COMPARISON OF HEART RATE IN FISHES: COLD, TEMPERATE SEA WATER VERSUS WARM, DESERT RIVERS

John N. Rinne
USDA Forest Service, Rocky Mountain Research Station,
2500 S. Pineknoll Drive, Flagstaff, Arizona, 86001.
ph 928-556-2187, jrinne@fs.fed.us

Bard Holand
SINTEF UNIMED, N-7034, Trondheim, Norway
ph +47-73 59 25 90 Bard.A.Holand@Unimed.sintef.no

Gunnar Sundnes
The Royal Norwegian Society of Sciences and Letters Foundation,
Trondheim, Norway. ph +47 72 55 68 05

Introduction

Globally, fish are found in a wide spectrum of water temperatures, ranging from cold sea water (-2 C, Scholander et al. 1954) to the hot desert springs, streams and rivers with temperatures above 30 C (Deacon & Minckley 1974, Soltz & Naiman 1978). Because of being eurythermic organisms, all functions of fishes are effected by ambient water temperature. Research on fishes in the past few decades have shown that heart rate is a good indicator of reactions in fish (Kanwisher et al. 1972, Holand 1987). Fish react physiologically, not only to physical and emotional stimuli, but also to environmental factors such as changes in water temperature.

Due to modern technology we can now study the heart rate and electrocardiogram (EKG) of free swimming fishes (Kanwisher et al. 1972). From coastal waters in Norway we have found correlation between heart rate of fish and water temperatures, but these temperatures rarely exceed 20 C. No studies of heart rate in fishes inhabiting cool (20-25 C), to warm (25-30 C), to hot (> 30 C) waters have been conducted. Likewise, the effect on the heart of extreme diurnal temperature changes in desert rivers is not known. Therefore, we were interested in comparing heart activity of fishes living in the cold Norwegian seawater to fishes living in warm desert rivers in Arizona. The diversity of fish species is low in the southwestern United States (Minckley 1973, Sublette et al. 1990, Rinne & Stefferud 1998), however their adaptations to environmental conditions are great (Deacon & Minckley 1974, Rinne & Stefferud 1997). With the ever-increasing impact of humans, these adaptations to rather harsh environments is of great comparative importance. Although important, basic data on the response of the heart rate in fishes living in hot desert streams in arid deserts is lacking. We decided to investigate the heart rate of two desert species from the Verde River, Arizona, USA because of their subjection to and adaptation for flooding, drought, and characteristic elevated water temperatures,. Our primary objectives were: 1) to observe and define heart rate/temperature relationships of the two desert fish species in the field and laboratory, 2) to compare these rates with those of a cold temperature marine fish species, and 3) to suggest possible management implications from results of study.

Materials and Methods

Research animals

The species chosen for this comparative study were: 1) cod, *Gadus morhua (Gadiformes: Gadidae)* caught in sea waters in the Trondheimsfjord, Norway, and 2) Sonora sucker*, Catostomus insignis (Cypriniformes: Catostomidae),* and roundtail chub, *Gila robusta (Cypriniformes: Cyprinidae)* captured in a large desert river (Verde River) in Arizona, USA (Stefferud & Rinne 1995).

Experimental design

Cod were held in large tanks of 5 m^3 where the water temperature was controlled by an electric heater and kept near temperature of capture (7 C). The water was approximately one meter in depth. Temperature stratification was avoided by aeration with a small compressor injecting air at the bottom of the tank. Prior to experiment initiation, experimental animals were allowed to acclimatize thermally (5 C) and behaviorally in the tanks for two weeks after
capture. Data were collected from three individual cod varying from 450 to 650 mm total length (TL).

Initial (1994) experiments in the desert Southwest were conducted, *in situ,* in net cages and in small stream enclosures on the Verde River, near Camp Verde, Arizona. To refine definition of the relationship of increasing water temperature and heart rate, subsequent (1997), controlled experiments were conducted in artificial raceways in the laboratory, Flagstaff, Arizona. Roundtail chub and Sonora sucker were captured in the Verde River and held in cages and/or exclosures for several days to acclimate behaviorally, thermally (10-15 C), and to restrained conditions. For laboratory studies, captured fishes were transported live in oxygenated coolers and similarly permitted to acclimate for several days at 15 C before transmitter implantation. Sample size was one sucker and one chub in 1994, two chubs and two suckers in 1995, and three suckers and two chubs in 1997. Experimental individuals used for the desert experiments ranged from 230 to 500 mm TL.

Fish were retained and monitored in net cages (1.5 X 1.0 X 3.0 m, .06 cm mesh) in the Verde River in October 1994 and in July 1995 . In 1995, two additional fish (one chub and one sucker) were released after tagging and allowed to swim freely in a small enclosure (ca. 10 m long) in a side channel of the Verde River. One sucker was released to swim freely in the river. Prior to taking measurements, both in the river and the laboratory, fish were allowed
to behaviorally stabilize for 24 hours. Because of the effect on heart rates as personnel approached the experimental site, longer electronic cables (20 m) were used between the hydrophone (which was permanently placed in the water near experimental fish) and the receiving/recording equipment to avoid the effects on heart rate of personnel approaching the research site.

Laboratory fish were allowed to re-stabilize their heart rate for more than 12 hours to acclimate after each temperature change before heart rates were recorded at a new environmental temperature. This procedure allowed fish to re-stabilize their heart rate, prior to recording heart rate/ temperature (ambient water temperatures) relationship data. In the laboratory, the receiving and recording equipment was installed in adjacent rooms to avoid disturbances from human activity. In laboratory experiments in Flagstaff, artificial, circular raceways (Frigid Units, Inc.) were filled to a depth of 25 cm with Verde River water, oxygenated by agitating chiller units set at their highest temperature (15 C) and water was then circulated by small, 1/3 hp pumps. Industrial heating units capable of 15,000 btu's per hour were inserted into raceways to facilitate rate of temperature elevation. All experiments began at 12-13 C and ceased upon loss of equilibrium (ecological death) of individual fish. Heart rate was continuously measured as described above. Raceway water temperature was monitored with a continuous-recording Hydrolab sonde unit.

Transmitters

Acoustical heart transmitters were developed at SINTEF to be used on the desert cypriniform fishes. Similar transmitters have been used successfully on cod from the North sea (Mohus and Holand 1983). However, in the study of desert fishes, it was important to construct a transmitter which was smaller in size, but had a battery life of at least 10 days. The smaller-sized transmitter used on the smallest chub (230 mm, TL) from the Verde River was cylindrical in shape, measured 8 mm OD, 18 mm long and weighed 1.7 g in air and 0.8 g in water. For the larger suckers and chubs, transmitters were 11 mm OD, 35 mm long, and weighed 5.8 g in air and 2.6 g in water. Transmitters used on codfish in studies in Norway were similar in size to the larger (35 mm) units used for the cypriniform species.

Heart rate signals

The EKG signal that is generated by the heart muscles, is detected by means of two electrodes. The reference electrode is normally attached to the transmitter housing, while the "active" electrode is soldered to the end of an insulated wire, protruding from the transmitter. Normally, the transmitter is placed within the stomach of the experimental fish with the reference electrode in contact with the stomach wall. The insulated wire containing the active electrode extends throughout the esophagus and the gill cavity. The electrode is then inserted through the skin and positioned close to the pericardium (Figure 1a). To secure the electrode, the electrode wire is sutured to the skin, close to the point of insertion. However, in the Sonora sucker, the transmitter could not be placed in the stomach because of the specific anatomy of the species. This species, unlike the predaceous cod and chub, is an omnivore and its esophagus and stomach morphology were not compatible to such implantation. The transmitter, therefore, was sutured to the back of the sucker (Figure 1b).

Figure 1. Photo showing normal implantation of electrode on a) a roundtail chub, Gila robusta, and b) attachment of a transmitter to the back of a Sonora sucker, Catostomus insignis.

The EKG signal causes a frequency modulation (FM) of the continuous carrier frequency of the transmitter. The modulated signal is received by a hydrophone and an acoustical receiver also developed and constructed at SINTEF. The audio signal from the receiver may be recorded for later processing, or used for manual counting of the heart beat signal on site. Normally, to determine the heart rate, heart beats were counted and averaged over a period of 30 seconds.

Results

The summary of heart rates measured in fishes (three suckers and three chubs in the Verde River in July, 1995 are shown in Figure 2. During maximum elevated water temperature and diurnal variations, temperature at 0.5 m depth varied up to 8 C daily (July 14). Considerably greater variation in water temperature occurred during the duration of experimentation, July 11 to 17 (Figure 3). There were no obvious differences between heart rates recorded at similar temperatures for fish swimming freely in the 10 m enclosures in the Verde River compared to those restrained in net cages.

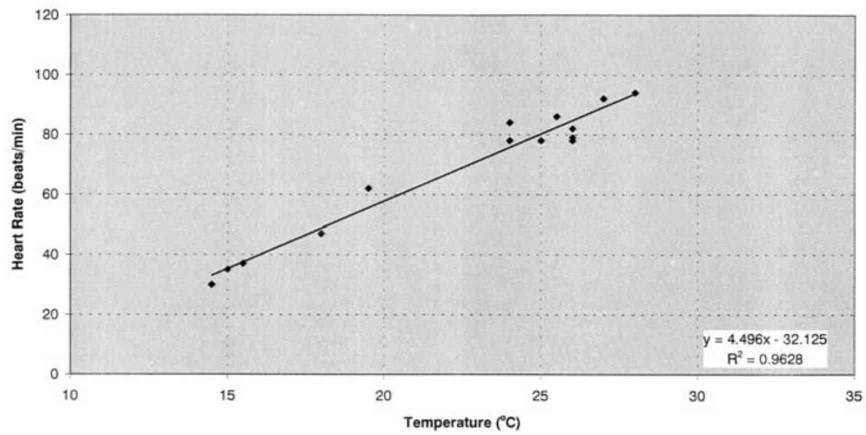

Figure 2. Heart rate and temperatures relationships measured in two desert cypriniform species in the Verde River, 1995.

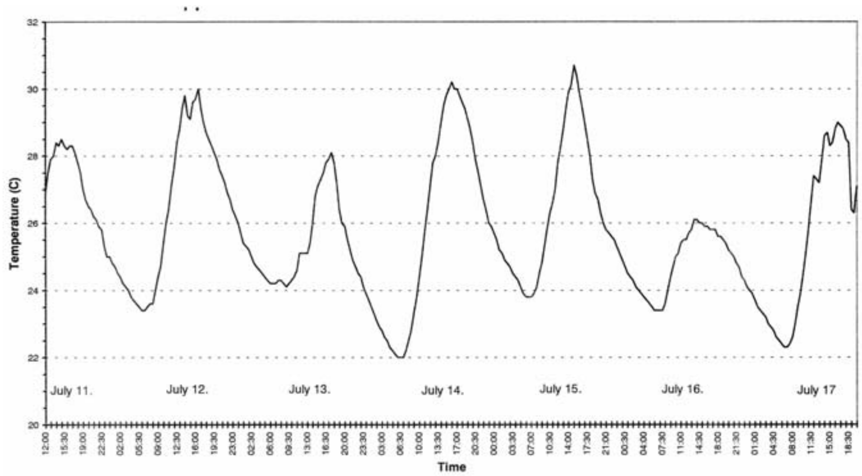

Figure 3. Diel temperature variations at the experimental site in the Verde River measured at approximately 0.5 m depth in July 1995.

Finally, a summary of heart rates measured under laboratory conditions with controlled temperatures in 1997 is shown in Figure 4. First, the relationships measured in the field and laboratory were markedly similar and not significantly different ($P < 0.05$, DF 4). Coefficients of determination (R^2) were high for both the field (0.96) and the laboratory (0.92) relationships. Heart rates reached a high of 95 at 27 C in the field experiments (Figure 3) and a markedly high value of 117 for one of the Sonora sucker at 33 C in laboratory experiments (Figure 5). Individual rates of four the five individual fish are shown in Figure 6.

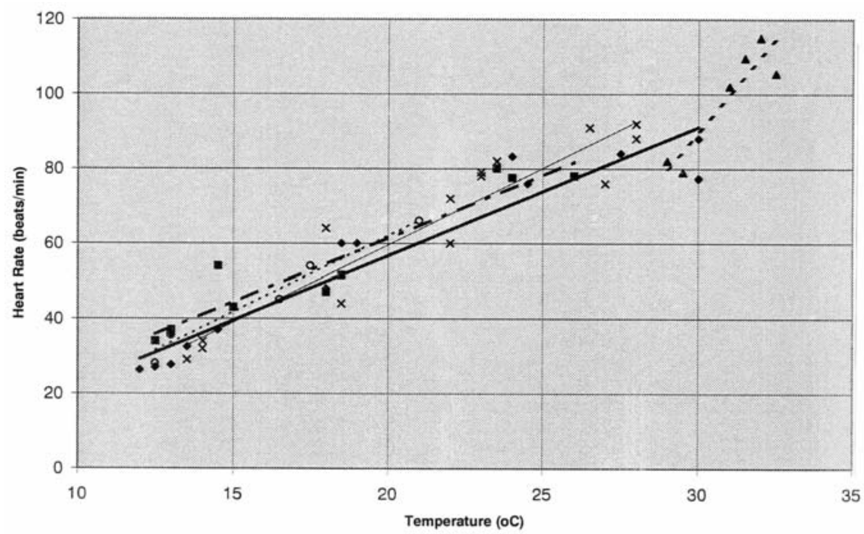

Figure 4. Summary of the recordings of heart rates of five native cypriniforms relative to temperature as measured under controlled laboratory conditions, 1997.

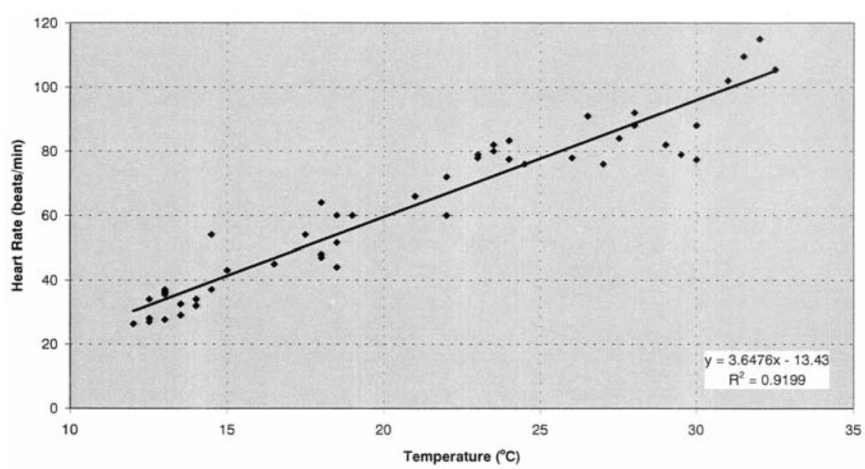

Figure 5. Heart rate/temperature relationships of two native individual cypriniform fishes monitored in the laboratory, 1997.

For comparison, a temperature/heart rate conversion relationship for cod under laboratory conditions in Norway are shown in Figure 6. Heart rates never exceeded 70 beats per minute for this coldwater species, however, the heart rate/temperature relationship was similar to desert cypriniform species, but was slightly lower at similar points on the plotted relationship line. Coefficient of determination was again significantly high ($R^2 = 0.89$).

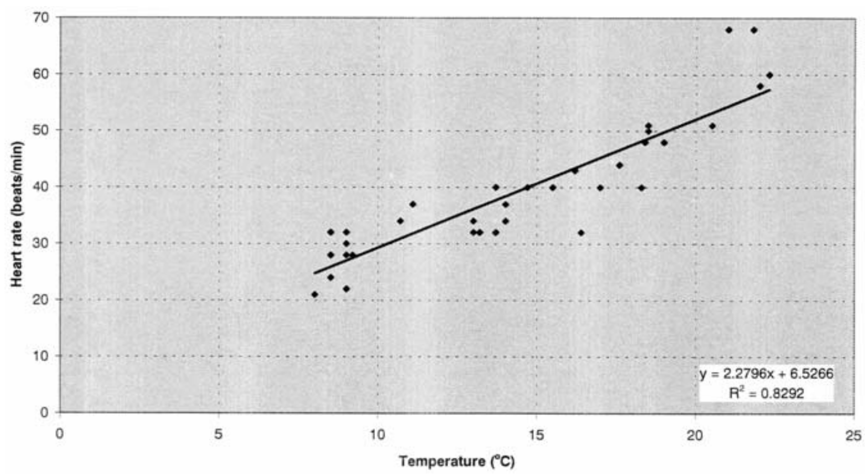

Figure 6. Heart rate and temperature relationships of cod measured under laboratory conditions in Norway.

Discussions and conclusions

Results of field and laboratory experimentation on the two native, cypriniform species do not show any significant difference in heart rate versus temperature between the two species (Figure 4). Further, there is a good resemblance between this relationship on data collected from free swimming fish in the river and that collected under laboratory conditions (Figure 5).

Water temperature in the Verde River may surpass 30 C daily (Figure 3). We hypothesize that these desert fishes may even survive at temperatures up to 35 C. However, all three fish exposed to water temperatures of 33-34 C in the laboratory for over 24 hours suffered mortality. Such sustained, diel, elevated temperatures do not normally occur in the wild (Figure 3). If such high temperatures should occur in the upper water layer, fish may normally have the capability to move to cooler bottom waters and areas of cooler water strata resulting from intra-gravel flow. However, entrapment in a shallow, disconnected pool during drought, or flow reduction resulting from irrigational diversion removal or pumping of river corridor, subterraneous aquifers may result in mortality--even in time periods of less than 24 hours.

In field experiments, suckers and chubs were caught, fitted with transmitters, and released in enclosures in the river in an area about a meter in maximum depth. Also, the area of enclosure was immediately below a high gradient riffle (Rinne and Stefferud 1996) where elevated water temperature may be mitigated by evaporational cooling. In addition, some thermal stratification in pools of greater than a meter in depth most probably occurs. Cooling of waters during evening hours (Figure 4) further provides desert fish species, such as the sucker and chub, ample time for re-stabilizing body temperatures and removal of physiological (cardio) stress.

Unlike the warm to hot conditions sustained by cypriniform species, cod experience temperature variations that are very slow and annual variations that are small compared to desert aquatic systems. North temperate sea waters vary less than 15 C annually. Water temperature in desert systems such as the Verde River vary half that amount on a diel basis (Figure 3) and perhaps more in other desert environments. By comparison, although heart rate/temperature relationships are similar between this Gadiform species and the two cypriniform species the rate is somewhat lower in the former. Nevertheless, even though cod and desert fish are generally living in different temperature and salinity regimes, there is a remarkable similarity between heart rate and temperature change in these members of three families of fishes (Figures 5 and 6). The main differences again, are that; 1) the maximum heart rate of cod (60-70 beats/min) is only about half that of the two cypriniform species, and 2) the rate of change versus temperature change is somewhat higher in the two desert fishes we examined (Figures 5 and 6).

Summary and Management implications

A comparison of heart rate/temperature relationships was made among fishes inhabiting warm to hot desert aquatic environments in the desert Southwest (USA) and cold temperate sea waters of Norway. Two species of Cypriniform and one Gadiform (cod) were compared. Relationships were markedly similar between the two orders and three families (and species) of fish, however, the cod displayed both a slower and lesser response to elevation in water temperatures. Maximum heart rate reached almost 120 beats per minute for one species of Cypriniform at 30 C. By comparison, cod attained half that rate in 20 C water. Heart rate and temperature relationships for the two native desert species studied, and perhaps other desert fish species, have management implications relative to urbanization, associated water demand and watershed management of a large, yet free-flowing desert river.

Relationships established between heart rate and elevated water temperatures have some management implications for these two, and perhaps other desert fish species. The Verde River, although yet one of the few free-flowing systems in the Southwest (Stefferud & Rinne 1995), is set in a perilous state (Rinne 1999). As with other desert rivers, damming, irrigation diversion and groundwater pumping have and potentially may markedly alter quantity and quality of water in time and space (Rinne et al. 1998). The only dam on the upper Verde is Sullivan, which is almost completely filled with sediment and retains only periodic surface water. Damming is not currently a threat to water quality in the upper Verde River (Rinne et al. 1998, Rinne et al. in press). However, the other two anthropogenic factors could potentially affect flow and water quality conditions including temperature.

In the Verde River headwaters wells are being established at an ever-increasing rate (Rinne et al. in press, Wirt and Hjalmarson 2002, Neary and Rinne 2001). Neary & Rinne (1997) documented an increase in base flow in the Verde over the past two decades, attributable, in part, to the wettest period in the Southwest over the past 1,000 years. In addition, irrigational pumping for agriculture in the headwaters has declined in that same time period. On the other hand, urbanization of this area is proceeding at an unprecedented rate. Yavapai County, which encompasses the Verde River headwaters, is currently one of the fastest growing rural area in the United States (Rinne et al. in press). Current population of the Prescott/Prescott Valley/Chino Valley is 43,000, but is projected to be 135,000 by the year 2040--a 300+% increase in human population.

Water demand will parallel these projected human populations. Already, increased pumping of ground water, indicated by the number of new wells for domestic use has occurred over the past two decades in the county. These increasing groundwater removal rates have a high probability of eventually reducing flows in the Verde River to intermittent levels. Under reduced flow regimes, elevated water temperatures and reduced dissolved oxygen during summer have a high probability of occurring. Concentration of fish into pools combined with accompanying changes in water quality may becomes lethal for not only suckers and chubs in the river, but all other fish species.

Irrigational diversions of river water is most intensive in the municipality complex of Cottonwood, Clarkdale, and Camp Verde in the Middle Verde Valley (Rinne et al. 1998); pumping of the river aquifer is very high in this reach. Rinne et al. (1998) documented a dramatic change in fish community structure in this reach of river, unexplainable by flow regimes alone. Change in quality of water may be responsible, in part, however, the combination of increased pumping in the headwaters and downstream in the middle Verde Valley could result in markedly reduced flows in both reaches of the river in the future. Reduced surface flows potentially will be accompanied by sustained, elevated water temperatures to the levels (>30 C) where mortality resulted in Sonora sucker and chub in the laboratory.

References

Deacon, J. E. and W. L. Minckley. 1974. Desert fishes. pp 385-488. *In,* G. W. Brown (ed.) Desert Biology. Vol 2. Academic Press.

Holand, B. 1987. Underwater telemetry as a tool in aquaculture research and development. Modeling, Indentification and Control 8(1): 11-18.

Kanwisher, J. W., J. W. Lawson, and G. Sundnes. 1972. Acoustic telemetry from fish. Fishery Bull. III, 72(32): 251-255.

Minckley, W. L. 1973. Fishes of Arizona. Arizona Game Fish Department. Phoenix, Arizona.

Ohus, I. and B. Holand. 1983. Fish Telemetry Manual, SINTEF Report STF48A83 040 for NFFR.

Neary, D. G. and J. N. Rinne. 1997. Baseflow trends in the upper Verde River relative to Fish Habitat requirements. Hydrology and Water Resources in Arizona 27:57-63.

Neary, D. G. and J. N. Rinne. 2001. Baseflow trends in the Verde River revisited. Hydrology and Water Resources of the Southwest 31; 37-44.

Rinne, J. N. 1999. The status of spikedace, *Meda fulgida,* in the Verde River, 1999. Implications for research and management. Hydrology and Water Resources in the Southwest 29: 57-64.

Rinne, J. N. and J. A. Stefferud. 1996. Relationships of native fishes and aquatic macrohabitats in the Verde River, Arizona. Hydrology and Water Resources in Arizona and the Southwest 26: 13-22.

Rinne, J. N. and J. A. Stefferud. 1997. Factors contributing to collapse yet maintenance of a native fish community in the desert Southwest (USA), pp 157-162. *In,* D. A Hancock, D. C. Smith, A. Grant, and J. P. Beaumer (eds). Developing and Sustaining World Fisheries Resources: The state of science and management. Second World Fish Congress, Brisbane, Australia. July 28-Aug 2, 1996. 797 pp.

Rinne, J. N. and J. A. Stefferud. 1998. Single versus multiple species management: Native fishes in Arizona. Forest Ecology and Management 114: 357-365.

Rinne, J. N, J. a. Stefferud, A. Clark, and P. Sponholtz. 1998. Fish community structure in the Verde River, Arizona, 1975-1997. Hydrology and Water Resources in Arizona and the Southwest 28: 75-80.

Rinne, J.N., P. Boucher, D. Miller, A. Telles, J. Monzingo, R. Pope, B.Deason, C. Gatton, and B. Merhage. in press. Comparative fish community structure in two southwestern desert rivers. *In* S. Leon, P. Stine, and C. Springer (eds) Restoring native fish to the lower Colorado River: Interactions of native and non-native fishes: A symposium and Workshop.

Scholander, P. F., L. van Dam, J. W. Kanwisher, H. T. Hammel, and M. S. Gordon. 1954. Super-cooling and osmoregulation in Arctic fish. J. Cellular Comparative Physiology 49(1): 5-24.

Soltz, D. L. and R. J. Naiman. 1978. The natural history of the native fishes of the Death Valley system. Nat. Hist. Mus. Los Angeles County, Calif., Science Series 30: 1-76.

Stefferud J. A. and J. N. Rinne. 1995. Preliminary observations on the sustainability of fishes in a desert river: The roles of streamflow and introduced fishes. In: Hydrology and Water Resources in Arizona and the Southwest 22-25: 26-32.

Sublette, J. E., M. D. Hatch, and M. Sublette. 1990. The Fishes of New Mexico. Univ. of New Mexico Press, Albuquerque, N. M.

Wirt L. and H. W. Hjalmarson. 2000. Sources of springs supplying base flow to the Verde River headwaters, Yavapai county, Arizona. U. S. Geol. Surv. Open File Report 99-0378.