variation	Degrees of freedom	Observed "F"
Razorback sucker	Temperature	2	2.7 ns ^{1/}
	Velocity	4	2/38.6
	Length	1	3/4.2
Colorado squawfish juvenile	Temperature	2	2/19.4
	Velocity	12	2/23.5
	Length	1	3.7 ns ^{1/}
Adults	Temperature	2	2.9 ns ^{1/}
	Velocity	3	2/71.1
	Length	1	0.1 ns ^{1/}
Bonytrawl chub	Temperature	2	2/7.7
	Velocity	7	2/14.6
	Length	1	2.8 ns ^{1/}
Humpback chub	Temperature	2	2/20.6
	Velocity	17	2/9.3
	Length	1	3/5.9

Table 12
 Swimming performance (minutes to fatigue) of juvenile Colorado squawfish (77-142 mm in length) at different water temperatures and velocities
 (A test was discontinued if a fish swam for 120 minutes)

Velocity (m/sec)	14°C			20°C			26°C		
	Number	Mean	Standard deviation	Number	Mean	Standard deviation	Number	Mean	Standard deviation
0.21	15	120	0.0						
0.24	5	120	0.0						
0.27	5	96.23	52.3						
0.30	5	72.8	64.6						
0.33	5	120	0						
0.36	6	80.95	60.5						
0.39	8	61.1	63.0						
0.42	8	16.77	41.7	6	120	0	10	120	0
0.45	8	1.48	1.65	9	67.58	62.2	8	120	0
0.48	7	1.05	0.58	10	37.25	57.1	10	61.33	61.9
0.51	6	0.98	0.72	12	11.55	34.1	9	42.88	58.1
0.54				12	1.07	0.73	10	25.90	49.6
0.57				12	0.98	0.63	10	1.2	1.28
							9	0.92	0.72

Table 13
 Swimming performance (minutes to fatigue) of large squawfish (375-497 mm in length) at different water temperatures and velocities
 (A test was discontinued if a fish swam for 120 minutes)
 Data were analyzed by analysis of variance^{1/}

Velocity (m/sec)	14°C			20°C			26°C		
	Number	Mean	Standard deviation	Number	Mean	Standard deviation	Number	Mean	Standard deviation
0.75	4	120.0	0.0	2	120.0	0.0	4	116.7	6.7
0.91	6	50.7	45.6	5	120.0	0.0	4	46.3	52.0
1.06	5	2.5	1.0	5	3.9	3.9	4	1.9	1.0
1.20	4	0.8	0.6	3	1.6	0.5	3	0.6	0.1

^{1/} Analysis of variance of the effects of water velocity (main effect), temperature (main effect), and fish length (covariate) on swimming-time-to-fatigue.

Table 14
Swimming performance (minutes to fatigue) of bonytail chub (72-120 mm in length)
at different water temperatures and velocities
(A test was discontinued if a fish swam for 120 minutes)
Data were analyzed by analysis of variance^{1/}

Velocity (m/sec)	14°C			20°C			26°C		
	Number	Mean	Standard deviation	Number	Mean	Standard deviation	Number	Mean	Standard deviation
0.33	4	120.0	0.0						
0.36									
0.39	10	108.1	37.6	4	120.0	0.0	4	120.0	0.0
0.42				10	74.1	59.3	3	120.0	0.0
0.45	10	72.7	61.1	10	60.9	62.3	12	80.5	58.4
0.48	10	25.6	49.8	11	66.4	61.7	12	51.1	60.8
0.51	10	0.8	0.5	16	1.8	2.3	10	61.7	61.4
0.54				4	2.7	0.7	12	0.6	0.3
0.57							12	0.7	0.6
0.60									
0.63									
0.69									
0.72									
0.75									

^{1/} Analysis of variance of the effects of water velocity (main effect), temperature (main effect), and fish length (covariate) on swimming-time-to-fatigue.

Table 15
Swimming performance (minutes to fatigue) of humpback chubs (73-134 mm in length)
at different water temperatures and velocities
(A test was discontinued if a fish swam for 120 minutes)

Velocity (m/sec)	14°C			20°C			26°C		
	Number	Mean	Standard deviation	Number	Mean	Standard deviation	Number	Mean	Standard deviation
0.27	10	116.27	11.8						
0.30	10	117.05	9.3						
0.33	10	95.18	47.8						
0.36	10	96.47	49.6						
0.39	10	74.15	59.2						
0.42	10	44.82	52.4						
0.45	10	28.05	48.6	10	74.38	58.9	8	120	0
0.48	10	4.68	2.8	-	-	-	10	108.07	37.8
0.51	10	2.22	1.4	10	85.22	56.0	10	60.65	62.6
0.54				-	-	-	10	60.62	62.6
0.57				10	39.8	56.5	-	-	-
0.60				10	2.03	1.3	14	61.75	60.4
0.63				11	23.77	47.6	-	-	-
0.66				-	-	-	14	61.45	60.8
0.69				10	13.43	37.4	-	-	-
0.72				10	4.0	4.8	10	2.32	3.8
0.75							-	-	-
0.78							9	2.08	1.8

Table 16
Sustained swimming speeds of various species of fish
(28-120 mm in length) compared to swimming speeds of juveniles
of three species of rare Colorado River fish

Species	Sustained speed ^{1/}		Reference
	ft./sec	m/sec	
Colorado River fish ^{2/}			
Humpback chub	2.2	0.66	This study
Colorado squawfish	1.6	0.51	This study
Razorback sucker	1.47	0.45	This study
Bonytail chub	1.9	0.57	This study
Other species (small fish or fingerlings)			
Striped bass (12 cm)	2.75	0.83	Bell 1973
Atlantic menhaden (6 cm)	0.70	0.21	Hettler 1977
Fathead minnow (5 cm)	0.8	0.24	Hettler 1977
Largemouth bass fingerlings	0.6	0.18	MacLeod 1967
Rainbow trout (6 cm)	0.75	0.23	MacLeod 1967
Emerald shiner (6.5 cm)	1.77	0.54	Fry and Cox 1970
Other species (adults)	1.7	0.52	Jones et al. 1974
White suckers	5.2	1.58	Bell 1973
Carp	4.0	1.22	Bell 1973
Whitefish	4.4	1.34	Bell 1973
Brown trout	6.2	1.89	Bell 1973
Coho salmon	10.8	3.29	Bell 1973
Squawfish	3.5	1.06	This study

^{1/} Sustained speed is that speed which the fish can maintain for a matter of minutes.
^{2/} Sustained speed at 20°C.

to test velocities may have resulted in reduced time-to-fatigue values compared to wild or exercised fish. Wild fish can swim at a rate of about 30 percent higher than cultured fish (Green 1964, Thomas et al. 1964). Exercised fish usually have greater swimming ability than unexercised fish (Brett et al. 1958, Hammond and Heckman 1966).

A direct relationship between fish length and swimming speed and stamina is fairly well established (Bainbridge 1958). However, small fish usually show greater speed as measured in body lengths per second than larger fish. We also noted the positive relationship between length and stamina in our studies. We expect that adult fish of each species have significantly greater stamina than do juveniles of the same species. Some preliminary data on stamina of adult squawfish support this expectation. The average sustained speed at 14° C of adult squawfish (373-416 mm in length) was 0.76-1.0 m/sec, about twice that of juveniles at 14° C. One might expect the difference to be greater, however, temperature effects have a relatively greater effect on large fish than on juveniles (Brett 1967, Jones et al. 1974).

Temperature influences the swimming ability of most fish (Brett et al. 1958). The typical pattern of influence is that of an adverse effect on either side of the optimum temperature range. Our data generally indicated that 20-26° C was in the range of the optimum temperature for each species. All fish performed more poorly at 14° C than at 20° C or 26° C. We did not examine swimming performance at temperature above 26° C where performance might have been adversely affected.

Brett and Glass (1973) in summarizing swimming literature on the Pacific salmon presented temperature-fish size-response surfaces for critical swimming speed. Uniform isopleths were evident, i.e. temperature effects on the swimming speed of large and small fish were similar. Our data indicate otherwise. The swimming ability of the juvenile, small (73-142 mm in length) squawfish, bonytail chubs, and humpback chubs was significantly and directly related to water temperature. On the other hand, swimming ability of the older, larger (132-497 mm in length) razorback suckers and squawfish was not significantly affected by water temperature. The difference between the generalizations made from salmonid literature and our data may be due to the oligothermal nature of salmonids and the eurythermal nature of the rare fish of the Colorado. Little information is available on temperature-fish size-effects on swimming speeds of warm water fish. There is some indication (Glova and McInerney 1977) that the relative change in critical swimming speed with temperature is less in large (12 cm) than in small (3 cm) salmon. Brett and Glass (1973) also concluded that optimum temperature produces a more pronounced maximum metabolic rate for small fish than for large. This may be another indication that the swimming ability of small fish may be more responsive to temperature change than that of large fish.

Swimming performance of fish has been investigated in various ways. Some investigators have measured "burst speed" at low water velocity. Others have determined the water velocity at which fatigue occurs using continual incremental increases in water speed. Still others have determined the time required to fatigue at a fixed water velocity. We

employed the latter technique to determine the range of water velocities each species could tolerate up to 2 hours swimming time. We feel that these data are more meaningful to workers who must predict the impact of various alterations in water flow regimes on fish behavior. And, this information can be readily employed in planning and designing man-made alterations to the stream or riverine environment.

The construction of highways requires the installation of culverts at river crossing. Faulty culvert design which allows excessive water flow rates can create barriers to upstream fish migration. The ability of fish to swim through culverts has been investigated by Wales (1950), Metsker (1970) and Blahn (1963). Watts (1974) and MacPhee and Watts (1976) discussed means of incorporating fish swimming speeds into culvert design. A simple way to use the data we have collected is to determine the distance a fish can swim at a certain flow through a proposed culvert using the following formula

$$D = 60VT$$

where D = distance in meters a fish can travel before becoming fatigued, V = velocity of water through the proposed culvert in m/sec, and T = fatigue time at V (T is found in the accompanying data tables for fatigue times of each species tested). For example, if at a water temperature of 20° C, the flow through a 100-m culvert was to be 1.2 m/sec, then most adult Colorado squawfish of the size tested in our experiments could travel only 96 m before becoming fatigued. Hence, most might not pass through the 100-m-long culvert. However, if the projected water velocity was about 1.0 m/sec then the fish would be able to travel 234 m and easily pass through the 100-m-long culvert,

$$(60) (1.0) (3.9) = 234 \text{ m.}$$

Hydroelectric plants and other industrial complexes usually remove water from a river at a water intake structure. When water flow rates at these structures are excessive, fish become impinged on intake screens (Barnes 1976). Knowledge of swimming abilities of resident fishes has been employed in estimating the risk in some cases (Hettler 1977, Barnes 1976). Bozeman (1977) summarized that 0.15 m/sec would be the maximum acceptable velocity for protecting small fish. Assuming average approach velocities of 0.3 m/sec at the trashrack of a powerplant, all species tested on our study should be able to avoid being overcome by the current.

Dams constitute a physical barrier which fish cannot overcome without the aid of a fish ladder or fishway. Swimming speeds of fish (in most cases salmonids) have been employed in designing fishways (Collins et al. 1961, Conner et al. 1963, Slatick 1970). Also of concern are effects of periodic releases of water on stream flows below damsites. For example, large quantities of released water may create such excessive in-stream flows that the habitat below the dam would be unsuited for fish. Adults frequently seek higher velocities at obstructions and this behavior could be used to attract adult fish to fishway entrances (Bell 1973). However, attractant velocities should be well under the darting speed but may exceed the cruising speed for species and sizes involved.

When guiding or directing fish with water velocity, smooth transitions and accelerations are required to prevent the fish from hesitating or refusing to enter an area. In summary, data attained in this study on swimming ability of Colorado River fishes are of value in the design of many structures which alter or control river flow rate.

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