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Literature Review of the Thermal Requirements and Tolerances of Organisms below Glen Canyon Dam

by

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A. Gammarus lacustris

The thermal tolerance of Gammarus lacustris was investigated by Smith (1973). G. lacustris acclimated to 18°C had a 96-hr TL_{50} of 26°C and a 30-day TL_{50} of 22-24°C. Organisms exposed to 18°C for 30 days had a 95% survival rate while no organisms survived exposure to 27°C. Reproduction was optimum at 18°C with decreased fecundity at 15, 21 and 24°C. Temperatures lower than 15°C were not tested. Results of this study would indicate that G. lacustris should be able to withstand temperature increases up to at least 18°C and possibly to 20°C. Smith (1973) worked with a population from Minnesota and the population of Gammarus lacustris in Glen and Grand canyons may have different thermal requirements and tolerances. In Glen Canyon there is a viable population of Gammarus present and the water temperature never rises above 15°C. This may indicate a different thermal tolerance of that population than the one from Minnesota. There is a need to study the effects of temperature on the population of Gammarus lacustris in Glen and Grand canyons.

B. Aquatic Insects

Below many impoundments with hypolimnetic releases there is an observed reduction in the diversity of macroinvertebrates (Ward and Stanford 1979). The seasonal thermal consistency below deep-release dams like Glen Canyon Dam, may disrupt thermal signals essential for completion of life cycles of many aquatic insects (Ward and Stanford 1979). A rapid increase in water temperature in the spring is required to initiate hatching of eggs of some species and the synchronization of adult emergence in others (Ward and Stanford 1979). The low summer temperatures below deep-release dams may eliminate some aquatic insect species because they are unable to grow fast enough to compete with other species. Adult insects may have low fecundity due to reduced size because of slow growth of immatures in the suppressed water temperatures. The increase in winter temperatures below deep-release dams may also disrupt aquatic insect life cycles. Many aquatic insects require a winter chill (temperature at or near 0°C) to break egg or larval diapause (Ward and Stanford 1979).

The insect fauna in the Colorado River below Glen Canyon Dam is impoverished and dominated by aquatic dipterans (Blinn and Cole 1991; Stevens 1976; Carothers et al. 1981; Leibfried and Blinn 1988). Aquatic dipterans comprise as much as 85% of the standing crop of drifting invertebrates (Leibfried and Blinn 1988). Little is known about the life history of aquatic insect species found in the Grand Canyon. The Aquatic Dipteran Report (Blinn et al. 1992) prepared for the EIS team addresses this subject but there is lack of information on thermal tolerances of these species. This is an area which will require further investigation. Laboratory tests on thermal tolerances of the major species present should be conducted.

The tributaries in the Grand Canyon contain a more diverse macroinvertebrate fauna than the mainstem (Blinn and Cole 1991; Polhemus and Polhemus 1976) and represent areas from which species could invade if conditions in the river were favorable. A temperature increase in the Colorado River below Glen Canyon Dam may not cause a great increase in the macroinvertebrate diversity. In a naturally cold-water river receiving warm water from a wide, shallow reservoir Fraley (1979) observed an increase in density of macroinvertebrates but a decrease in diversity. Mean water temperatures below the impoundment were 19.1°C during the summer and represented a warming of 3°C over stream temperatures above the dam. The increase in total number of organisms was dominated by filter-feeders which utilize the fine particulate organic matter (zooplankton and phytoplankton) which is released from a reservoir with epilimnetic withdrawal (Ward 1976). There was a decrease in diversity of macroinvertebrates, a shift to warm-water tolerant invertebrates, and a change in the emergence pattern of some aquatic insects.

It is very difficult to predict what changes in the macroinvertebrate fauna below Glen Canyon Dam would occur if there was selective withdrawal of warmer from Lake Powell. Only through extensive testing of the thermal tolerances and requirements of the existing macroinvertebrates in the tailwater and tributaries could inferences be made. Wrenn et al. (1979) evaluated the effect of temperature on a complex mixture of macroinvertebrates from the Tennessee River in 185 day tests. It may be possible to design similar experimental systems using naturally colonized communities from Glen Canyon. The experiemental system could be designed to receive epilimnetic water from Lake Powell and thereby mimic the thermal and chemical changes which would occur from the use of a selective withdrawal structure on Glen Canyon Dam. A study of thermal tolerances of macroinvertebrates would need to be done over a period of several years to examine if reproduction would occur. Insect nymphs and larvae in the tailwater may thrive in the warmer summer waters provided from a multiple level intake but the lack of winter cooling (the winter temperatures would not decrease below 7°C) may not allow the organisms to complete their life history.

C. Asian Tapeworm

Recently the asian tapeworm (Bothriocephalus acheilognathi) has been found in humpback chub from the Grand Canyon (Angradi et al. 1992). The degree of infestation in the entire population of humpback chub from Grand Canyon has not been determined but 80% of larval humpback chub (13-35 mm total length) examined in 1990 had tapeworms present. No tapeworms were found in humpback chubs from 1989 (Angradi et al. 1992). Asian tapeworm infestations have been reported in the endangered woundfin minnow (Plagopterus argentissimus), speckled dace (Rhinichthys osculus), Virgin roundtail chub (Gila robusta seminuda),Virgin spinedace (Lepidomeda mollispinis), and red shiner (Notropis lutrensis) in the Virgin River (Heckmann et al. 1986).

Bothriocephalus acheilognathi was introduced into the United States in grass carp in the 1970's and is well established in the southeastern United Sates (Granath and Esch 1983a). The asian tapeworm has a complex life cycle with operculate eggs shed into the water via feces from an infected fish. After a period of development (96 hr at 20°C) a motile coracidium emerges (Granath and Esch 1983a,b). Coracidia are consumed by and develop into a procercoid stage in several species of cyclopoid copepods, some of which are found in the Colorado River in Grand Canyon (Haury 1986). The infected copepod is ingested by a fish host and the maturation to the adult worm occurs in the intestine of a host fish (Granath and Esch 1983a,b). Bothriocephalus acheilognathi lacks specificity for a definitive host and is found fathead minnows (Pimephales promelas), red shiner (Notropis lutrensis) and mosquitofish (Gambusia affinis) in Belews Lake, North Carolina (Riggs and Esch 1987).

In a series of laboratory and field experiments Granath and Esch (1983b) determined the effects of temperature on the life cycle of B. acheilognathi. Temperature had a significant effect on maturation and growth of B. acheilognathi. Infected mosquitofish exposed to 20°C showed no maturation of the tapeworm to the mature egg producing worms while at 25 and 30°C the mature egg producing worms dominated the population present. However, the fish exposed to 20°C had the highest density of tapeworms. Egg hatching, development and survival of coracidia were all affected by temperature, with maximum egg hatching and development rate at 30°C. At 20°C egg maturation required a minimum of 60 hr with peak production of coracidia of 35% at 96 hr. Granath and Esch (1983b) concluded that above 25°C growth and development of segmented (sexually mature) worms was stimulated, egg maturation and hatching was stimulated and there was recruitment of coracidia by copepods. However, the highest densities of unsegmented tapeworms (sexually immature) were at 20°C, unfortunately temperatures below 20°C were not tested.

Bothriocephalus acheilognathi is present in humpback chub in Grand Canyon, therefore proper conditions must exist for the spread of the parasite. Increasing mainstem temperatures through the use of a multiple level intake structure would probably enhance the population of asian tapeworms since 1) increased temperatures (> 20°C) should enhance reproduction of the parasite, and 2) epilimnetic withdrawal from Lake Powell should increase the population of cyclopoid copepods in Grand Canyon. It is difficult to assess the potential effects of a multiple level intake structure on B. acheilognathi in the Grand Canyon without further evaluation of 1) the degree of infestation in Gila cypha, other native and nonnative fish, and cyclopoid copepods; 2) the effects of temperature on the population of B. acheilognathi in Grand Canyon.

D. Lernaea cyprinacea

The parasitic copepod, Lernaea cyprinacea, is present in native and nonnative fish populations in the Colorado River in Grand Canyon (Kaeding and Zimmerman 1983). The highest incidence of L. cyprinacea in humpback chub in the Little Colorado River was in the winter. Fish in the mainstem Colorado River had lower incidence of infestation . The lower incidence of infestation in fish in the Colorado River is probably due to the low temperatures. The development of all stages of L. cyprinacea is affected by temperature (Shields and Tidd 1968). Eggs hatch into naupli at temperatures as low as 10 C but the development to the next stage (metanaupli) did not occur below 20 C with optimum development at 26 to 28 C (Shields and Tidd 1968). The transformation from the metanaupli to the copepodid stages was optimum at 28 to 36 C. The critical low temperature for developement and penetration of the host is between 15 and 20 C with temperatures below 24 C increasing the length of time spent in the copepodid stages previous to host penetration (Shields and Tidd 1968). The production of egg sacs in L. cyprinacea has been observed down to 18 C (Nakai and Kokai 1931). The low number of infested Gila cypha in the mainstem of the Colorado River (Kaeding and Zimmerman 1983) and the inablity of L. cyprinacea to complete its lifecycle below 20 C (Shields and Tidd 1968) indicates that the cold hypolimnetic releases from Glen Canyon Dam are reducing the infestation of this parasite in native and nonnative fishes. In the Colorado River above Lake Powell Lernaea cyprinacea has been observed in significant numbers in native and nonnative fishes (Flagg 1981; Valdez 1990). The highest incedence of L. cyprinacea in Colorado squawfish (Ptychocheilus lucius) was observed in backwaters and isolated pools, where water temperatures frequently exceed 25 C (Valdez 1990).

E. Cladophora

There are different races of Cladophora glomerata which may have different thermal tolerances. The race growing in the Glen Canyon tailwater probably does best in cold water (< 15°C) but the species has a wide range of temperature tolerances and optimums (Whitton 1970). Herbst (1969) observed that Cladophora in the Great Lakes became dominate algal species when the temperature increased above 15°C and it thrived at temperatures up to 25°C. In seven Ontario rivers Cladophora dominated the phtyobenthos up to 18°C and had an upper thermal tolerance of 23.5°C (Wong et al. 1978). Whitton (1967) observed large growths of Cladophora in both a heated diversion of the River Wear, England (25-26°C) and the main river (15°C). Cladophora from Lake Michigan had a thermal optimum between 28 and 31°C (Lester et al. 1988). The effects of increased temperatures on the population of Cladophora in Glen and Grand canyons need to be determined before any predictions about the population response to increased temperatures can be made.

F. Diatoms

The effect of increased temperatures on epiphytic diatoms associated with Cladophora from the Colorado River below Glen Canyon Dam has been determined experimentally by Blinn et al. (1989). The epiphytic diatoms associated with Cladophora change within two weeks of exposure to higher temperatures. Species associated with Cladophora exposed to higher temperatures (18 and 21°C) are smaller and grow closer to the substrate replace the larger, upright, light-shielding overstory species that dominate in cool tailwater systems (Blinn et. al. 1989). The threshold temperature for this change was between 12 and 18°C.

Increasing the outflow temperature to increase humpback chub reproduction (optimum egg hatching at 19 to 20°C (Marsh 1985)) could cause a major shift in the diatom composition associated with Cladophora in Glen and Grand canyons. A large assemblage of diatoms are present below Glen Canyon Dam (Usher et al. 1986). Changes in composition, density, and diversity of diatoms will occur if thermal conditions are modified (Blinn et al. 1989). A shift in diatom species composition may affect the macroinvertebrates below Glen Canyon Dam since the larger, upright diatom species are preferred by grazers (Sumner & McIntire 1982).

G. Native and Nonnative Fish

The thermal tolerances and requirements of native and nonnative fish are presented in Figures 1 through 3 and Tables 1 through 3.

Important Research Issues

Because of the lack of specific information on the thermal tolerances of aquatic organisms below Glen Canyon Dam there are several research projects which need to be done before any conclusions about the effect of increased temperature on the aquatic ecosystem can be made. Many of these studies could be done under laboratory conditions and others could be done in artificial streams. A set of experimental streams could be constructed at Glen Canyon Dam and be designed to receive epilimnetic water from Lake Powell and thereby mimic the thermal and chemical changes which would occur from the use of a selective withdrawal structure on Glen Canyon Dam. These streams could be used to study the effects of operating the selective withdrawal structure to maximize the temperature for humpback chub reproduction as developed under objective 1. A number of different organisms could be placed in the streams including Cladophora and associated diatoms, macroinvertebrates, native and non-native fishes. Below are the major projects which should be initiated to better understand the effects of temperature on the aquatic ecosystem below Glen Canyon Dam.

1) **Determine the thermal tolerance of Gammarus lacustris from the Colorado River below Glen Canyon Dam.**

These experiments could be done in the laboratory and also in experimental streams at Glen Canyon Dam. The tolerances to acute and chronic temperature changes should be determined. The effect of temperature changes on fecundity, reproduction, and production should be determined. Again the thermal regime should mimic the proposed changes that would occur if a selective withdrawal structure is constructed (i.e. maximum temperature of 15-20°C in July, August and September). The secondary production of Gammarus in the Colorado River is not know under the current conditions and any study on the effect of temperature would need to establish this baseline as a control.

2) **Determine the thermal tolerance of significant macroinvertebrate species in the Colorado River below Glen Canyon Dam.**

The major insect species below the dam are dipterans (Blinn et al. 1992) and the life histories and thermal tolerances of these species are unknown. As with Gammarus, the thermal tolerances could be determined in both laboratory studies and in experimental streams at Glen Canyon Dam. A study of thermal tolerances of macroinvertebrates would need to be done over a period of several years to examine if reproduction would occur. The thermal tolerances of macroinvertebrates from Colorado River tributaries could also be determined. The macroinvertebrate fauna of the tributaries in the Grand Canyon is more diverse than the mainstem fauna and the tributaries could serve as source for aquatic macroinvertebrates to colonize the mainstem (Blinn and Cole 1991; Hofknecht 1981). Carothers and Minckley (1981) found increased biomass and diversity of aquatic invertebrates at the confluence of 15 tributaries as compared to sites 200 m upstream of the confluence. Changing the temperature of the mainstem may allow for colonization of the Colorado River from the tributaries. The species of insects which might invade the main river if the temperature regime was modified should be identified and their thermal tolerances investigated. However, the increased temperature during the summer months may not be sufficient to allow the propagation of these species in the river. Insect nymphs and larvae in the tailwater may thrive in the warmer summer waters provided from a multiple level intake but the lack of winter cooling (the winter temperatures would not decrease below 7°C) may not allow the organisms to complete their life history.

3) Determine the viability and egg maturation of the asian tapeworm (*Bothriocephalus acheilognathi*) below 20°C.

Laboratory tests on the viability and egg maturation of the asian tapeworm have not been tested below 20°C (Granath and Esch 1983a,b). Temperatures in the Colorado River in Grand Canyon never exceed 20°C yet *Bothriocephalus acheilognathi* is present in the Grand Canyon population of humpback chub (Angradi et al. 1992). Tests on egg viability and maturation could be conducted in a laboratory.

4) Determine the degree of *Bothriocephalus acheilognathi* infestation of in *Gila cypha*, other native and nonnative fishes, and cyclopoid copepods in the Colorado River in Grand Canyon.

Angradi et al. (1992) determined that 80% of larval humpback chub (13-35 mm total length) examined in 1990 had tapeworms present. No tapeworms were found in humpback chubs from 1989 (Angradi et al. 1992). A systematic study needs to be done to determine the presence of asian tapeworm in the fishes of Grand Canyon. Currently Bio/West is evaluating the presence or absence of tapeworms in adult humpback chub in Grand Canyon as part of their investigation of food habits using a non-lethal stomach pump method.

5) Determine the effects of increased temperature on *Cladophora glomerata* from the Colorado river below Glen Canyon Dam.

The population of *Cladophora glomerata* growing in the Glen

Canyon tailwater probably does best in cold water (< 15°C) but the species has a wide range of temperature tolerances and optimums (Whitton 1970). To predict what changes to the population may occur by increasing the temperature the thermal tolerances of Cladophora from below Glen Canyon Dam should be tested in both laboratory and on-site artificial streams.

6) **Determine the effects of temperature on Lernaea cyprinacea from Grand Canyon.**

In laboratory experiments investigate the effects of temperature on L. cyprinacea stages (egg, metanauplii, copepodid and adult) using a representative native (i.e. speckled dace) and nonnative (i.e. fathead minnow) fish as host organisms.

Table 1. Upper and lower lethal temperatures and temperatures for optimum growth and final preferred temperatures for native and nonnative fishes of the Colorado River.

Species	Life stage	Upper and Lower Lethal Temp (°C)	Optimum Growth Temp (°C)	Final Preference (°C) (Acclimation Temp)
Humpback Chub (Gila cypha)	Juvenile 80 to 120 mm in length			21.0 ± 1.26 (14) 24.4 ± 1.20 (20) 23.5 ± 1.72 (26)[19]
Razorback sucker (Xyrauchen texanus)	Adult			17.1 (8) 23.5 (14) 20.6 (20) 22.3 (26)[18]
Razorback sucker (Xyrauchen texanus)	Juvenile 150 to 300 mm in length			25.0 ± 0.96 (8) 29.0 ± 0.52 (14) 22.7 ± 1.07 (20) 23.1 ± 0.902 (26)[19]
Bonytail chub (Gila elegans)	Juvenile 25 to 50 mm in length			17.9 ± 0.92 (14) 22.5 ± 1.94 (20) 25.1 ± 1.71 (26)[19]
Colorado Squawfish (Ptychocheilus lucius)	Adult 300 to 500 mm in length			21.5 ± 3.07 (14) 22.5 ± 2.50 (20) 25.7 ± 0.50 (26)[19]
Colorado Squawfish (Ptychocheilus lucius)	Juvenile 75 to 100 mm in length			21.9 ± 0.74 (14) 27.6 ± 0.44 (20) 23.7 ± 0.64 (26)[19]
Speckled dace (Rhinichthys osculus)				
Flannelmouth sucker (Catostomus latipinnis)				
Bluehead sucker (Catostomus discobulus)				

Rainbow Trout (Onchorhynchus mykiss)	Adult	25 to 26.5 Upper[26,55] 0 Lower[9]	12 to 17.2[9,55,76,113]	12.0 (25)[49a] ; 22.0 (24)[25b] 20.1 (21)[25b] ; 9.8 (20)[49a] 18.1 (18)[25b] ; 10.3 (15)[49a] 16.9 (15)[25b] ; 14.4 (12)[25b] 12.7 (10)[49a] ; 12.6 (9)[25b] 11.6 (6)[25b] ; 11.8 (5)[49a] [a] 24 hour preference test [b] 1 hour preference test
Rainbow Trout (Onchorhynchus mykiss)	Juvenile (fingerling)	22.4 to 25.7 Upper[10]	14.8 to 18.6[51]	
Cutthroat trout (Onchorhynchus clarki)	Adult	23 to 25 Upper[8,9] 0 Lower[74]	12 to 15[9,49]	

Table 1. Continued

Species	Life stage	Upper and Lower Lethal Temp (°C)	Optimum Growth Temp (°C)	Final Preference (°C) (Acclimation Temp)
Brook Trout (Salvelinus fontinalis)	Adult	20.1 to 25.3 Upper[25,35,55] 0 Lower[9,82]	11 to 16.1[7,52,55,61]	19.0 (24) 18.3 (21) 18.0 (18) 15.2 (15) 13.7 (12) 11.3 (9) 11.2 (6)[25,26]
Brook Trout (Salvelinus fontinalis)	Juvenile	20.1 to 25.3 Upper[26,55,82] 0 Lower[82]	11 to 14[82]	
Brook Trout (Salvelinus fontinalis)	Fry	21 to 25.8 Upper[15]	8 to 12[79]	
Brown Trout (Salmo trutta)	Adult	23 to 26.4 Upper [26,55] 2 Lower[9]	10 to 15.5[55,110]	18.5 (23) 18.8 (21) 17.9 (18) 15.5 (15) 11.7 (12)[25,26]
Carp (Cyprinus carpio)	Adult	35.7 to 40.6 Upper[10,55]	15 to 30[9,54,55] poor growth below 13 and above 30; feeding ceases at 5[39]	17 (10) 25 (15) 27 (20) 31 (25) 31 (30) 32 (35)[58]
Carp (Cyprinus carpio)	Juvenile	38 Upper[33,71]	30[1]	27 to 33.5[28]
Carp (Cyprinus carpio)	Fry	38 Upper[71] 7 Lower[42]	30[1]	27[6]
Channel Catfish (Ictalurus punctatus)	Adult	36.1 to 36.4 Upper[55]	28 to 30[3,4,55] 26.6 to 29.4[89] Poor growth below 21[3]	30.5 (30) 29.5 (27) 29.4 (24) 26.1 (21) 22.9 (18) 21.7 (15) 19.9 (12) 20.4 (9) 18.9 (6)[25,26]

Channel Catfish (Ictalurus punctatus)	Fry	35 to 38 Upper[2]	29 to 30[69,107] Poor growth below 21[3]	
Fathead minnow (Pimephales promelas)	Adult	33.2 Upper[55]	25.5 to 26.0[17,55]	28.9 (27) 26.6 (24) 23.8 (21) 22.1 (18) 21.3 (15) 19.8 (12)[25,26]
Walleye (Stizostedion vitreum)	Juvenile (64 to 110 mm)[64]	31.6 Upper[91]	22.1[91]	20 to 23[28,55]
Striped bass (Morone saxatilis)	Adult	32 Upper[30]	23 to 30[29]	21.6[30]

Table 1. Continued.

Species	Life stage	Upper and Lower Lethal Temp (°C)	Optimum Growth Temp (°C)	Final Preference (°C) (Acclimation Temp)
Striped bass (Morone saxatilis)	Larvae	24 Upper 10 Lower[30]	18 to 21[30]	21.6[30]
Red Shiner (Cyprinella lutrensis)	Adult (29 to 47 mm in length)[21]	39 Upper[64,65]		23.0 (10)[a] 21.2 (10)[b] 27.8 (20)[a] 22.3 (20)[b] 30.9 (30)[a] 28.5 (30)[b] [a] Population from unregulated river [b] Population from regulated river[21]
Threadfin shad (Dorosema pentenense)	Adult	4 Lower[43] 7 Inactive[43]		
Smallmouth bass (Micropterus dolomieui)	Adult	32-35 Upper[34,55] 0 Lower[34] 10 Inactive[34]	26 to 29[77]	29.4 (33) 30.9 (30) 29.7 (27) 28.2 (24) 25.8 (21) 25.5 (18) 20.2 (15)[25,26]
Smallmouth bass (Micropterus dolomieui)	Juvenile	35 Upper[26] 6.7 Lower (22)[53] 3.7 Lower (18)[53] 1.6 Lower (15.5)[53]	25 to 29[90]	28[28]
Smallmouth bass (Micropterus dolomieui)	Fry	10 Inactive[34]	25 to 29[90]	

Table 2. Spawning and egg hatching temperatures for native and nonnative fishes of the Colorado River.

Species	Spawning Temperature (°C; Optimum and Range)	Egg Hatching Temperature (°C; Optimum and Range)	Time of year spawning occurs in the Colorado River (location)
Humpback Chub (Gila cypha)	22 Upper 16 Lower[22,57]	19-20 Optimum 26 Upper 10 Lower[19,45,63]	April-June (Grand Canyon)[22,57] June-July (Black Rocks)[58]
Razorback sucker (Xyrauchen texanus)	18-22 Upper[14,97] 9.5-10.5 Lower[14,97]	20 Optimum 25 Upper 15 Lower[63]	May-June (Green River)[97] November-March (Lake Mohave)[14,32]
Bonytail chub (Gila elegans)	18 Upper 18 Lower[103]	20 Optimum 26 Upper 14 Lower[19,44,63]	June-July (Green River)[103]
Colorado Squawfish (Ptychocheilus lucius)	26 Upper 19 Lower[75,98,103]	20 Optimum 25 Upper 20 Lower[63]	June-July (Green and Yampa Rivers)[75,98]
Speckled dace (Rhinichthys osculus)	23 Upper 17 Lower[22]		May (Grand Canyon)[22]
Flannelmouth sucker (Catostomus latipinnis)	23 Upper 17 Lower[22]		Winter to early summer (Grand Canyon)[22,62] April to June (Yampa and Green Rivers)[66]
Bluehead sucker (Catostomus discobulus)	23 Upper 17 Lower[22]		Spring to early summer (Grand Canyon)[22,62] Mid to late June (Upper Colorado River)[101]
Rainbow Trout (Onchorhynchus mykiss)	10 Optimum 20 Upper 2 Lower[9,83]	10 Optimum 15 Upper 3 Lower[8,36,83] increased mortality below 7[20]	October to February (Bright Angel Creek)[22] November to April (Lee's Ferry)[62]

Cutthroat Trout (Onchorhvnchus clarki)	10 Optimum 17 Upper 6 Lower[9]	10 Optimum 13 Upper 4 Lower[9,93]	
Brook Trout (Salvelinus fontinalis)	7 Upper 3 Lower[9,68]	12 Upper 4 Lower[9,36,68]	Winter and Spring (Grand Canyon)[62]
Brown Trout (Salmo trutta)	10 Optimum 13 Upper 6 Lower[9,84]	10 Optimum 15 Upper 2 Lower[9,36,84]	Winter and Spring (Grand Canyon)[62]
Carp (Cyprinus carpio)	23 Optimum 26 Upper 18 Lower[9,33,96]	21 Optimum 25 Upper 20 Lower[9,33]	
Channel Catfish (Ictalurus punctatus)	27 Optimum 29 Upper 21 Lower[9,69]	27 Optimum 29.5 Upper 15.5 Lower[16,69]	Spring and Summer (Grand Canyon)[62]

Table 2. Continued.

Species	Spawning Temperature (°C; Optimum and Range)	Egg Hatching Temperature (°C; Optimum and Range)	Time of year spawning occurs in the Colorado River (location)
Fathead minnow (Pimephales promelas)	25 Optimum 30 Upper 16 Lower[39]	26 Optimum 30 Upper 22 Lower[17]	
Walleye (Stizostedion vitreum)	6 Optimum 12 Upper 3 Lower[9,27]	6 Optimum 15 Upper 5 Lower[56,91]	
Striped bass (Morone saxatilis)	17-19 Optimum 24 Upper 15 Lower[9,102,104]	18 Optimum 28 Upper 12 Lower[30,72] Low survival above 24[30]	June (Lake Powell)[77,78]
Red Shiner (Cyprinella lutrensis)	30 Upper 15 Lower[31]		
Smallmouth bass (Micropterus dolomieui)	27 Upper 21 Lower[9]	26 Upper 13-16 Lower[9,34]	

Table 3. Available information on egg survival and hatching success for native and nonnative fishes of the Colorado River.

Species	Percent Hatching at various acclimation temperatures	Time from fertilization to hatch (hours)	Percent survival of hatched eggs to fry* at various acclimation temperatures *24 hour larvae for striped bass	Time (hours) from hatching to swimup at various acclimati on temperatures	Percent of abnormal fry at various acclimation temperatures
Humpback Chub	0% (5)[19,63]				
(Gila cypha)	0% (10)[63]				
	30% (10)[19]	456 (10)[19]			
	12% (12-13)[45]	475 (12-13)[45]	15% (12-13)[45]	168 (12-13)[45]	
	50% (14)[19]	384 (14)[19]			
	0.8% (15)[63]	223 (15)[63]		372 (15)[63]	33% (15)[63]
	62% (16-17)[45]	266 (16-17)[45]	91% (16-17)[45]	120 (16-17)[45]	
	84% (19-20)[45]	160 (19-20)[45]	95% (19-20)[45]	72 (19-20)[45]	
	100% (20)[19]	96 (20)[19]			
	60% (20)[63]	133 (20)[63]		249 (20)[63]	13% (20)[63]
	79% (21-22)[45]	146 (21-22)[45]	99% (21-22)[45]	72 (21-22)[45]	
	2% (25)[63]	80 (25)[63]		166 (25)[63]	17% (25)[63]
	95% (26)[19]	72 (26)[19]			
	0% (30)[63]				
Razorback sucker	0% (5)[63]				
(Xyrauchen texanus)	0% (10)[63]				
	19% (15)[63]	324 (15)[63]		312 (15)[63]	15% (15)[63]
	35% (20)[63]	312 (20)[63]		146 (20)[63]	8% (20)[63]
	29% (25)[63]	168 (25)[63]		103 (25)[63]	32% (25)[63]
	0% (30)[63]				

Bonytail chub	0% (5)[19,63]				
(Gila elegans)	0% (10)[19,63]				
	4% (12-13)[44]	498 (12-13)[44]	25% (12-13)[44]	120 (12-13)[44]	
	50-70% (14)[19]	240 (14)[19]			
	35% (15)[63]	264 (15)[63]		396 (15)[63]	4% (15)[63]
	55% (16-17)[44]	269 (16-17)[44]	96% (16-17)[44]	72 (16-17)[44]	
	40-100% (20)[19]	144 (20)[19]			
	32% (20)[63]	131 (20)[63]		217 (20)[63]	1% (20)[63]
	88% (20-21)[44]	174 (20-21)[44]	99% (20-21)[44]	48 (20-21)[44]	
	91% (21-22)[44]	165 (21-22)[44]	98% (21-22)[44]	48 (21-22)[44]	
	0.5% (25)[63]	103 (25)[63]		148 (25)[63]	0% (25)[63]
	70-90% (26)[19]	72 (26)[19]			
	0% (30)[63]				
	0% (31)[19]				
	0% (37)[19]				
Colorado Squawfish	0% (5)[63]				
(Ptychocheilus lucius)	0% (10)[63]				
	0% (15)[63]				
	2-27% (20)[63]	96-135 (20)[63]		267 (20)[63]	11% (20)[63]
	0-9% (25)[63]	78 (25)[63]		114 (25)[63]	26% (25)[63]
	0% (30)[63]				

Table 3. Continued.

Species	Percent Hatching at various acclimation temperatures	Time from fertilization to hatch (hours)	Percent survival of hatched eggs to fry* at various acclimation temperatures *24 hour larvae for striped bass	Time (hours) from hatching to swimup at various acclimation temperatures	Percent of abnormal fry at various acclimation temperatures
Striped bass (Morone saxatilis)	36.3% (12)[72] 61.9% (14)[72] 82.5% (16)[72] 87.4% (18)[72] 62.3% (20)[72] 61.3% (22)[72] 44.6% (24)[72] 30.1% (26)[72] 7.6% (28)[72]	58 (15.6)[87] 51.8 (18)[87] 34 (21)[87]	43.0 ± 2.9 (12)[72] 46.3 ± 2.8 (14)[72] 65.0 ± 4.8 (16)[72] 76.1 ± 3.5 (18)[72] 68.6 ± 2.8 (20)[72] 34.8 ± 4.1 (22)[72] 13.3 ± 2.4 (24)[72] 9.6 ± 1.8 (26)[72]		
Walleye (Stizostedion vitreum)	84% (6)[91] 66.5% (8.9)[91] 61.5% (12)[91] 15% (15)[91] 32% (18.1)[91] 0% (20.9)[91]	1176 (6)[91] 744 (8.9)[91] 432 (12)[91] 264 (15)[91] 192 (18.1)[91]	0 (6)[91] 78 (8.9)[91] 88 (12)[91] 95 (15)[91] 97 (18.1)[91]		1.0% (6)[91] 3.8% (8.9)[91] 3.3% (12)[91] 1.0% (15)[91] 15.0% (18.1)[91]
Rainbow Trout (Onchorhynchus mykiss)		1464 (6)[36] 984 (8)[36] 696 (10)[36] 600 (12)[36] 432 (15)[36]			
Brook Trout (Salvelinus fontinalis)		1752 (6)[36] 1440 (8)[36] 1008 (10)[36] 888 (12)[36] 672 (15)[36]			
Brown Trout (Salmo trutta)		1752 (6)[36] 1416 (8)[36] 924 (10)[36] 816 (11)[36]			

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