EFFECTS OF REDUCED WATER TEMPERATURE ON SWIMMING PERFORMANCE AND PREDATION VULNERABILITY OF AGE-0 FLANNELMOUTH SUCKER (*Catostomus latipinnis*)

by

David Lance Ward

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SIGNED: David Wind

APPROVAL BY THESIS COMMITTEE

This thesis has been approved on the date shown below:

Scott A. Bonar
Associate Professor, Wildlife and Fisheries Science

William J. Matter
Associate Professor, Wildlife and Fisheries Science

Kevin Fitzsimmons
Associate Professor, Soil and Water Science

April 10, 2001

April 10, 2001

April 10, 2001

Date

Date

Date
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TABLE OF CONTENTS

LIST OF FIGURES ................................................................. 6
LIST OF TABLES ...................................................................... 7
ABSTRACT ............................................................................... 8
INTRODUCTION ......................................................................... 9
PRESENT STUDY ....................................................................... 11
   AN INEXPENSIVE SWIM TUNNEL FOR AGE-0 FISH ............... 11
   EFFECTS OF REDUCED WATER TEMPERATURE ON SWIMMING PERFORMANCE ........................................ 11
   EFFECTS OF COLD SHOCK ON VULNERABILITY TO PREDATION ................. 13
   GROWTH OF AGE-0 FLANNELMOUTH SUCKER AT 20°C .......... 13

APPENDIX A. AN INEXPENSIVE SWIM TUNNEL FOR MEASURING THE SWIMMING ABILITY OF AGE-0 FISH
   ABSTRACT ........................................................................ 14
   INTRODUCTION .................................................................. 14
   METHODS .......................................................................... 15
   RESULTS AND DISCUSSION .................................................. 20

APPENDIX B. EFFECTS OF REDUCED WATER TEMPERATURE ON SWIMMING PERFORMANCE OF AGE-0 FLANNELMOUTH SUCKER
   ABSTRACT ........................................................................ 22
   INTRODUCTION .................................................................. 23
   METHODS .......................................................................... 24
      Effects of Retesting ......................................................... 26
      Effects of Cold Shock ..................................................... 26
      Effects of Captive-rearing ................................................. 27
   RESULTS ........................................................................... 27
      Effects of Retesting ......................................................... 29
      Effects of Cold Shock ..................................................... 29
      Effects of Captive-rearing ................................................. 29
   DISCUSSION ...................................................................... 33
TABLE OF CONTENTS - Continued

APPENDIX C.  EFFECTS OF COLD SHOCK ON VULNERABILITY
OF AGE-0 FLANNELMOUTH SUCKER TO
PREDATION BY RAINBOW TROUT

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>38</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>38</td>
</tr>
<tr>
<td>METHODS</td>
<td>39</td>
</tr>
<tr>
<td>RESULTS</td>
<td>41</td>
</tr>
<tr>
<td>DISCUSSION</td>
<td>43</td>
</tr>
</tbody>
</table>

APPENDIX D.  GROWTH AND LENGTH-WEIGHT RELATIONSHIP
OF AGE-0 FLANNELMOUTH SUCKER REARED
AT 20°C

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>INTRODUCTION</td>
<td>46</td>
</tr>
<tr>
<td>METHODS</td>
<td>46</td>
</tr>
<tr>
<td>RESULTS AND DISCUSSION</td>
<td>47</td>
</tr>
</tbody>
</table>

REFERENCES............................................................................. 52
LIST OF FIGURES

Figure A.1  Side view line drawing of apparatus used to measure swimming ability of age-0 fish.................................................................16

Figure A.2  Side view line drawing of screened knife gate valve modified to allow observers to see fish that fail to swim and become impinged on the screen.................................................................18

Figure A.3  Side view line drawing of test section showing position of fish during testing and electric barriers to keep fish from leaving the test section and to prevent fish from resting on the downstream screen......................................................................19

Figure B.1  Fatigue velocity (FV50) of age-0 flannelmouth sucker 25 - 114 mm total length at 20°C, 14°C and 10°C, following 4 d of acclimation to test temperatures. FV50 is the velocity at which 50% of fish fail to swim.............................30

Figure B.2  Fatigue velocity (FV50) of wild versus captive-reared flannelmouth suckers 50 mm TL at 20°C, 14°C, and 10°C. FV50 is the velocity at which 50% of fish fail to swim..............................31

Figure B.3  Fatigue velocity (FV50) of flannemouth sucker at 20°C in comparison to other native Colorado River fishes of similar size ............37

Figure D.1  Minimum and maximum total length (TL) of flannelmouth suckers reared at 20°C from 0 to 430 d post-hatch...............................48

Figure D.2  Relationship between total length (TL) and mass of flannelmouth suckers 0 to 430 d post-hatch..................................................51
**LIST OF TABLES**

| Table B.1 | Fatigue velocity (FV50) of age-0 flannelmouth suckers after 4 d of acclimation to test temperatures. FV50 is the velocity at which 50% of fish fail to swim and become impinged on a downstream screen. |
| Table B.2 | Fatigue velocity (FV50) of wild-caught flannelmouth suckers within 48 h of capture. FV50 is the velocity at which 50% of fish fail to swim. |
| Table B.3 | Representative Colorado River velocities 2.5 m from shore over different substrate types. |
| Table C.1 | Number of attacks and number of prey consumed by rainbow trout during 10-min predation tests. |
| Table D.1 | Size of flannelmouth suckers compared to other native Colorado River fish at 90 d post-hatch when reared at 20°C. |
ABSTRACT

The flannelmouth sucker (*Catostomus latipinnis*) is one of the few native fish that persist in the lower Colorado River basin. Cold water discharged below Glen Canyon Dam may impair swimming ability of age-0 flannelmouth suckers. Reduced swimming ability may increase predation and restrict flannelmouth suckers to low velocity areas. I conducted laboratory tests to quantify reduction in swimming ability of age-0 flannelmouth suckers due to cold water and to evaluate effects of reduced swimming ability on predation. Flannelmouth suckers 25 to 115 mm TL were subjected to swimming performance tests at 10, 14, and 20°C. At 10°C, swimming ability was an average of 40% lower than at 20°C. Age-0 flannelmouth suckers acclimated to 20°C were introduced individually into tanks containing a single rainbow trout (*Oncorhynchus mykiss*) at 20 or 10°C. Rainbow trout attacked more often at warm temperatures, but were more likely to capture prey at cold temperatures.
INTRODUCTION

Construction and operation of hydroelectric dams have transformed the Colorado River from a warm, turbid, highly dynamic stream into a system dominated by large reservoirs and cold tailwaters. These changes have dramatically affected the abundance of many native fishes including the flannelmouth sucker. Reduced summer water temperature has been implicated in the decline of native fish in Glen and Grand canyons (Kaeding and Zimmerman 1983; Childs and Clarkson 1996; Robinson et al. 1998; Clarkson and Childs 2000). After completion of Glen Canyon Dam in 1963, maximum summer river temperatures were reduced from 25 - 30°C to a nearly constant 10°C, and nonnative rainbow trout (*Oncorhynchus mykiss*) and brown trout (*Salmo trutta*) were introduced. Young native fish now experience colder water temperatures and predation from introduced trout which may result in low survival.

Flannelmouth suckers spawn in the Paria River, a tributary of the Colorado River located 25 km below Glen Canyon Dam (Weiss 1993). Young flannelmouth suckers use mouths of tributaries as nursery areas until late summer when they move into the Colorado River mainstem (Thieme 1997). Large numbers of age-0 flannelmouth suckers are commonly captured at the mouth of the Paria River (Hoffnagle 1999), but catch data from a variety of sampling methods indicate that low numbers of juvenile flannelmouth suckers are present in the Colorado River in Glen and Grand Canyons (Valdez and Ryel 1995; McKinney et al. 1999b). This lack of recruitment may lead to population declines and extirpation of flannelmouth suckers below Glen Canyon Dam. Three other species of fish endemic to the Colorado River, Colorado pikeminnow (*Ptychocheilus lucius*),
bonytail chub (*Gila elegans*), and razorback sucker (*Xyrauchen texanus*) have already been extirpated or are exceedingly rare downstream of Glen Canyon Dam (Minckley 1991).

Probable explanations for the rarity of age-0 and juvenile flannelmouth suckers in the Colorado River in Glen and Grand Canyons include: 1) cold shock that causes direct mortality of age-0 flannelmouth suckers as they exit the warm Paria River and enter the cold, swift water discharged from Glen Canyon Dam; 2) reduced swimming ability of young suckers that leads to increased predation; 3) impaired swimming ability that causes age-0 flannelmouth suckers to be displaced downstream and only return as adults.

The Bureau of Reclamation has proposed installation of a modified intake structure on Glen Canyon Dam that could raise summer water temperatures downstream by 4°C (USDI 1999). The effects of these proposed modifications on native fishes are unknown. I tested age-0 flannelmouth suckers in the laboratory to determine the effects of temperature, fish size, water velocity, and exercise on prolonged swimming ability.

Swimming performance tests of this type are commonly used to assess the physiological limits of specific size classes and species of fish (Beamish 1978; Berry and Pimentel 1985; Mesa and Olson 1993). I also performed laboratory tests to evaluate the effects of an abrupt 10°C temperature reduction on vulnerability of age-0 flannelmouth suckers to predation by rainbow trout.
PRESENT STUDY

The methods, results, and conclusions of this study are presented in four papers appended to this thesis. Each paper discusses some aspect of the swimming performance of flannelmouth suckers and will be submitted for publication in peer reviewed journals. The reference sections for each chapter are combined at the end of this document to facilitate location of cited literature. The following is a summary of the most important findings in these papers.

AN INEXPENSIVE SWIM TUNNEL FOR AGE-0 FISH

Testing the swimming ability of sub-yearling fish is difficult because body size and swimming ability increase dramatically over a short time. I used common aquaculture and plumbing supplies to construct an inexpensive swim tunnel that can effectively test the swimming ability of age-0 fish. The total estimated cost of my apparatus is $600 US dollars. This swim tunnel can produce non-turbulent flows of 0 to 66 cm/s and effectively confine fish 20 to 120 mm TL to the test section. The combination of DC electric barriers and screened knife gate valves are effective at confining fish to the test section while maintaining non-turbulent flow. This type of swim tunnel allows a wide size range of age-0 fish to be tested within a single apparatus and permitted evaluation of changes in swimming ability during critical early life stages.

EFFECTS OF REDUCED TEMPERATURE ON SWIMMING PERFORMANCE

Swimming ability of age-0 flannelmouth suckers increased with fish size and water temperature. A decrease in temperature from 20°C to 14°C resulted in a 23.5% average decrease in mean swimming ability (range = 19.0% to 29.0%). A decrease in water
temperature from 20°C to 10°C resulted in a 40.2% decrease in mean swimming ability (range = 32.3% to 43.7). Fatigue velocities of 40 mm TL flannelmouth suckers that were previously tested were not significantly different from untested fish ($P = 0.94$). Continued, repeated testing may alter swimming ability but I saw no evidence of differing swimming ability with only two test events. Flannelmouth suckers acclimated to cold temperatures for four d before testing did not have different fatigue velocities than cold shocked fish ($P = 0.18$, for 20°C to 14°C thermal shock, $P = 0.12$, for 20°C to 10°C thermal shock). Thermal shock of 10°C or less resulted in no mortality of the 264 fish tested.

At 20°C and 14°C, wild-caught flannelmouth suckers tested within 48-h of capture showed higher fatigue velocities than captive-reared, non-exercised individuals of about the same size. At 20°C, the fatigue velocity of wild-caught flannelmouth suckers (45.7 cm/s) was 7.1 cm/s higher (95% C.I. = 4.6 to 9.6 cm/s higher) than the fatigue velocity of captive-reared fish. At 14°C, the fatigue velocity of wild-caught flannelmouth suckers was 7.2 cm/s higher (95% C.I. = 4.7 to 9.8 cm/s higher) than the fatigue velocity of captive-reared fish. At 10°C, the fatigue velocities of wild-caught flannelmouth suckers and captive-reared fish were not significantly different ($P > 0.05$).

Modifications to Glen Canyon dam which increase summer water temperature below the dam are likely to increase swimming ability of age-0 flannelmouth suckers. Increased swimming ability may increase the availability of habitat for age-0 flannelmouth sucker, but whether this temperature increase will allow higher survival of flannelmouth suckers in the Colorado River is unknown.
EFFECTS OF COLD SHOCK ON PREDATION VULNERABILITY

Reduced river temperatures below hydroelectric dams could potentially increase the vulnerability of age-0 fish to predation. In the laboratory, rainbow trout attacked flannelmouth suckers more often at 20°C than at 10°C. The proportion of successful attacks on flannelmouth suckers was significantly higher at 10°C than at 20°C (Fisher exact test, \( P = 0.007 \)). The combination of cold water released from Glen Canyon Dam in conjunction with high predator densities may contribute to high predation mortality of age-0 flannelmouth suckers in the Grand Canyon.

GROWTH OF AGE-0 FLANNELMOUTH SUCKER AT 20°C

The TL of flannelmouth suckers increased with age from 0 to 430 d post-hatch according to the relationship: TL (mm) = 8.89 + 0.42(age in d) - 0.0005 (age in d)². Average body mass also increased with fish length according to the equation: ln weight (g) = -11.70 + 2.79 ln length (mm), (linear regression, \( R^2 = 0.93 \)). While my estimates of maximum and minimum growth are lower than those reported in the literature, they provide a reference for assessing the effects of altered environmental conditions on growth.
APPENDIX A. AN INEXPENSIVE SWIM TUNNEL FOR MEASURING
THE SWIMMING ABILITY OF AGE-0 FISH

ABSTRACT

Laboratory swim tunnels are valuable for studying fish physiology and responses of fish to controlled environmental conditions. Many swim tunnels have been developed for testing larval fish or groups of adult fish, but age-0 fish are often excluded. Testing the swimming ability of sub-yearling fish is difficult because body size and swimming ability increase dramatically during a short time. I combined aspects of both large and small swim tunnels to construct an apparatus that can confine age-0 fish to a specific area while producing a wide range of non-turbulent velocities. I used low-cost plumbing supplies and a centrifugal pump to create a swim tunnel capable of producing velocities from 1 to 66 cm/s. A DC electric barrier and screened, knife-gate valves prevented fish from leaving the test section. A flow meter, incorporated into the swim tunnel, measured water velocity within the apparatus.

INTRODUCTION

Laboratory swim tunnels are valuable tools in fisheries research. They have been used to assess the quality of fish produced in hatcheries (Thomas et al. 1964; Bams 1967), examine respiration rates (Beamish 1981; Bernachez and Dodson 1985), measure sublethal effects of temperature changes (Griffiths and Alderice 1972; Hocutt 1973; Berry and Pimentel 1985), evaluate fish movement around water diversion structures (Peake et al. 1997; Toepfer et al. 1999), and evaluate displacement of larval fish in
streams (Houde 1969; Meng 1993; Childs and Clarkson 1996). Although many different types of swim tunnels have been developed, evaluating changes in swimming capacity of age-0 fish remains problematic. During the first year, body size and swimming ability increase dramatically. Most juvenile fish are too large to test in gravity-flow swim tunnels designed for larval fish and too small to test in swim tunnels designed for groups of adult fish. I combined aspects of both large and small swim tunnels to produce a device that can confine many sizes of age-0 fish to the test section while producing a wide range of non-turbulent velocities.

METHODS

I constructed the swim tunnel with common aquaculture and plumbing supplies. All plumbing connections were made with aquarium-grade silicone. Silicone retains a watertight seal while allowing easy disassembly for storage and transportation. I used a 0.13 hp centrifugal pump to circulate water between two, 150-L reservoirs. A 50 cm x 7.5 cm acrylic cylinder formed the test chamber. I used commercial water storage boxes as reservoirs, but inexpensive plastic storage containers or garbage cans would work equally well. I used 3.8-cm bulk head fittings and 3.2-cm PVC pipe to attach the head and tail reservoirs to the centrifugal pump. I regulated water velocity with a 3.8-cm adjustable gate valve on the pump outlet. A 1.3-cm PVC pipe attached to the pump outlet returned water to the tail reservoir and allowed the pump to operate continuously regardless of flow in the test section. I used tank-mount, knife-gate valves of 7.6 cm diameter to attach the acrylic cylinder to the water reservoirs (Figure A.1). Two other 7.6-cm knife gate
Figure A.1. Side view line drawing of apparatus used to measure swimming ability of age-0 fish. Abbreviations: A = head reservoir, B = fish entry port, C and D = screened knife gate valves, E = flow meter, F = tail reservoir, G = contraction cone, H = electric barrier, I = test section, J and O = turbulence diffusers, K = adjustable gate valve, L = centrifugal pump, M = water return pipe, N = fish removal port, P = pressure release pipe.
valves were modified by removing the plastic center from the valves and replacing them with 3-mm mesh metal screens held in place with silicone (Figure A.2). These modified gate valves allowed water to flow through the test chamber while confining fish to the test section. A small section of plastic housing was removed from the downstream valve to allow observers to see if fish became impinged on the downstream screen during swimming tests (Figure A.2).

A Marsh-McBirney flow meter, fixed near the exit of the swim chamber, measured water velocity to within 1 cm/s. Water velocity increases near the exit of an enclosed pipe, so the acrylic tube extended 20 cm into the tail reservoir to prevent artificially high velocity readings. I cut a hole in the top of this extension and inserted the flow meter to continuously measure water velocity within the test section. I timed the passage of dye through the swim chamber to verify accuracy of flow meter readings.

Turbulence within the test section was minimized by placing the top portion of a plastic funnel at the entrance to the swim chamber to form a contraction cone (Figure A.1). Contraction cones minimize the formation of a turbulent boundary layer where constrictions to water flow occur (Bell and Terhune 1970). Irrigation diffusers commonly used on garden hoses were attached to the pump outlet and minimized turbulent flow within the head and tail reservoirs.

Fish were introduced and removed from the swim chamber through 7.6 cm x 2.5 cm plastic sewer drains positioned above and below the test section. I used expansion plugs to seal openings following entry or removal of fish from the swim chamber. Fish were prevented from leaving the test section by an electric barrier on the upstream end of the
Figure A.2. Side view line drawing of screened knife gate valve modified to allow observers to see fish that fail to swim and become impinged on the screen.
Figure A.3. Side view line drawing of test section showing position of fish during testing and electric barriers to keep fish from leaving the test section and to prevent fish from resting on the downstream screen.
cylinder and an electrified screen on the downstream end. During testing, the upstream screen was raised to prevent turbulence within the test section. Two rings of copper wire were attached to a variable 1 to 30-V, DC power supply to prevent fish from leaving the test section (Figure A.3). The power supply transformed AC current from the wall outlet into a variable DC current. Pilot tests revealed that 5 to 7 V DC was sufficient to keep fish from leaving the test section. Fish that attempted to swim through the electric barrier were briefly stunned and forced back into the test section by the flowing water. This same type of barrier could not be used on the downstream end of the test section because stunned fish would be swept into the tail reservoir. The downstream screen remained in place during testing because turbulence created behind this screen did not alter flow within the test section. I used a 6-V, automotive blinker circuit to apply intermittent electricity to the downstream screen and keep fish from resting against it as they began to fatigue. When a fish stopped swimming, I manually disconnected the power to prevent death of the fish from continued electric shock.

RESULTS AND DISCUSSION

Common aquaculture and plumbing supplies can be used to construct inexpensive swim tunnels for fisheries research. The total estimated cost of this apparatus is $600 US dollars. This swim tunnel can produce non-turbulent flows of 0 to 66 cm/s and effectively confine fish 20 to 120 mm TL to the test section. The combination of DC electric barriers and screened knife gate valves were effective at confining fish to the test section while maintaining non-turbulent flow. This type of swim tunnel allowed a wide
size range of age-0 fish to be tested within a single apparatus and permitted evaluation of changes in swimming ability during critical early life stages.
APPENDIX B. EFFECTS OF REDUCED WATER TEMPERATURE ON SWIMMING PERFORMANCE OF AGE-0 FLANNELMOUTH SUCKER

ABSTRACT

Cold, swift water released from Glen Canyon Dam may cause direct mortality or impair swimming ability of age-0 flannelmouth suckers. Reduced swimming ability may increase predation and may restrict young flannelmouth suckers to low velocity areas, effectively reducing available habitat. The Bureau of Reclamation has proposed installation of a modified intake structure on Glen Canyon Dam to increase downstream water temperatures and enhance survival of native fish. I conducted fatigue velocity tests on age-0 flannelmouth suckers in the laboratory to evaluate the effects of water temperature, fish size, and water velocity on swimming ability. Fish 25 - 114 mm total length (TL) were subjected to incremental increases in water velocity to the upper limit of their swimming ability. Swimming tests were conducted at 10, 14, and 20°C. Swimming ability was directly related to water temperature at all sizes. A decrease in water temperature from 20 to 10°C resulted in an average decrease in swimming ability of 40%. Mean swimming ability of wild-caught flannelmouth suckers was 7 cm/s higher than the mean swimming ability of captive-reared flannelmouth suckers of similar size at 20 and 14°C. My study suggests that water velocity in much of the Colorado River in Glen and Grand Canyons is beyond the swimming ability of age-0 flannelmouth suckers at current temperatures.
INTRODUCTION

Construction and operation of hydroelectric dams have transformed the Colorado River from a warm, turbid, highly dynamic stream into a system dominated by large reservoirs and cold tailwaters. These changes have dramatically affected the abundance of many native fishes including the flannelmouth sucker. Reduced summer water temperature has been implicated in the decline of native fish in Glen and Grand canyons (Kaeding and Zimmerman 1983; Childs and Clarkson 1996; Robinson et al. 1998; Clarkson and Childs 2000). After completion of Glen Canyon Dam in 1963, maximum summer river temperatures were reduced from 25 - 30°C to a nearly constant 10°C, and nonnative rainbow trout (*Oncorhynchus mykiss*) and brown trout (*Salmo trutta*) were introduced. Young native fish now experience colder water temperatures and predation from introduced trout which may result in low survival.

Flannelmouth suckers spawn in the Paria River, a tributary of the Colorado River located 25 km below Glen Canyon Dam (Weiss 1993). Young flannelmouth suckers use mouths of tributaries as nursery areas until late summer when they move into the Colorado River mainstem (Thieme 1997). Large numbers of age-0 flannelmouth suckers are commonly captured at the mouth of the Paria River (Hoffnagle 1999), but catch data from a variety of sampling methods indicate low numbers of juvenile flannelmouth suckers are present in the Colorado River in Glen and Grand Canyons (Valdez and Ryel 1995; McKinney et al. 1999b). This lack of recruitment may lead to population declines and extirpation of flannelmouth suckers below Glen Canyon Dam. Three other species of
fish endemic to the Colorado River, Colorado Pikeminnow \textit{(Ptychocheilus lucius)}, Bonytail chub \textit{(Gila elegans)}, and Razorback sucker \textit{(Xyrauchen texanus)} have already been extirpated or are exceedingly rare downstream of Glen Canyon Dam (Minckley 1991).

Alternative explanations for the rarity of age-0 and juvenile flannelmouth suckers in the Colorado River in Glen and Grand Canyons include: 1) cold shock that causes direct mortality of age-0 flannelmouth suckers as they exit the warm Paria River and enter the cold, swift water discharged from Glen Canyon Dam; 2) reduced swimming ability of young suckers that leads to increased predation; 3) impaired swimming ability that causes age-0 flannelmouth suckers to be displaced downstream and only return as adults.

The Bureau of Reclamation has proposed installation of a modified intake structure on Glen Canyon Dam that could raise summer water temperatures downstream by 4°C (USDI 1999). The effects of these proposed modifications on native fishes are unknown. I tested age-0 flannelmouth suckers in the laboratory to determine the effects of temperature, fish size, water velocity, and exercise on prolonged swimming ability. Swimming performance tests of this type are commonly used to assess the physiological limits of specific size classes and species of fish (Beamish 1978; Berry and Pimentel 1985; Mesa and Olson 1993).

\textbf{METHODS}

I captured adult flannelmouth suckers on May 8 - 9, 1999 by seining the Paria River 3.5 km from the confluence. Eggs from three ripe females were fertilized with milt from
six males on site. Gametes were transported to the Environmental Research Laboratory in Tucson, Arizona, where fish were reared in 1-m³ recirculating tanks. Water temperature was maintained at 20°C (± 2°C) throughout hatching and rearing. Timers were used to maintain a 14-h light and 10-h dark cycle throughout the study because photoperiod may alter swimming performance (Kolok 1991).

I used a flow-through system modified from designs by Thomas et al. (1964) and Berry and Pimentel (1985) to assess swimming performance (see Appendix A). I tested the swimming ability of fish at 10-mm intervals from 26 - 114 mm mean TL. Fish of similar size (n = 15 - 20) were acclimated to test temperatures four d before testing. The test temperatures used were 10°C (current temperature of the Colorado River), 14°C (river temperature if a modified intake structure is placed on Glen Canyon Dam), and 20°C (pre-dam summer temperatures). Fish were acclimated in 76-L tanks by reducing water temperature with a chiller over a 24-h period and held at test temperature for three d. Tests were initiated by placing individual fish into the swim chamber at 50% of the test velocity for 10 min. I then exposed fish to full test velocity for 30 min. A fish that successfully swam for 30 min was scored as a pass whereas a fish that became pinned against the downstream screen and remained motionless for 10 s was scored as a failure. Fixed velocity tests of this type are commonly used for larval fish because they exhibit high variability in swimming performance (Meng 1993; Childs and Clarkson 1996).

I calculated 50% fatigue velocity (FV50) as the velocity at which one half of the fish failed to swim for 30 min at a given test flow. For each size class, at least five fish were tested at each of three different velocities, for each temperature. Test velocities were
chosen based on several pilot trials at each size class. When the three selected velocities did not produce failure, higher velocities were tested until 50% failure occurred.

I measured total length, mass, and maximum dorsal-ventral width of each fish after testing. All tested fish were then returned to the 1-m³ rearing tanks for approximately three weeks until the average length had increased by 10 mm. I used logistic regression to estimate FV50 (Ruetz and Jennings 2000) and 95% confidence intervals for each temperature and size class separately. Linear regression was used to identify the relationship between temperature, fish size, water velocity and swimming ability. The measured FV50 values from the laboratory were compared to reported river velocity measurements at USGS gauging stations in Glen and Grand Canyons (Garrett et al. 1993).

EFFECTS OF RETESTING

Individual fish were used a maximum of nine times throughout the study with at least 21 d between tests. I compared the swimming ability of 77 flannelmouth suckers (40 mm mean TL) not previously tested and 75 flannelmouth suckers of the same size that were previously tested to evaluate the effects of a prior testing event on swimming performance. I used a stepwise increase in water velocity of 4 cm/s every 5 min to determine a fatigue velocity for each fish. Two-sample t-tests were used to compare mean swimming ability of previously tested and untested fish.

EFFECTS OF COLD SHOCK

I tested the swimming ability of fish not acclimated to test temperatures to assess whether cold shock led to direct mortality or reduced swimming ability at each size.
These tests simulated the 10°C temperature change flannelmouth suckers might experience as they exit warm tributaries and enter the Colorado River. For these cold shock tests, I removed fish from the rearing tank at 20°C and placed them directly into the test chamber at the test temperature. Cold shocked fish were returned to the rearing tank following testing and monitored for delayed mortality for three d. The procedures for cold shock tests were identical to those for acclimated fish in all other aspects. Two-sample t-tests were used to determine differences in mean swimming ability of acclimated versus non-acclimated fish.

EFFECTS OF CAPTIVE-REARING

Seventy-five wild flannelmouth suckers (averaging 50 mm TL) were seined from the mouth of the Paria River and subjected to fixed velocity swimming tests in the laboratory within 48 h of capture. I compared FV50 values of wild flannelmouth suckers to captive-reared individuals of the similar size.

RESULTS

Fatigue velocities increased with fish size and water temperature (Table B.1). The relationship between fish size, water temperature, flow velocity, and swimming ability (FV50) of age-0 flannelmouth suckers 25 - 114 mm mean TL was:

\[
FV50 = 1.80 + 0.45 \text{ (temperature)} + 0.36 \text{ (water velocity)} + 0.05 \text{ (fish length)} + 0.01 \text{(temperature x length interaction)}.
\]
Table B.1 - Fatigue velocity (FV50) of age-0 flannelmouth suckers after 4 d of acclimation to test temperatures. FV50 is the velocity at which 50% of fish fail to swim and become impinged on a downstream screen.

<table>
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<th>Number of fish</th>
<th>FV50 cm/s (95% C.I.)</th>
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<td>16</td>
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<td>25.1 22.4 - 28.0</td>
<td>4</td>
<td>23</td>
<td>15.7 (14.3 - 17.2)</td>
</tr>
<tr>
<td>20</td>
<td>38.9 33.4 - 46.0</td>
<td>5</td>
<td>36</td>
<td>31.7 (30.4 - 33.0)</td>
</tr>
<tr>
<td>14</td>
<td>39.3 31.0 - 46.3</td>
<td>4</td>
<td>36</td>
<td>25.8 (24.9 - 26.6)</td>
</tr>
<tr>
<td>10</td>
<td>42.5 36.0 - 49.6</td>
<td>3</td>
<td>30</td>
<td>21.0 (19.8 - 22.1)</td>
</tr>
<tr>
<td>20</td>
<td>49.6 46.2 - 54.1</td>
<td>3</td>
<td>18</td>
<td>38.6 (37.5 - 39.7)</td>
</tr>
<tr>
<td>14</td>
<td>50.4 46.0 - 56.3</td>
<td>3</td>
<td>16</td>
<td>29.5 (28.0 - 31.0)</td>
</tr>
<tr>
<td>10</td>
<td>51.3 47.1 - 56.3</td>
<td>3</td>
<td>15</td>
<td>21.9 (20.3 - 23.5)</td>
</tr>
<tr>
<td>20</td>
<td>62.0 57.7 - 64.9</td>
<td>3</td>
<td>15</td>
<td>44.8 (43.6 - 46.0)</td>
</tr>
<tr>
<td>14</td>
<td>61.4 59.1 - 66.1</td>
<td>3</td>
<td>18</td>
<td>34.0 (33.2 - 35.0)</td>
</tr>
<tr>
<td>10</td>
<td>63.0 57.6 - 66.0</td>
<td>3</td>
<td>15</td>
<td>26.4 (24.7 - 28.1)</td>
</tr>
<tr>
<td>20</td>
<td>70.2 67.3 - 73.6</td>
<td>4</td>
<td>17</td>
<td>45.8 (44.8 - 46.8)</td>
</tr>
<tr>
<td>14</td>
<td>71.1 65.9 - 75.7</td>
<td>4</td>
<td>17</td>
<td>33.7 (32.7 - 34.8)</td>
</tr>
<tr>
<td>10</td>
<td>69.9 66.7 - 73.8</td>
<td>5</td>
<td>27</td>
<td>25.8 (24.7 - 27.0)</td>
</tr>
<tr>
<td>20</td>
<td>80.7 77.8 - 82.9</td>
<td>3</td>
<td>15</td>
<td>52.3 (51.0 - 53.5)</td>
</tr>
<tr>
<td>14</td>
<td>80.5 75.7 - 86.2</td>
<td>4</td>
<td>20</td>
<td>41.6 (40.7 - 42.6)</td>
</tr>
<tr>
<td>10</td>
<td>82.1 78.6 - 88.9</td>
<td>4</td>
<td>16</td>
<td>32.0 (31.0 - 33.0)</td>
</tr>
<tr>
<td>20</td>
<td>91.0 88.4 - 95.8</td>
<td>3</td>
<td>15</td>
<td>57.9 (56.9 - 58.8)</td>
</tr>
<tr>
<td>14</td>
<td>91.3 87.3 - 95.2</td>
<td>3</td>
<td>15</td>
<td>44.5 (43.3 - 45.7)</td>
</tr>
<tr>
<td>10</td>
<td>91.5 88.4 - 95.7</td>
<td>3</td>
<td>16</td>
<td>34.9 (34.0 - 35.9)</td>
</tr>
<tr>
<td>20</td>
<td>100.0 96.3 - 105.3</td>
<td>3</td>
<td>16</td>
<td>58.8 (56.5 - 61.1)</td>
</tr>
<tr>
<td>14</td>
<td>100.1 95.0 - 105.3</td>
<td>3</td>
<td>15</td>
<td>45.3 (44.0 - 46.5)</td>
</tr>
<tr>
<td>10</td>
<td>99.7 94.9 - 106.4</td>
<td>3</td>
<td>15</td>
<td>36.3 (35.0 - 37.5)</td>
</tr>
<tr>
<td>20</td>
<td>114.1 107.4 - 122.7</td>
<td>3</td>
<td>15</td>
<td>66.3 (64.1 - 68.1)</td>
</tr>
<tr>
<td>14</td>
<td>111.2 105.0 - 116.6</td>
<td>3</td>
<td>16</td>
<td>47.0 (44.7 - 49.2)</td>
</tr>
<tr>
<td>10</td>
<td>114.0 104.6 - 123.2</td>
<td>3</td>
<td>17</td>
<td>38.3 (36.5 - 40.1)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td>513</td>
<td></td>
</tr>
</tbody>
</table>
Temperature, water velocity, fish length, and the interaction between temperature and fish length all had a significant effect on swimming ability ($P < 0.001$). With all other factors held constant, swimming ability was directly related to temperature. A decrease in temperature from 20°C to 14°C resulted in a 23.5% average decrease in mean swimming ability (range = 19.0% to 29.0%). A decrease in water temperature from 20°C to 10°C resulted in a 40.2% decrease in mean swimming ability (range = 32.3% to 43.7%, Figure B.1).

EFFECTS OF RETESTING

Fatigue velocities of 40 mm TL flannelmouth suckers that were previously tested were not significantly different from untested fish ($P = 0.94$). Repeated testing may alter swimming ability but I saw no evidence of differing swimming ability with only two test events.

EFFECTS OF COLD SHOCK

Flannelmouth suckers acclimated to cold temperatures for four d before testing did not have significantly different fatigue velocities than cold shocked fish ($P = 0.18$, for 20°C to 14°C thermal shock, $P = 0.12$, for 20°C to 10°C thermal shock). Thermal shock of 10°C or less resulted in no mortality of the 264 fish tested.

EFFECTS OF CAPTIVE-REARING

At 20°C and 14°C wild-caught flannelmouth suckers tested within 48-h of capture showed higher fatigue velocities than captive-reared, non-exercised individuals of about the same size (Table B.2). At 20°C, the fatigue velocity of wild-caught flannelmouth suckers (45.7 cm/s) was 7.1 cm/s higher (95% C.I. = 4.6 to 9.6 cm/s higher) than the
Figure B.1. Fatigue velocity (FV 50) of age-0 flannelmouth sucker 25 - 114 mm TL at 20°C, 14°C, and 10°C, following 4 d of acclimation to test temperatures. FV 50 is the velocity at which 50% of the fish fail to swim.
Table B.2. - Fatigue velocity (FV50) of wild-caught flannelmouth suckers within 48 h of capture. FV50 is the velocity at which 50% of fish fail to swim.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Total Length, mm</th>
<th>Number of velocities</th>
<th>Number of Fish</th>
<th>FV50 cm/s (95% C.I.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20°C</td>
<td>Mean 50.3; Range 46.1 - 56.8</td>
<td>4</td>
<td>23</td>
<td>45.7 (44.3 - 47.1)</td>
</tr>
<tr>
<td>14°C</td>
<td>Mean 49.5; Range 44.5 - 53.7</td>
<td>3</td>
<td>15</td>
<td>36.7 (35.7 - 37.8)</td>
</tr>
<tr>
<td>10°C</td>
<td>Mean 49.8; Range 44.6 - 56.9</td>
<td>5</td>
<td>25</td>
<td>21.0 (20.0 - 22.1)</td>
</tr>
</tbody>
</table>

Total 63
fatigue velocity of captive-reared fish. At 14°C, the fatigue velocity of wild-caught flannelmouth suckers (36.7 cm/s) was 7.2 cm/s higher (95% C.I. = 4.7 to 9.8 cm/s higher) than the fatigue velocity captive-reared fish. At 10°C, the fatigue velocities of wild-caught flannelmouth suckers and captive-reared fish were not significantly different ($P > 0.05$; Figure B.2).

**DISCUSSION**

Cold shock is often cited as a potential cause of mortality for age-0 native fish that exit seasonally warm tributaries and enter cold water in the Colorado River (Lupher and Clarkson 1993; Valdez and Ryel 1995; Theime 1997). A 10°C cold shock simulating the temperature change age-0 flannelmouth suckers experience when exiting the Paria River did not result in mortality in my experiments. Flannelmouth sucker larvae 7 - 43 d post-hatch also show no direct mortality due to cold shock (Clarkson and Childs 2000). Flannelmouth suckers appear to have evolved the physiological ability to withstand relatively large temperature fluctuations.

Fish reared in non-moving water have significantly reduced swimming ability compared with wild fish or exercised individuals (reviewed in Davidson 1997). Results agree with these findings only at 20°C and 14°C. Water temperature limited swimming ability at 10°C for both wild and captive-reared fish. My estimates of swimming ability at 10°C are likely to reflect the swimming ability of wild fish when they exit the Paria River and enter the Colorado River, whereas estimates of swimming ability at 14°C and 20°C are likely to be low due to the greater swimming ability of exercised wild fish at
Figure B.2. Fatigue velocity (FV50) of wild versus captive-reared flannelmouth suckers 50 mm TL at 20°C, 14°C, and 10°C. FV50 is the velocity at which 50% of fish fail to swim.
these temperatures. The increased swimming ability of wild fish is consistent with swimming tests performed on wild-caught and captive-reared salmonids (Green 1964). Addition of 7 cm/s to the FV50 at 14°C and 20°C corrects for the increased swimming ability of wild fish and more accurately represents the swimming ability of flannelmouth suckers in the Paria River. Average mid-channel water velocities in the Colorado River are well above the estimated swimming ability of age-0 flannelmouth suckers, even after this correction.

Flannelmouth suckers showed a 40% decrease in swimming ability at 10°C compared with 20°C. This reduction in swimming performance may limit the ability of age-0 flannelmouth suckers to escape predators, especially cold-water predators. The number of adult rainbow trout, in the area from Glen Canyon Dam to Lees Ferry, is estimated to be at least 7,800/km (McKinney et al. 1999a). The high number of trout in Glen Canyon in combination with reduced swimming ability of young fish may lead to high predation mortality of young native fish.

Cold, swift water in the Colorado River may reduce growth rate of age-0 flannelmouth suckers and further increase the risk of predation. Predation rates for fish are highly dependent on size (Coutant et al. 1979), so environmental changes that cause reduced growth rate can increase the amount of time that small fish are vulnerable. Cold water slows growth of flannelmouth suckers and delays transformation to juvenile stages (Clarkson and Childs 2000). In addition high water velocity increases metabolic costs further reducing growth rate (Simonson and Swenson 1990). The size at which flannelmouth suckers enter the Colorado River varies among years (Hoffnagle 1999).
This may have important implications for recruitment because larger fish have greater swimming ability which may result in higher survival.

Areas with water velocity above the maximum swimming ability of age-0 fish are not available for use (Scheidegger and Bain 1995; Ruetz and Jennings 2000). Mid-channel water velocities in the Colorado River (Garrett et al. 1993) are several times higher than the fatigue velocities I measured in the laboratory and may block movement of age-0 fish between low-velocity environments. In many areas, water velocity within 2.5 m of the bank exceeds the fatigue velocities I measured for age-0 flannelmouth suckers at 10°C (Converse 1996) (Table B.3). Age-0 Warner suckers (Catostomus warnerensis) placed in swift, mid-channel sites took refuge behind rocks and vegetation to avoid displacement downstream (Kennedy and Vineyard 1997). Sub-yearling flannelmouth suckers that are unable to access low velocity areas or find refuge behind instream objects will be displaced. If young fish become entrained in high velocity current they may be injured or killed by turbulence and abrasion against substrates (Clarkson and Childs 2000).

Age-0 flannelmouth suckers that exit the Paria River may move downstream to western portions of the Grand Canyon where water is warmer and return to the Lee's Ferry area only after reaching sexual maturity. McKinney et al. (1999b) found that the size structure of the adult aggregation of flannelmouth suckers in the Lees Ferry area was stable between 1992 and 1997. They suggest this stability is due to influx of adults from downstream. Reduced swimming ability of age-0 flannelmouth suckers at 10°C and high numbers of trout in Glen and Grand Canyons may make it difficult for age-0 flannelmouth suckers produced in the Paria River to survive migration downstream and
return as adults. Low recruitment of juvenile fish produced in the Paria River may affect persistence of the flannelmouth sucker population below Glen Canyon Dam.

Information on swimming ability of flannelmouth suckers may aid in restoration of other endangered Colorado River fishes. The Colorado pikeminnow (*Ptychocheilus lucius*), humpback chub (*Gila cypha*), and bonytail chub (*Gila elegans*) all have thermal preferences similar to the flannelmouth sucker (Bulkley et al. 1981), and exhibit comparable swimming abilities for similar-sized fish (Berry and Pimentel 1985) (Figure B.3). Humpback chub spawn in tributaries to the Colorado River similar to flannelmouth suckers and may also experience decreases in swimming ability and increased predation or displacement when entering the Colorado River.

Modifications to Glen Canyon dam which increase summer water temperature below Glen Canyon Dam is likely to increase swimming ability of age-0 flannelmouth suckers. Increased swimming ability may reduce predation risk and improve the availability of habitat for age-0 flannelmouth sucker, but whether this temperature increase will allow higher survival of flannelmouth suckers in the Colorado River is unknown.
Figure B.3. Fatigue velocity (FV 50) of flannelmouth sucker at 20°C in comparison to Colorado pikeminnow, Humpback chub, and Bonytail chub of similar size (Berry and Pimentel 1985).

Table B.3. Representative Colorado River velocities in The Grand Canyon, 2.5 m from shore over different substrate types (Converse 1996).

<table>
<thead>
<tr>
<th>Shoreline Type</th>
<th>Velocity cm/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Talus</td>
<td>11</td>
</tr>
<tr>
<td>Debris Fan</td>
<td>20</td>
</tr>
<tr>
<td>Sand</td>
<td>20</td>
</tr>
<tr>
<td>Vegetation</td>
<td>20</td>
</tr>
<tr>
<td>Bedrock</td>
<td>31</td>
</tr>
<tr>
<td>Cobble</td>
<td>62</td>
</tr>
</tbody>
</table>
APPENDIX C. EFFECTS OF COLD SHOCK ON VULNERABILITY OF AGE-0 FLANNELMOUTH SUCKER TO PREDATION BY RAINBOW TROUT

ABSTRACT

Hydroelectric dams throughout the world have altered river temperatures creating conditions that allow non-native fishes to proliferate in many areas. Age-0 flannelmouth suckers experience an abrupt temperature decrease when they exit warm tributaries and enter cold water released from Glen Canyon Dam. This temperature change could increase susceptibility of young flannelmouth suckers to predation. Predation by rainbow trout (*Oncorhynchus mykiss*), which are abundant in the Colorado River in Grand Canyon, may limit recruitment of flannelmouth suckers. I conducted laboratory tests to evaluate the effects of an abrupt 10°C decrease in water temperature on predation rate of age-0 flannelmouth sucker by rainbow trout. Flannelmouth suckers 58 mm total length were maintained at 20°C and introduced individually, without acclimation, into tanks at 20°C or 10°C containing a single rainbow trout. Rainbow trout attacked more often at 20°C than at 10°C, but were less likely to capture prey at 20°C than at 10°C. Reduced river temperatures below hydroelectric dams may increase predation mortality of juvenile native fish.

INTRODUCTION

The continued decline of many native fish in the Colorado River is largely due to interactions with non-native fishes (Miller et al. 1989; Minckley 1991; Tyus and
Non-native fishes harm endangered Colorado River fish primarily through predation (Tyus and Saunders 2000). The combination of cold water and high densities of introduced trout in Glen and Grand Canyons may cause especially high predation mortality for native fish such as flannelmouth sucker.

Flannelmouth suckers spawn in several tributaries of the Colorado River within Glen and Grand Canyons and use these tributaries as nursery areas before moving into the mainstem of the Colorado River (Thieme 1997; Hoffnagle 1999). Age-0 flannelmouth suckers experience an abrupt temperature decrease of about 10°C when moving from tributaries into the Colorado River. A similar abrupt decrease in temperature from 20°C to 10°C did not cause direct mortality of age-0 flannelmouth suckers in laboratory experiments but did reduce prolonged swimming ability (see Appendix B). Recent estimates indicate the number of adult trout in the area from Glen Canyon Dam to Lee’s Ferry exceeds 7,800 per km (McKinney et al. 1999a). These high trout densities in combination with reduced swimming ability at low temperatures may lead to high predation and low recruitment of flannelmouth suckers below Glen Canyon Dam. I performed laboratory tests to evaluate the effects of an abrupt 10°C temperature reduction on vulnerability of age-0 flannelmouth suckers to predation by rainbow trout.

METHODS

I captured age-0 flannelmouth suckers 58 mm mean total length (range 51 to 70 mm) in August 2000 by seining at the mouth of the Paria River, a tributary to the Colorado River, 26 km below Glen Canyon Dam. I transported the fish to the Environmental
Research Laboratory in Tucson, Arizona and maintained them in a circular 1000-L fiberglass tank at 20°C. Ten adult rainbow trout 246 mm mean total length (range 235 to 270 mm) were obtained from Bubbling Ponds Fish Hatchery in Arizona and maintained in a separate 1000-L tank at 20°C. All trout were pit tagged and fed live goldfish for three weeks before testing, in order to accustom them to eating live fish. I acclimated trout to 10°C by circulating chilled water between a 300-L chiller reservoir and the holding tank with a 1/10-hp submersible pump. Water temperature was reduced to 10°C over a 24-h period and maintained at 10°C (± 2°C) for five d. I withheld food from the trout for four d before testing to ensure a high degree of motivation for feeding.

In all predation tests one trout was randomly selected from the rearing tank and placed in an adjoining 1000-L circular tank supplied with a continuous flow of water. One flannelmouth sucker was also randomly selected and isolated within the flannelmouth holding tank. Both fish were held for a minimum of eight h to allow them to recover from being moved. I introduced the selected flannelmouth sucker into the experimental tank from behind a canvas blind. I used a funnel attached to the end of a 2.5 cm diameter plastic pipe to insert the flannelmouth sucker into the test tank. The flannelmouth sucker was entrained in 150 ml of water and poured slowly into the test tank through the pipe. This method allowed the flannelmouth sucker to be placed into the test tank without disturbing the trout. I recorded number of attack events as well as whether or not the flannelmouth sucker was consumed during a 10-min period.
I defined an attack event as burst swimming of the rainbow trout in the direction of the flannelmouth sucker. When the trout consumed the flannelmouth sucker it was recorded as a successful attack. If a flannelmouth sucker avoided predation for 10 min, the test was terminated. Trout either showed strong motivation to eat immediately or did not attack for the entire test period. No refuge or cover was provided within the test tank. I returned trout to a separate holding tank following testing. The tests at 10°C simulated conditions that exist when young flannelmouth suckers exit warm tributaries and enter the cold Colorado River. I repeated these tests in water held at 20°C as a control. Procedures for these control tests were identical to those used at 10°C. Two experimental and two control trials were run with each of the 10 trout over a period of 3 months. I used a 2 x 2 contingency table and a two-tailed Fisher's exact test to evaluate differences in the proportion of successful captures at each temperature.

RESULTS

There were more attacks on flannelmouth suckers at 20°C than at 10°C (Table C.1). The proportion of successful attacks on flannelmouth suckers was significantly higher at 10°C than at 20°C (Fisher exact test, $P = 0.007$).

Although no refuge was provided within the test tank, flannelmouth suckers often remained motionless or swam near the edge of the tank at the water surface to avoid being detected. Flannelmouth suckers even jumped out of the water to avoid a pursuing trout. A trout not successful at capturing prey usually ceased attacks after several
Table C.1. Number of attacks and number of prey consumed by rainbow trout during 10-min predation tests.

<table>
<thead>
<tr>
<th>Temperature °C</th>
<th>Number of attacks</th>
<th>Number consumed</th>
<th>% Successful attacks</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>52</td>
<td>3</td>
<td>5.8</td>
</tr>
<tr>
<td>10</td>
<td>23</td>
<td>9</td>
<td>39.1</td>
</tr>
</tbody>
</table>
attempts. Activity level of individual trout was highly variable and several trout did not attempt to attack prey at either temperature.

DISCUSSION

Temperature affected the number of times rainbow trout attacked age-0 flannelmouth suckers and the number of flannelmouth suckers that were consumed. An abrupt 10°C decrease in water temperature increased vulnerability of age-0 flannelmouth suckers to predation by rainbow trout in my laboratory tests. Young flannelmouth suckers or other native fish that exit tributaries and enter cold water released from hydroelectric dams may experience a similar increased vulnerability to predation because of abrupt temperature decreases. Abrupt temperature declines result in increased predation in other fish species. An immediate decrease in temperature from 25°C to 16°C results in increased predation of juvenile channel catfish (*Ictalurus punctatus*) by largemouth bass (*Micropterus salmoides*) (Coutant et al. 1974). Age-0 bluegill (*Lepomis macrochirus*) subjected to a 9°C reduction in temperature also show increased vulnerability to predation by largemouth bass (Wolters and Coutant 1976).

Reduction in swimming ability may limit the capacity of flannelmouth suckers to escape predation. A difference in burst swimming ability causes differential susceptibility of coho salmon (*Oncorhynchus kisutch*) to predation (Taylor and Mcphail 1985). In prolonged swimming performance tests, flannelmouth suckers average a 40% reduction in prolonged swimming ability at 10°C compared with 20°C (see appendix B).
A similar reduction in burst swimming ability because of cold shock may result in higher predation of flannelmouth suckers.

Abrupt temperature changes may also result in reduced responsiveness or elusiveness of prey to predators even if no visible loss of equilibrium occurs (Coutant 1973). Goldfish subjected to abrupt increases in water temperature show reduced reaction distance to trout (Webb and Zhang 1994). Although young flannelmouth suckers showed no visible signs of abnormal swimming behavior in my tests, reaction distance or elusiveness may have been affected by cold shock.

Predation by introduced fishes has been implicated in the decline of many native fishes of the southwestern United States. Diet analysis of predatory non-native fishes, revealed rainbow trout as a threat to the persistence of humpback chub and other native fish in the Little Colorado River (Marsh and Douglas 1997). Predation on young Gila topminnow (*Poeciliopsis occidentalis*) by mosquitofish (*Gambusia affinis*) is considered the primary cause for loss of Gila topminnow populations in Arizona (Schoenherr 1981; Meffe 1985). Predation by rainbow trout may limit the distribution of Little Colorado spinedace (*Lepidomeda vittata*) in Nutrioso Creek, Arizona (Blinn et al. 1993). Efforts to restore razorback sucker (*Xyrauchen texanus*) to its former range in Arizona by restocking hatchery-raised fish have largely failed due to predation by non-native fishes (Marsh and Brooks 1989). High predation of flannelmouth suckers by rainbow trout may also be responsible for low numbers of juvenile flannelmouth suckers in the Colorado River in Grand Canyon.
Higher temperatures increase metabolic demands and consumption rates in trout (Railsback and Rose 1999). The higher number of attacks at warmer temperatures was likely the result of increased metabolism. In my experiments, flannelmouth suckers always exhibited an escape response when approached by a rainbow trout. Because a higher number of attack events did not lead to higher predation mortality at 20°C, it is likely that the higher predation mortality at 10°C was the result of decreased escape ability of the prey.

The abrupt temperature decrease that age-0 flannelmouth suckers experience as they exit warm tributaries and enter the cold Colorado River mainstem, may reduce swimming ability or cause behavioral responses that reduce elusiveness or responsiveness to predators. The combination of cold water released from Glen Canyon dam in conjunction with high predator densities may contribute to high predation mortality of age-0 flannelmouth suckers in the Grand Canyon. Reduced river temperatures below hydroelectric dams can increase the vulnerability of age-0 fish to predation and may result in decline of native fishes.
APPENDIX D. GROWTH AND LENGTH-WEIGHT RELATIONSHIP OF AGE-0 FLANNELMOUTH SUCKERS REARED AT 20°C

INTRODUCTION

Age-0 flannelmouth suckers exhibit large differences in size within a single year class. This size variability within a cohort may be adaptive to the fluctuating environment of southwestern rivers by permitting some individuals to grow quickly and reproduce during favorable conditions while others remain small to enhance survival during droughts (Minckley 1983). Size variation within an age class can make determining the age of small fish difficult in the field. We raised flannelmouth suckers in the laboratory at 20°C to determine maximum and minimum growth rate for a single cohort of age-0 flannelmouth suckers. Growth rate under controlled conditions provides a reference for assessing ages of wild fish and identifying effects of altered environments on growth.

METHODS

We captured ripe adult flannelmouth suckers by seining the Paria River 3.5 km upstream from the confluence of the Colorado River on May 8 - 9, 1999. Eggs were stripped from 3 ripe females, and milt from 6 males was immediately added and stirred. We allowed fertilized eggs to water-harden for 1h and transported them to the Environmental Research Laboratory in Tucson, Arizona. Eggs were placed in four hatching trays suspended in 38-L aquaria. An airstone placed below each strainer basket created water movement which gently turned the eggs. Eggs were treated in a 1250 ppm formalin bath for 15 min at two and five d post-hatch to control fungus. Eggs began hatching five d following fertilization, and swim up was complete in an additional five d.
After swim-up, larval fish were moved to four, 38-L aquaria and fed day-old live brine shrimp nauplii every four h. We began feeding fish microencapsulated (Argent grade III) larval fish food four times a day at 30 d post-hatch. At 39 d post-hatch, we moved fish to a 1-m³ recirculating tank and began feeding them #1.5 sinking crumble ad libitum with a 12-h belt feeder. Water temperature was maintained at 20°C (± 2°C) throughout hatching and rearing. Bulkley et al. (1981) found 20°C to be the thermal optimum for flannelmouth suckers. We maintained 14-h light and 10-h dark cycles in the laboratory with timers to approximate a summer photoperiod.

Every ten d, a group of flannelmouth suckers were captured from the rearing tank and sorted into four buckets according to size. We measured total length (TL) of three randomly selected fish from each size group. This method assured that both fast and slow-growing fish were measured every ten d. We measured mass of each fish with an electronic balance to 0.01g. We used linear regression to evaluate the relationship between fish length and age and fish length and body mass. We compared growth rates of flannelmouth suckers to those reported for other native Colorado River fish.

RESULTS AND DISCUSSION

The TL of flannelmouth suckers increased with age from 0 to 430 d post-hatch according to the relationship:

\[
TL (\text{mm}) = 8.89 + 0.42\text{(age in d)} - 0.0005 \text{(age in d)}^2, \quad (\text{Figure D.1}).
\]
Figure D.1. Minimum and maximum TL of flannelmouth suckers reared at 20°C from 0 to 430 days post-hatch.
Growth rate of age-0 flannelmouth suckers decreased throughout the study so a quadratic term was included in the regression model \((R^2 = 0.87)\). We found average body mass also increased with fish length (Figure D.2) according to the equation:

\[
\ln \text{ weight (g)} = -11.70 + 2.79 \ln \text{ length (mm)}, \quad \text{(linear regression, } R^2 = 0.93). 
\]

Average daily growth rate of age-0 flannelmouth suckers caught in the Paria River from May to October in 1996 was 0.52 mm per day (Thieme 1997). The average daily growth rate of flannelmouth suckers in the laboratory over a similar time period (40 to 180 d post-hatch) was 0.33 mm per day. Average daily growth rate changes with age, so if fish are not sampled over the same age interval, comparison of daily growth rates can be misleading.

There are several potential reasons why my laboratory growth rate is lower than that reported for wild fish in the Paria River. Flannelmouth suckers used for this study were also subjected to swimming performance tests on nine separate occasions throughout the 430-day growth period. These tests required additional handling of fish. Sonora suckers \((Catostomus insignis)\) subjected to bimonthly handling for length and weight measurements exhibited lower growth rate than unhandled individuals (Deason 1998). My estimates of growth rate may be low due to repeated handling during swimming tests. Although food was not limiting, crowded conditions in the laboratory may also have reduced growth rates. Weak or sick fish that survive under laboratory conditions are less likely to survive in wild populations where predators exist. The persistence of weak individuals in laboratory populations may also lead to lower estimates of growth rate for captive-reared fish than for wild fish.
Humpback chub and Colorado pikeminnow grow at rates similar to those we observed for flannelmouth suckers when reared at 20°C in the laboratory (Lupher and Clarkson 1993) (Table D1). Laboratory estimates of growth may underestimate growth rates in wild fish. Razorback suckers reared in outdoor ponds at Dexter national fish hatchery were 71 to 135 mm TL at 150 d post-hatch (Minckley 1983) whereas, our laboratory reared flannelmouth suckers of the same age were only 46 mm to 83 mm TL. Although these two species are similar, the difference in growth rate may be species specific not the result of rearing conditions.

Size variation within age-0 fish can make age determination difficult in the field. Individuals may be slow growing age-1 fish or fast growing age-0 fish. This difficulty can lead to poor estimates of survival and recruitment. Laboratory growth rates allow age of wild fish to be estimated from their length. While my estimates of maximum and minimum growth are lower than those reported in the literature, my growth data provides a reference for assessing the effects of altered environmental conditions on growth.
Figure D.2. Relationship between total length and mass of age-0 flannelmouth suckers

Table D.1. Size of flannelmouth suckers compared to other native Colorado River fish at 90 days post-hatch when raised at reared at 20°C.

<table>
<thead>
<tr>
<th>Species</th>
<th>Mean (TL)</th>
<th>95% C.I.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flannelmouth sucker (this study)</td>
<td>40 mm</td>
<td>32 - 51 mm</td>
</tr>
<tr>
<td>Colorado pikeminnow (Lupher and Clarkson 1993)</td>
<td>36 mm</td>
<td>33 - 39 mm</td>
</tr>
<tr>
<td>Humpback chub (Lupher and Clarkson 1993)</td>
<td>50 mm</td>
<td>48 - 57 mm</td>
</tr>
</tbody>
</table>
REFERENCES


