Notes

Characterizing Growth and Condition of Endangered Humpback Chub in the Lower Colorado River

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Abstract

This paper is a preface to the two papers that follow in this issue. The two papers (by Pine et al. and Hayes et al.) use long-term fish sampling data from ongoing Humpback Chub monitoring efforts and archival otolith samples (from museums) collected in the lower Colorado and Little Colorado Rivers during periods of both cold- and warm-water conditions to assess whether Humpback Chub growth characteristics may have responded to changes in water temperature. Growth patterns are often of interest to resource managers because growth integrates a large range of environmental and ecological factors, including habitat conditions. Together, these papers contribute information to a large collection of recent studies, developing a line of evidence designed to inform management decisions related to water releases, dam operations, and management actions that could be taken to aid recovery of native fish populations in regulated river systems around the world.

Keywords: Humpback Chub; Colorado River; regulated river; growth

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Introduction

Riverine ecosystems undergo well-documented hydrologic, geomorphic, and ecological responses to dams and flow regulations (Ligon et al. 1995; Stanford and Ward 2001; Nilsson et al. 2005). Understanding the effects of dam construction and operation on riverine ecosystems can help to inform decisions regarding dam removal (Shuman 1995; Poff and Hart 2002), the operation of existing dams for conservation purposes (Richter and Thomas 2007; Olden and Naimen 2010), or policy decisions and conservation actions related to new dam construction.
The adaptive management program work group comprises a diverse group of stakeholders that represent a variety of interests, including conservation of resources in Grand Canyon National Park, cultural values, recreational use of Colorado River resources, native fish conservation in the Colorado River ecosystem, and dam operations that meet the water and power needs of millions of people in the southwestern United States (Gloss et al. 2005; Melis et al. 2015).

Native fish populations in the lower Colorado River basin have been in decline since the 1800s, a trend exacerbated by the construction of Hoover and Glen Canyon dams, the filling of Lakes Mead and Powell, and attendant establishment of nonnative fish communities (Minckley et al. 2003). One high-profile native fish species is still extant in the lower Colorado River basin, the Humpback Chub *Gila cypha*. This large and morphologically distinct minnow is currently classified as endangered under the U.S. Endangered Species Act (U.S. Fish and Wildlife Service [USFWS] 1967; ESA 1973, as amended) and has received protected status since the Endangered Species Act was passed in 1973. The largest extant population of Humpback Chub persists around the confluence of the Little Colorado River and the regulated Colorado River in Grand Canyon National Park (Kaeding and Zimmerman 1983; Gorman and Stone 1999). Adult Humpback Chub in this population exhibit a spring spawning migration into the Little Colorado River from the Colorado River, while offspring rear in the Little Colorado River or return actively and passively to the Colorado River at various life stages (Gorman and Stone 1999; Limburg et al. 2013). The timing and factors influencing outmigration of juvenile Humpback Chub are not well understood by researchers, and most life stages (i.e., juveniles, subadults, and adults) can be found in both the mainstem Colorado River and the Little Colorado River throughout the year (Valdez and Ryel 1995; Hayden et al. 2012; Limburg et al. 2013).

Researchers have used Humpback Chub as a focal species in assessments of ecosystem response to management actions in Grand Canyon (USDOI 1996), particularly since the decline of the adult population during the 1990s (Coggins et al. 2006b). Researchers do not know the mechanisms by which Humpback Chub populations declined following dam construction, but their leading hypotheses include 1) habitat changes related to flow modifications and reductions in sediment input (Converse et al. 1998), 2) competition with or predation by nonnative fish (Yard et al. 2011; Coggins et al. 2011), 3) nonnative parasites (Hoffnagle et al. 2006), or 4) changes in water temperature (Clarkson and Childs 2000).

The hydrology and temperature of the Colorado River in Grand Canyon is driven by complex interactions between Glen Canyon Dam operations, Lake Powell elevation, and water inputs from the upper Colorado River basin. Key changes in this reach of the Colorado River since the completion of Glen Canyon Dam and the filling of Lake Powell (1963–1980) include the replacement of seasonal low flows with daily minimum water releases, increases in median daily river discharge, retention of sediment above Glen Canyon Dam in Lake Powell, erosion...
of sandbars, and decreased variation in seasonal river temperature (Wright et al. 2005; Melis et al. 2015).

Since about 2001, a combination of factors—including changes in Glen Canyon Dam daily operations (which began in 1996) and drought conditions in the upper Colorado River basin—have led to declining reservoir elevations and variable levels of inflow to Lake Powell (Pulwarty and Melis 2001). This has resulted in warmer epilimnetic water being withdrawn through the penstocks of Glen Canyon Dam (Wright et al. 2008) thus increasing lower Colorado River water temperature since about 2002 (Melis et al. 2015; Figure 1). While the annual water temperature variation is still considerably less than during the pre-dam era, water temperatures in recent years were similar to those expected under possible management actions (i.e., low summer steady flow; Ralston 2011) or as a result of low reservoir levels related to climate change (Christensen et al. 2004). The USFWS, in consultation with the Bureau of Reclamation, has issued a number of Biological Opinions on the operations of Glen Canyon Dam that identified warming the mainstem Colorado River as an essential action to create suitable habitat for Humpback Chub to spawn in the mainstem Colorado River (USDOI 1994; USDOI 2008, Trammell et al. 2002). Several laboratory and modeling studies have further suggested that warm water discharges from Glen Canyon Dam may benefit native fish species through improvements in growth rate (Clarkson and Childs 2004; Petersen and Paukert 2005; Coggins and Pine 2010). This hypothesis led to experimental low-discharge water releases during summer (Trammell et al. 2002; Ralston 2011) to test these responses, as well as consideration of a selective water withdrawal device on the upstream face of the dam to allow for water withdrawals above the thermocline (Vermeyen 2008). Both options involve substantial financial cost and uncertainty as to whether the ecosystem will have a positive, negative, or neutral response.

We developed two manuscripts for this issue (Hayes et al. 2017; Pine et al. 2017) using long-term fish sampling data from ongoing Humpback Chub monitoring efforts and archival otolith samples (from museums) collected in the lower Colorado and Little Colorado rivers during periods of both cold- and warm-water conditions to assess whether Humpback Chub growth characteristics may have responded to changes in water temperature. Growth patterns are often of interest to resource managers because growth integrates a large range of environmental and ecological factors, including habitat conditions (Quinn and Peterson 1996; Rosenfeld and Boss 2001), food availability (Aresco and Guyer 1999), and predation risk (Werner and Gilliam 1984). Growth metrics are widely used by researchers to evaluate how fish populations respond to management actions, due in part to the positive correlation of growth and survival (Lorenzen 2000; Charnov et al. 2012). These growth metrics are also used by researchers to characterize spatial variations across different biotic conditions, such as changes in prey availability or gradients in environmental conditions (Nicieza and Metcalfe 1997; King et al. 1999). Any management actions that lead to improvements in Humpback Chub growth rates are therefore of significant interest to resource managers to aid in recovery of this species. Taking advantage of existing samples collected prior to and during the observed river warming period creates a research opportunity that can help inform future management actions at little additional risk to the species or costs to stakeholders.

In the first paper (Pine et al. 2017 [this issue]) we fit growth models to all available Humpback Chub age and growth data to improve on parameter estimates and uncertainties of Humpback Chub growth. This information is of key importance in population assessment models (Coggins et al. 2006a, 2006b; Coggins and Walters 2009). We then take advantage of data on hydrologic conditions in recent decades (since 2001; Melis et al. 2015) to compare growth of juvenile Humpback Chub during an earlier period of cooler, more hydrologically variable riverine conditions (1980–1998; epoch 1; Figure 2) to growth during the more recent period of warmer water and less variable flows (2001–2011; epoch 2; Figure 2). We defined these epochs based on the ages of fish and years of collection so that the growth patterns that we examined were reflective of
environmental conditions observed during the life of the fish. We finally compare growth of juvenile Humpback Chub (< age 2) between the lower Colorado River and Little Colorado River to compare growth in a system where environmental conditions are modified by dam operations (Colorado River) to growth in a system with less-modified environmental conditions (Little Colorado; Figure 3).

In our second paper (Hayes et al. 2017 [this issue]), we describe length–weight relationships for juvenile and subadult (< 200-mm total length) Humpback Chub in the lower Colorado and Little Colorado rivers. For another native species in the Colorado River basin (Colorado pikeminnow Ptychocheilus lucius), a positive relationship has been shown between fish condition, size, and survival (Thompson et al. 1991). This relationship has not been examined for Humpback Chub. As a first step we assess length–weight relationships for juvenile and subadult Humpback Chub in these two systems. We compare length–weight relationships between months in the Colorado River to examine monthly patterns, and we then assess annual variation in length–weight relationships both within the lower Colorado and Little Colorado rivers and then between these rivers. Finally, we relate our estimates of length–weight parameters to environmental conditions in each river, again including periods with contrasting water temperature and river discharge patterns in the mainstem Colorado River and the unregulated Little Colorado River. This information provides a line of evidence to merge with a large collection of recent studies (Coggins et al. 2011; Hayden et al. 2012; Cross et al. 2013; Gerig et al. 2013; Limburg et al. 2013; Van Haverbeke et al. 2013; Finch et al. 2014, 2015; Dodrill et al. 2015 and others) designed to inform management decisions related to water releases, dam operations, and management actions that could be taken to aid recovery of native fish populations in regulated river systems around the world.

**Methods**

**Study site**

The Grand Canyon reach of the Colorado River is an approximately 400-km section of river bounded by the two largest reservoirs in the United States: upstream Lake Powell and downstream Lake Mead (Andrews 1991; USDOI 1996; by convention Lee’s Ferry is river kilometer [rkm] 0). This river reach is considered an area of cultural, biological, and geologic significance by tribal, state, federal, and nongovernmental interests in the United States, and as a result is safeguarded by the Grand Canyon Protection Act of 1992. Due to hypolimnetic discharge from stratified Lake Powell, the Colorado River within Grand Canyon is generally stenothermic and cool (Voichick and Wright 2007) with average water temperatures ranging from about 8 to 10°C during the initial filling of Lake Powell (1963–1980), warming to about 8 to 15°C during years of lower reservoir levels, and with warmer water releases occurring since about 2001 (Figure 1). Due to the influence of Glen Canyon Dam, river turbidity is generally low, yet can seasonally increase by tributary flooding from the Paria and Little Colorado rivers (Topping et al. 2000).

The Little Colorado River is the largest tributary of the Colorado River between Lakes Powell and Mead. It enters the Colorado River 126 km below Glen Canyon Dam and 100 km below Lee’s Ferry. The lower 21 km is spring fed, with perennial base flows of ~ 229 ft³/s (6.5 m³/s; Gorman and Stone 1999; Stone 2010). The carbonated spring water forms large travertine dam complexes as it degasses. The largest of these dam complexes is located 14 km upstream from the confluence with the Colorado River and may act as a barrier to upstream fish movement. Headwater reaches of the Little Colorado River are modified by agricultural and groundwater use; Little Colorado River flows are seasonally variable, with peak flows coinciding with spring runoff and late-summer monsoon rains. Turbidity is generally low during periods of base flow, but can reach very high levels (> 10,000 formazin nephelometric units) during periods of flooding (Stone 2010). Water temperatures in the Little Colorado River are also seasonally variable and, compared to the mainstem Colorado River, are warmer during spring, summer, and fall, and cooler in winter.
Fish collections
Researchers have intensively studied Humpback Chub in the Little Colorado River and mainstem Colorado River near the confluence for more than three decades (Valdez and Ryel 1995, Gorman and Stone 1999; Coggins et al. 2006; Voichick and Wright 2007). These two areas are frequently studied by fisheries biologists because most Humpback Chub in this reach of the mainstem Colorado River undertake a potamodromous spawning migration into the Little Colorado River (Gorman and Stone 1999; Limburg et al. 2013), where they are more easily sampled. We compiled different subsets of data from Humpback Chub sampling programs from 1979 to 2011, depending on data availability and the relevant hypotheses. In general, field personnel collected data for Humpback Chub in the Little Colorado River using seines, hoop nets, and trammel nets, and in the mainstem Colorado River using seines, boat-mounted electrofishing, hoop nets, minnow traps, and trammel nets (see additional details in Valdez and Ryel 1995). Sampling occurred in the lower 13.5 km of the Little Colorado River, and in the mainstem Colorado River between km 96 and 200, with the majority of sampling taking place directly downstream of the Little Colorado River confluence (km 126.1–128.6 for samples collected 2009–2011). Researchers measured total length of each fish to the nearest millimeter and weight in grams. In all cases, they took care to measure and weigh fish out of the wind and on a stable surface to maximize accuracy of all measurements and minimize injury to fish.

River conditions
We obtained all river discharge and water temperature data for the mainstem Colorado River from the U.S. Geological Survey (USGS) gauge 0938000 at Lee’s Ferry or records from other USGS sources (S. Wright, USGS Grand Canyon Monitoring and Research Center, personal communication). This is the only mainstem river gauge in this river reach with temperature records covering the same time period as our fish samples. This gauge is located 100 km upstream of our study site. While water warming does occur as water flows downstream to our study site, we assumed that this warming rate was similar across years and that water temperature was mostly driven by reservoir elevation and hydrology (Wright et al. 2009). We assessed Little Colorado River flow patterns from USGS gauge 0940200 (the gauge station with the most complete records, near Cameron, Arizona) and temperature data from USGS gauge 09402300, the only gauge with water temperature records in the Little Colorado River beginning in 1992. We could not use the same gauge for both discharge and temperature information because the Little Colorado River gauge near Cameron, Arizona (0940200) has a long record of discharge information (but no temperature data) while the gauge farther downstream near the confluence (09402300) is the only Little Colorado River gauge with temperature data (but limited discharge information). We visually compared river discharge and seasonal temperature regimes before and after dam closure in 1963 to examine annual patterns and variability. We constructed discharge and temperature duration curves for two epochs that encompassed residency of sampled fish (1980–1993, 2001–2011). Because individual years within these two time periods have different data available, we identify in our two manuscripts the specific years for which data are available to test our hypotheses about how growth patterns may have changed in response to planned and unplanned changes in Colorado River discharge and water temperature (Melis et al. 2015).

Supplemental Material
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