Prepared in cooperation with the U.S. Fish and Wildlife Service

Colorado River Fish Monitoring in Grand Canyon, Arizona: 2002–14 Humpback Chub Aggregations

By William R. Persons, David R. Van Haverbeke, and Michael J. Dodrill

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U.S. Department of the Interior
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Cover. Photograph of a humpback chub lying on a hoop net. Photograph courtesy of David R. Van Haverbeke, U.S. Fish and Wildlife Service.

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Conversion Factors

[This report uses metric units for all measurements except for river flow, the standard measure of which is cubic feet per second (ft^3/s), and river mile (RM), which is used to describe distances along the Colorado River downstream of Glen Canyon Dam]

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
mile (mi)	1.609	kilometer (km)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F = (1.8 × °C) + 32.

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Abstract

The humpback chub (*Gila cypha*) is an endangered cyprinid species endemic to the Colorado River. The largest remaining population of the species spawns and rears in the Little Colorado River in Grand Canyon. Construction and operation of Glen Canyon Dam has altered the main-stem Colorado River in Glen and Grand Canyons. Cold, clear water releases from the dam result in a river that is generally unsuitable for successful humpback chub reproduction. During the early 1990s, nine locations within the main-stem Colorado River were identified as humpback chub aggregations—areas with a consistent and disjunct group of fish with no significant exchange of individuals with other aggregations. We monitored main-stem Colorado River aggregations of humpback chub in Grand Canyon during 2010 to 2014 and compared our results to previous investigations. Relative abundance, as described by catch per unit effort (fish per hour) of adult humpback chub at most main-stem aggregations, generally increased from the 1990s to 2014. In addition, distribution of humpback chub in the main-stem Colorado River has increased since the 1990s. Movement of humpback chub between the Little Colorado River and other aggregations likely adds fish to those aggregations. There is clear evidence of reproduction near the 30-Mile aggregation, and reproduction at Middle Granite Gorge and downstream seems likely based on catches of gravid fish and captures of very young fish, especially during relatively warm water releases from Glen Canyon Dam, 2004 to 2011. Humpback chub relative abundance at Shinumo and Havasu Creek inflows increased following translocations of young humpback chub starting in 2009. In light of this information, we modify the original nine aggregations, combining two previously separate aggregations and dropping two locations to form six distinct aggregations of humpback chub. Trends in humpback chub abundance at main-stem aggregations, relative to management actions (for example, translocations) or changing environmental conditions (for example, river warming), informs management of the species across a riverscape scale within the Colorado River.

Introduction

The humpback chub (*Gila cypha*) is an endangered cyprinid species endemic to the Colorado River Basin of western United States. The species was described by R. Miller (1946) from a specimen taken near the mouth of Bright Angel Creek, Grand Canyon National Park, Arizona; listed as endangered in 1967; and grandfathered into the Endangered Species Act of 1973. Since the closure of Glen Canyon Dam in 1963, three of eight native fish species have been extirpated in Grand Canyon, including Colorado pikeminnow (*Ptychocheilus lucius*), bonytail (*Gila elegans*), and roundtail chub (*Gila robusta*). A fourth, the razorback sucker (*Xyrauchen texanus*), was suspected to be extirpated (Suttkus and others, 1976; Minckley, 1991) but has recently been captured in western Grand Canyon (Kegerries and others, 2015; Rogowski and Wolters, 2014). Humpback chub is the last remaining native big-river cyprinid in Grand Canyon and belongs to a native fish community that includes flannelmouth sucker (*Catostomus latipinnis*), bluehead sucker (*Catostomus discobolus*), and speckled dace (*Rhinichthys osculus*). Grand Canyon is also occupied by about 20 species of nonnative fish (Valdez and Ryel, 1995).

Six populations of humpback chub remain, including five in the upper Colorado River Basin upstream of Glen Canyon Dam and one in Grand Canyon (U.S. Fish and Wildlife Service, 2011). The Grand Canyon population consists of several main-stem aggregations and one known spawning aggregation around the Little Colorado River (LCR) inflow. Nine humpback chub aggregations were originally identified based on fish collected during 1990–93, and closed population abundance estimates were generated for six of those aggregations (table 1, fig. 1) (Valdez and Ryel, 1995). An aggregation was defined as "a consistent and disjunct group of fish with no significant exchange of individuals with other aggregations, as indicated by recapture of passive integrated transponder (PIT) tagged juveniles and adults and movement of radio-tagged adults" (Valdez and Ryel, 1995). Humpback chub are obligate warm-water species with preferred spawning, hatching, and growth temperatures of 16 to 22 °C (Hamman, 1982). Depression of spring and summer water temperatures in the Colorado River following closure of Glen Canyon Dam in 1963 likely has precluded significant main-stem reproduction by humpback chub, owing to mortality during incubation (Hamman, 1982; Kaeding and Zimmerman, 1983; Marsh, 1985) and thermal shock of newly hatched larvae (Clarkson and Childs, 2000). The LCR aggregation of humpback chub has been studied extensively (Douglas and Marsh, 1996; Marsh and Douglas, 1997; Coggins and others, 2006a,b; Van Haverbeke and others, 2013; Yackulic and others, 2014). Both closed- and open-population models are used to estimate abundance of chub in the LCR and near the confluence of the Colorado River (Coggins and Walters, 2009; Van Haverbeke and others, 2013; Yackulic and others, 2014). Reasons for use of areas outside of the LCR vicinity by adult humpback chub is unclear, but most aggregations are associated with seasonally warm tributary streams (LCR, Bright Angel Creek, Shinumo Creek, and Havasu Creek) or warm springs (30-Mile, Pumpkin Spring).

The LCR serves as the main spawning location for humpback chub, and this location is potentially at risk to catastrophic loss. For long-term conservation of the species, a second spawning population outside of the LCR is needed (U.S. Fish and Wildlife Service, 2002). Since 2009, the National Park Service stocked 840 and 1,102 humpback chub into Havasu and Shinumo Creeks, respectively, in an effort to establish a second spawning population within Grand Canyon (Trammel and others, 2012). Main-stem aggregations are associated with Havasu and Shinumo Creeks, and it may be that stocked fish are contributing to these aggregations through passive or active dispersal from the tributaries. Information on the contribution of stocked fish to aggregations and on the status and trends of humpback chub is needed for managers to assess impacts of operations of Glen Canyon Dam on main-stem populations of humpback chub. This information may also be important in determining if recovery criteria for the humpback chub can be achieved in the Grand Canyon population.

Purpose and Scope

The purpose of this report is to (1) present and summarize fish sampling results at humpback chub aggregations from 2010 through 2014, (2) compare these results to previous investigations conducted between 2002 and 2006 (Ackerman, 2008) and between 1990 and 1993 (Valdez and Ryel, 1995), and (3) summarize humpback chub data collected in the main-stem Colorado River from 1981 to 2014. Population variables evaluated for the study include humpback chub catch per unit effort (CPUE), size structure, and movement from PIT tag recapture information, as well as overall fish species composition. This report clarifies locations of aggregations and redefines aggregations based on updated capture and PIT tag recapture information. This report also provides information on humpback chub translocated to Shinumo and Havasu Creeks that have subsequently moved into the main-stem Colorado River.

Study Area

All locations are referred to in river miles (RM) downstream of Lees Ferry (Coconino County; north-central Arizona, RM 0), approximately 15 miles downstream of Glen Canyon Dam (fig.1)[1]. Sampling was conducted between RM 0 and RM 259.7, from Lees Ferry to Quartermaster Canyon in the Lake Mead inflow. In general, the river varies in character from large eddy complexes in depositional areas to narrow, deeply incised sections composed of resistant rock types (Webb and others, 1989; Schmidt and others, 1998). Water quality is strongly influenced by hypolimnetic water discharged from Glen Canyon Dam at RM –15, near Page, Ariz. Water discharged from Glen Canyon Dam is typically clear (<5 nephelometric turbidity units) (Vernieu, 2009), cold (8 to 11 ºC) (Stanford and Ward, 1991; Voichick and Wright, 2007), and has intermediate conductivity (700 to 900 microsiemens per centimeter [µS/cm]) (Vernieu, 2009). However, inputs from side tributaries can dramatically alter turbidity and flows. Water temperatures can also vary from long-term averages. For example, during 2004–2005, and again in 2011, water temperatures from Glen Canyon Dam exceeded 14 ºC in October and November at the Lees Ferry gage (station No. 09380000), and during 2003 to 2014, water temperatures regularly exceeded 12 ºC at the Lees Ferry gage.

Different investigators studying the aggregations have used distinct river maps with river mile designations varying slightly between mapping methods. Earlier sampling projects used a variety of river maps (Carothers and Minckley, 1981; Kaeding and Zimmerman, 1983; Maddux and others, 1987); Valdez and Ryel (1995) used the Belknap and Belknap-Evans (1989) river map; and Ackerman (2008) used the Stevens (1990) river map and also obtained RM locations from orthorectified aerial photos developed by the U.S. Geological Survey's (USGS) Grand Canyon Monitoring and Research Center (GCMRC). Since 2010, orthorectified aerial photos developed by GCMRC with matching river maps (Martin and Whitis, 2007) have been used, and all references to aggregation boundaries in this report refer to these designations.

Flow and Temperature Regimes

Discharge, measured every 15 minutes at the USGS Grand Canyon river gage (USGS gage 09402500), ranged from 6,670 to 22,000 cubic feet per second (ft^3/s) during the surveys from 2002–14 (table 2). Discharge from Glen Canyon Dam during some sampling trips was relatively constant (for example 2010, 2011), whereas during other years there were large fluctuations in discharge (for example, 2013). Effect of stage change on the ability of nets to catch fish is unknown, but in general, nets are easier to set and retrieve when river stage does not change. For example, hoop nets can be dewatered when river stage decreases, particularly along low angle shorelines; alternatively, trammel nets may foul when increasing discharge alters eddy velocities or flow patterns.

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[1]The use of river mile has a historical precedent and provides a reproducible method for describing locations along the Colorado River below Glen Canyon Dam. Lees Ferry is the starting point, river mile 0, with mileage measured for both upstream (–) and downstream (+).

Water released from Glen Canyon Dam is generally warmed by solar radiation as it moves downstream; maximum warming in summer is about 0.02 °C per kilometer (Wright and others, 2008), so water temperature at the LCR confluence is usually about 2 °C warmer than Glen Canyon Dam releases. Mean water temperatures during sampling trips in the main-stem Colorado River just upstream of the LCR confluence ranged from 13.1 to 15.6 °C. Mean water temperatures at the same location were 15.6 and 15.3 °C in 2011 and 2014, respectively; these temperatures were warmer than other sampling trips, largely owing to increased water release temperatures from Glen Canyon Dam (table 2) (Wright and others, 2008).

Previous Investigations

Studies of humpback chub in Grand Canyon began in the 1970s. Early efforts included morphological studies (Suttkus and others, 1976), life history summaries (Kaeding and Zimmerman, 1983), and early fish surveys (Carothers and Minckley, 1981; Maddux and others, 1987). Catches of adult humpback chub outside of the immediate area of the LCR confluence (approximately RM 62) were uncommon, probably because of limited logistical capabilities, and the distribution of humpback chub throughout Grand Canyon remained obscure. Kaeding and Zimmerman (1983) described a "bell shaped" distribution of humpback chub near the LCR inflow, and others reported sporadic captures throughout the Grand Canyon from about RM 19.5 to Spencer Creek at RM 246, including a few select tributaries summarized in Minckley (1996).

In the early 1990s, studies were conducted to better understand the population abundance and distribution patterns of humpback chub (Valdez and Ryel, 1995; Douglas and Marsh 1996; Arizona Game and Fish Department, 1996) in order to gather information for the Operation of Glen Canyon Dam Environmental Impact Statement (U.S. Department of the Interior, 1995). Valdez and Ryel (1995) identified nine aggregations of humpback chub in the main-stem Colorado River in Grand Canyon based on fish captured by electrofishing and netting during 1990–1993; these nine aggregations were 30-Mile, LCR inflow, Lava Chuar to Hance, Bright Angel Creek inflow, Shinumo Creek inflow, Stephen Aisle, Middle Granite Gorge, Havasu Creek inflow, and Pumpkin Spring (table 1). Of these, the LCR inflow aggregation has been sampled extensively, and population status and trend data have been regularly reported (Coggins and others, 2006a, 2006b; Coggins and Walters, 2009, Van Haverbeke and others, 2013). The LCR inflow supports the largest aggregation, and spawning is known to occur in the LCR (Kaeding and Zimmerman, 1983; Douglas and Marsh, 1996). Limited reproduction has also been documented from the 30-Mile aggregation (Valdez and Masslich, 1999; Andersen and others, 2010). Aggregations from the LCR to Havasu Creek are genetically relatively homogeneous, indicating gene flow between aggregations (Douglas and Douglas, 2010). Most recaptures of humpback chub occurred in the same main-stem river reach or tributary as original captures, and most fish were captured near the LCR (Paukert and others, 2006).

Methods of Investigation

Humpback chub aggregations were sampled with trammel nets and hoop nets as part of USGS's monitoring and research program during 2002–4 and 2006 (Ackerman, 2008). Methods and gear types used by Ackerman (2008) were also used in 2010–14, although sampling locations varied between trips. In addition, the method of baiting hoop nets changed after 2010 from using perforated PVC bait tubes that prevented fish from ingesting bait to using mesh bait bags that allow fish to consume small bait particles.

Data Compilation

Humpback chub aggregations were sampled during 1990–93, 2002–4, and 2006 and documented in published and unpublished reports (Valdez and Ryel 1997; Valdez and Ryel, 1995; Ackerman, 2008). Data collected during previous investigations were transferred into a Microsoft Access database maintained by GCMRC. Data were imported into SPSS software (SPSS Inc., Chicago, Illinois) or program R (R Core Development Team, 2014) for analysis. For most analyses, data were filtered to exclude samples not collected using standard methods, and checked for errors. The entire database was searched for PIT-tagged fish for analyses of movement and distribution of humpback chub. Data from 38 main-stem sampling trips that used trammel and hoop nets at aggregations from 1990–93 were compared with more recent data from 2002–14 (11 trips).

Aggregation Boundaries

River mile designations of nine humpback chub aggregations described by Valdez and Ryel (1995) were modified slightly based on sampling conducted during 2002–14 to include adjoining locations where fish were sampled (table 1, fig. 2). We assigned catches to aggregations based both on the river mile location of catches in the GCMRC fish database and distribution of catches near those locations. In some cases, fish catches were assigned to river miles based on maps other than Belknap and Belknap-Evans (1989), so although fish may have been caught in the same location, they were recorded in the database at different river miles. For example, between 1981 and 2011 there were 653 humpback chub recorded as being caught between RM 65.4 and 65.7, which is the area originally identified as Lava Chuar rapid, the boundary between the LCR aggregation and the Lava Chuar to Hance aggregation. In this instance, these fish were assigned to the LCR aggregation because the reach in the rapid and for a distance below the rapid is not fishable. In order to assign fish catches to particular aggregations, we modified the defined boundaries of aggregations based on where fish were reported to be captured in the GCMRC database (see table 1). Fish captured in Shinumo Creek downstream of the first waterfall barrier were assigned to the Shinumo Creek inflow aggregation, and fish captured in the mouth of Havasu Creek were assigned to the Havasu Creek inflow aggregation.

We also examined movement of fish between the LCR inflow aggregation and the Lava Chuar to Hance aggregation based on individual PIT-tagged fish recaptures. Because of the high rate of movement between the two aggregations, we merged the Lava Chuar to Hance aggregation into the LCR inflow aggregation.

Fish Sampling

Monitoring the fish community of the Colorado River by boat electroshockers has provided information on the status and trends of most common nonnative and native fishes, but adult humpback chub are relatively invulnerable to nearshore electrofishing (Makinster and others, 2010). However, adult humpback chub have been effectively captured both in the main-stem Colorado River and the LCR by hoop nets and trammel nets (Gorman and others, 2005; Coggins and others, 2006a; Ackerman, 2008; Van Haverbeke and others, 2013). The Colorado River upstream of the LCR is numerically dominated by the nonnative rainbow trout (*Oncorhynchus mykiss*) (Makinster and others, 2010; Makinster and others, 2011). The LCR is a spawning tributary for native fishes including flannelmouth sucker, bluehead sucker, and speckled dace (Kaeding and Zimmerman, 1983; Valdez and Ryel, 1995; Douglas and Marsh, 1996; Coggins and others, 2006b), and these native fish are common in the Colorado River downstream from the LCR confluence. Rainbow trout relative abundance declines downstream of the LCR, whereas relative abundance of native suckers, common carp, and warm water species increases (Makinster and others, 2010).

Humpback chub aggregation surveys were conducted in June, July, or September, 2002–14, and nets were fished for 12 to 16 days (table 2). Two motorized boats with 50-horsepower, 4-stroke outboard motors (5.3-meter [m] aluminum hulled Osprey or 4.9-m inflatable Achilles boats) were used for netting operations. One boat operator and two fish handlers were employed per boat.

Trammel nets measured 22.9 m to 30.5 m × 1.8 m (length × width) with 2.54 cm and 20.5 cm, mesh and panel mesh, respectively). Trammel nets were typically set off of debris fan points where eddy and main river currents converged, along cut bank and vegetated shoreline habitat inside of eddy and backwater complexes, and across the mouths of small coves. Trammel net locations were limited by water velocity, and nets were generally set in fairly slow moving or slack water. Trammel nets were initially set each day at approximately 1600 to 1800 hours and fished for three approximately 2-hour sets (mean soak time = 2.0 hours). Two-hour net sets were conducted to limit stress and injury to fish (Hunt and others, 2012). Each netting boat generally set 4 to 5 trammel nets for three 2-hour sets for a total of 24 to 30 trammel net sets per night. Netters moved or discontinued netting at their discretion if sampling conditions were unsuitable for effective netting or if nets became entangled in debris. This was a similar sampling protocol to that employed by Valdez and Ryel (1995).

Hoop nets were 0.5 to 0.6 m in diameter, 1.0 m long, with 6-mm mesh and a single 10-cm throat. Nets were set in suitable locations, usually in areas of low velocity current. Nets were tied to shore and set at depths typically less than 3 m but deep enough to ensure that nets were not dewatered during fluctuating flows (Ackerman, 2008). Each boat set 10 to 25 baited hoop nets overnight (mean soak time = 19.3 hours). Hoop nets were baited with commercial fish food (Aqua-Max Carnivorous Fish Food, Purina Mills, Inc.) placed inside of mesh bags tied toward the cod end of the net, although during 2002–6, nets were baited with Aqua-Max placed inside of small perforated PVC scent tubes that prevented fish from eating the bait. Beginning in 2011, hoop nets were more heavily baited using mesh bags to attempt to increase capture probability. Hoop nets were used by Ackerman (2008) but not by Valdez and Ryel (1995).

Data Collection and Fish Handling

Total length (TL) in millimeters (mm) was measured for all fish collected, and fork length (FL) in mm was measured for humpback chub, flannelmouth sucker, and bluehead sucker. Fish were not weighed to reduce handling time. Sex and stage of maturity of captured fish were determined based on external morphological characteristics (for example, coloration, tubercles, swollen cloaca; Suttkus and others, 1976) and on manual extrusion of gametes.

Humpback chub were implanted with PIT tags, according to standard protocols for handling fish in Grand Canyon (Persons and others, 2013). All PIT tag numbers were recorded on data sheets and stored in battery-powered PIT tag readers. Reader files were downloaded and archived to confirm accuracy of data sheets and databases. All PIT tags used were 134.2-kHz (kilohertz), full duplex, 12.5-mm-long (Biomark HPT 12) tags.

Data Analysis and Summaries

A variety of data were analyzed and summarized for this report. For comparisons of relative abundance between time periods, we used only trammel net and hoop net captures. Size composition was evaluated by examining length-frequency distributions and mean length of fish captured by trammel and hoop nets. Information about previously PIT-tagged fish is from the fish database maintained by GCMRC and includes fish captured by any gear that were tagged with external Floy or Carlin tags that may have later received a PIT tag (table 3). We used only recaptures for fish that were at large at least 14 days between capture and recapture (Paukert and others, 2006). Fish captures included in table 4 were from sampling trips identified in table 2 as well as from trips using hoop and trammel nets conducted during 1990–93. We used data from both of these gear types for the analysis and report the number of sexually mature humpback chub (table 6).

Adult humpback chub (>200 mm TL) caught by hoop and trammel nets were summarized by counts (for example, total catch) and total effort (for example, hours of either hoop or trammel net effort) by year and sample location (see below). Catch and effort were computed separately for hoop and trammel nets. We used generalized linear models to test hypotheses describing factors thought to affect catch of adult humpback chub in the main-stem Colorado River. The river was divided into 5-mile bins from Lees Ferry to RM 260, resulting in 52 sections of river. Each 5-mile bin was located within a reach of river either previously described as an aggregation (for example, RM 60–65 is located within the Little Colorado River inflow aggregation) or consisted of a reach of river between previously described aggregations (for example, RM 40–45 is located between the 30-Mile aggregation and the Little Colorado River inflow aggregation). The catch within each 5-mile bin was assigned to an aggregation (for example, the bin fell within river miles previously described as an aggregation) or a reach of river between aggregations (a non-aggregation location). This resulted in 17 discrete reaches of river (each potentially consisting of multiple 5-mile bins). For the generalized linear model fitting, these river reaches are described by a factor called "Location." Three reaches of river were removed from the analysis, owing to the absence or scarcity of humpback chub captures in these locations, leaving 14 locations. The amount of effort (net hours) for both hoop nets and trammel nets was also tabulated for each reach of river as described above for catch.

To test whether catch of humpback chub was higher in known aggregations compared to other locations, we used a factor that indicated if a river location was an aggregation or non-aggregation (Aggregation). Additionally, we fit models that included a term that allowed catch estimates to vary at all aggregations, whereas catch at all non-aggregation locations was estimated with one common term (Location – Non-Aggregation). Models that included this term represent an intermediate condition between catch varying at all locations (Location) and catch varying only between aggregations and non-aggregations (Aggregation). In order to test whether catch was higher near the confluence of the Little Colorado River, we used a factor specifying the reach of river closest to the LCR (LCR inflow). Humpback chub catch is also known to vary across years, and this was modeled by including the year captured as a covariate (Year). In order to account for differences in capture efficiency between gear types, a covariate specifying sampling gear (Gear) was included in all models. Main-stem netting has occurred in three distinct time periods: Period 1 (1991 to 1993), Period 2 (2002 to 2006), and Period 3 (2010 to 2013), and time period (Period) was included in addition to sampling year. Previous sampling indicated that the catch of humpback chub in the LCR inflow may exhibit a different response than other main-stem locations. This may be due to the influence of the LCR on catch of humpback chub in the main-stem Colorado River. Therefore, we included an interaction between the factor specifying the LCR inflow aggregation and time period.

Generalized linear models are an extension of linear models (for example, regression, ANOVA), which allow for non-normal error structures, such as the Poisson distribution for modeling count data (Bolker, 2008). We fit generalized linear models with a negative binomial error distribution to model humpback chub catch (counts) and included the log of effort (hours) as an offset to account for varying levels of effort. This allowed us to essentially model the rate of fish captured per hour of effort. Additionally, using the negative binomial distribution allows us to account for over-dispersion in catch (for example, variation in the data beyond what would be expected from the Poisson distribution alone). The Poisson distribution assumes a variance equal to the mean, while using the negative binomial distribution allows for variance to be greater than the mean (for example, over-dispersion), a common attribute of ecological data (Lindén and Mäntyniemi, 2011). Models were fit with likelihood methods using the “glm.nb” function in the program R package “mass” (R version 3.0.2). Model fit was compared using Akaike information criterion corrected for small sample sizes (AICc) (Burnham and Anderson, 2002). We fit 19 models, and the models with substantial support (0 – 2ΔAICc) were evaluated.

In order to examine the influence of translocated fish in influencing catch of humpback chub in the main-stem Colorado River, we compared CPUE from two models differing only in the inclusion of translocated fish. All translocated fish were PIT tagged, and this allowed us to discern these fish from fish captured and tagged in the main-stem Colorado River. During Period 3, translocated fish were encountered in three locations during main-stem sampling with both hoop nets and trammel nets. We fit a negative binomial model with location and gear as effects to compare the catch with and without fish from translocations.

Results and Discussion

Species Composition, Distribution, and Relative Abundance

In total, 15 species represented by 16,854 fish were captured at aggregations in more than 107,000 hours of netting effort during 1990 to 2014 sampling trips (table 4I). Data include individuals captured more than once within the same trip or different trips as well as those captured only once. Flannelmouth sucker was the most numerically dominant species (40.1 percent of total individuals sampled), followed by rainbow trout (21.8 percent), humpback chub (18.1 percent), and speckled dace (10.7 percent). Native fish ranged from 42 percent to 87 percent of the annual catch and averaged approximately 67 percent of the catch from 1990 to 2014. Humpback chub made up 18.1 percent and 0.6 percent of the catch at aggregations and at locations other than aggregations, respectively (tables 4I, 4J).

Trammel nets and hoop nets captured different size classes of humpback chub (fig. 3). Hoop nets tended to capture fish between 60 and 300 mm TL, and trammel nets primarily caught fish ≥200 mm TL. Collectively, these two gear types provide a good cross section of sizes of humpback chub in the areas sampled.

We found the most support for a model of adult humpback chub catch that varies by time period, river location at previously described aggregations, and a term that groups adult humpback chub at non-aggregation locations together into one estimate (table 5). This model also includes an interaction with time period for the LCR inflow aggregation that allows estimates to vary between time periods compared to other main-stem locations (table 5). The most supported model included the term specifying a different catch rate at each aggregation location and a common rate at non–aggregation locations. The difference between this model and the next most supported model including different catch rates at all locations was small (<1 ΔAICc). The difference between the two most highly supported models was whether the non-aggregation locations were grouped into a single estimate (Location – Non-Aggregation) or estimated separately (Location, see below). Models that included a term specifying whether a location is an aggregation or non-aggregation

(Aggregation, table 5) were not as highly supported (>19 ΔAICc), highlighting the variation in catch rate between aggregations and not only between aggregation and non-aggregation locations.

Modeled catch was higher in Period 3 compared to Periods 1 or 2 for both hoop nets (fig.4) and trammel nets (fig.5). Generally, the lowest catches occurred from 1991 to 1993, with increasing catch from 2002 to 2006, and the highest catch from 2010 to 2013. For many locations, the differences in catch are significantly higher from 2010 to 2013. This result may be in part due to changes in the sampling protocol between time periods, namely switching from un-baited to baited hoop nets during 2010 to 2013, although the trammel net catch rates show a similar trend between time periods. The switch to baited hoop nets during 2010 to 2013 could potentially alter the capture probability of the gear, leading to biased estimates during this time period. Unfortunately, we are not able to currently determine the effect of baiting on the CPUE indices, and this represents a fruitful area for future research. The LCR inflow exhibited a different temporal pattern with moderate levels of catch during Period 1, then lower catch during Period 2, and the highest levels of catch in Period 3. Catch rate at non-aggregation locations was low compared to previously described aggregations, especially during Periods 1 and 2, and has increased during Period 3 (figs. 4, 5). Two models received substantial support (0 – 2ΔAICc) and differed only by the inclusion of one term specifying whether non-aggregation locations are grouped into one estimate (Location – Non-Aggregations, table 5) or estimated separately (Location). Estimates for a common gear (hoop nets) and time period (Period 3) are used to compare the two model structures, and these estimates show no significant difference between these effects for the two models (fig. 6, compare Non-Aggregations, above dashed line, with other estimates). Some estimates for non-aggregation locations (under the second most highly supported model) are unbounded, owing to the low or no catch of humpback chub occurring in these sections of river (fig. 6).

Fish translocated into Shinumo and Havasu Creeks were recaptured in three sections of the main-stem Colorado River (table 3). In the two sections of river closest to these tributaries, the point estimates for modeled hoop net catch are 68 percent and 27 percent higher at Shinumo and Havasu Creeks, respectively, when including translocated fish (fig. 7). Trammel net catch is 65 percent higher in the Shinumo Creek inflow and 22 percent higher in the Havasu Creek inflow when including translocated fish (fig.7).

30-Mile Aggregation

Humpback chub were reported near Lees Ferry by Holden (cited in Valdez and Ryel 1995), in the vicinity of Tiger Wash (RM 27) by Carothers and Minckley (1981), and near RM 25 by Kaeding and Zimmerman (1983). The 30-Mile aggregation was described by Valdez and Ryel (1995) based on netting and electrofishing captures of 26 adults between RM 30 and 31.3 during 8 surveys[2]. The aggregation is located near a series of warm springs associated with Fence Fault (see Huntoon, 1981). Most adults were captured in the proximity of the warm (21.5 °C) spring near RM 31.5 (Spring 5 in Huntoon, 1981). Based on recapture of 6 adults, the population was estimated to be 52 fish in 1993 (Valdez and Ryel, 1995) (table 1). Evidence of reproduction was also reported from this spring, when about 100 postlarval fish were observed and 14 were captured and measured (18–31 mm TL) (Valdez and Masslich, 1999). Small humpback chub (<100 mm TL) that likely originated near RM 30 were commonly captured between RM 30 and the LCR (fig. 8B; Andersen

[2]Valdez and Ryel (1995) generated population estimates based on fish captured by both electrofishing and netting, whereas table 4 includes only fish captured by netting, hence numbers in text and table 4 do not always agree.

and others, 2010). During 2013 and 2014, we sampled downstream of RM 31.3 and captured 105 adult humpback chub between RM 34.2 and RM 35.7. This area, between Redwall Canyon and 36-Mile rapid, had not been previously sampled by hoop nets or trammel nets, although it was sampled extensively by electrofishing (Valdez and Ryel, 1995; GCMRC, unpub. data, January 2016). It is unclear if this is an expansion of the 30-Mile aggregation or if there have been humpback chub in this area for decades. Based on catches in 2013 and 2014, we extended the lower boundary of this aggregation an additional 5 miles to RM 36.3.

Of 162 unique humpback chub tagged in the 30-Mile aggregation, 44 were subsequently recaptured, and 43 of these fish were recaptured within the 30-Mile aggregation (table 3). Four individuals tagged in the LCR and seven individuals tagged in the LCR inflow aggregation were later captured at the 30-Mile aggregation, illustrating limited movement between the LCR and this aggregation. One individual tagged in the LCR (348 mm TL, March 1992) was recaptured twice at the 30-Mile aggregation (September 1995 and September 1996) and was also later recaptured in the LCR (May 2003 and April 2006). One humpback chub tagged in the LCR Aggregation (June 2005) was subsequently recaptured at 30-Mile (April 2007) and later near Little Redwall (RM 34.6, July 2013). All other humpback chub tagged at 30-Mile have only been recaptured at the 30-Mile aggregation, indicating high apparent site fidelity. Between 1990 and 2014, 11 ripe male and 4 ripe female humpback chub were captured between RM 29.8 and 36.3 (table 6). In addition, ultrasound images taken during 2013 and 2014 revealed female humpback chub with well-developed eggs (Morgan Brizendine, University of Arizona, oral commun., January 2016).

Adult rainbow trout dominated the catch numerically and made up 70 percent of the catch at the 30-Mile aggregation from 1990 to 2014 (table 4A). Sampling the 30-Mile aggregation by hoop net and trammel net from 1990 to 2014 resulted in the collection of 187 humpback chub that ranged in size from 188 to 464 mm TL (mean = 320 mm) (fig. 8A). The 30-Mile aggregation meets the criteria of persistence and little exchange of individuals with other aggregations. In addition, capture of ripe adult fish showing secondary sexual characteristics (color and tubercles) (table 6) and capture of young-of-the-year (YOY) fish at the spring (Valdez and Masslich, 1999) and immediately downstream of RM 31.3 (Andersen and others, 2010) suggests local reproduction is occurring. This information, along with an increase in the trammel net and hoop net catch rates, indicates that this aggregation of humpback chub is persistent and possibly increasing.

Little Colorado River Inflow Aggregation

The LCR inflow aggregation is the largest aggregation known in the Colorado River within Grand Canyon National Park. Movement of humpback chub between the LCR and the main-stem Colorado River was reported by Kaeding and Zimmerman (1983). The LCR inflow aggregation was originally described based on capture of 1,558 adults between RM 57.0 (Malagosa Crest) and Lava Chuar rapid between 1990 and 1993 (Valdez and Ryel, 1995). They estimated 3,482 adult humpback chub in this area using a multiple pass mark-recapture method. Using an Age-Structured Mark-Recapture (ASMR) model, which includes captures of fish in the LCR, Coggins and Walters (2009) generated an estimate of 7,650 adult humpback chub. More recently, Yackulic and others (2014) estimated abundance of approximately 10,000 to 14,000 (95 percent confidence interval [CI]) adult humpback chub. Within a 2.8-km reach of the main-stem Colorado River near the confluence with the LCR, Finch and others (2015) estimated 615 to 2,801 juvenile fish/km and 94 to 1,515 juvenile fish/km from open and closed population models, respectively. Mean annual hoop net and trammel net modeled CPUE of humpback chub ≥200 mm decreased at this aggregation from Period 1 to Period 2, then increased in Period 3 (figs. 4, 5).

There appears to be little dispersal of humpback chub from the LCR inflow aggregation other than with the nearby Lava Chuar to Hance aggregation. Almost all (99.9 percent) of the humpback chub recaptured in the LCR or the LCR inflow aggregation from 1990 to 2014 were previously tagged in the same area (table 3). Fish tagged in the LCR or the LCR inflow aggregation were recaptured in all other aggregations, at distances of about 30 to 90 miles from the LCR, with the exception of Pumpkin Spring (147 RM from the LCR; table 3). In addition, 37 humpback chub previously tagged at other aggregations were recaptured in the LCR or the LCR inflow aggregation. This included fish from all other aggregations except Pumpkin Spring. Between 1990 and 2014, 7 ripe females and 25 ripe males were captured between RM 57 and 77.2 (table 6).

Humpback chub were the most common species in the catch at the LCR inflow aggregation. From 1990 to 2014, 1,967 humpback chub were collected in the main-stem LCR inflow aggregation (table 4B). Humpback chub made up the highest proportion of the total catch at this site (39 percent), followed by flannelmouth sucker (28 percent) and rainbow trout (26 percent). Humpback chub ranged in size from 50 to 480 mm TL (mean = 311 mm) (fig. 8B). Small humpback chub were common in this reach (fig. 8B) because of YOY and juveniles that originated in the LCR (Valdez and Ryel, 1995; Yackulic and others, 2014; Finch and others 2015).

Based on exchanges of fish (see below), we expanded the original boundaries of the LCR inflow aggregation (RM 57 to 65.9) to include captures between RM 57 to just upstream of Hance rapid (RM 77.2). This includes the area previously defined as the Lava Chuar to Hance aggregation.

Lava Chuar to Hance Aggregation

Based on relatively high rates of movement of tagged fish between the original Lava Chuar to Hance aggregation and the original LCR inflow aggregation, we grouped the two areas into a single aggregation. The Lava Chuar to Hance aggregation was originally described by Valdez and Ryel (1995) based on the capture of 15 adults between the base of Lava Chuar rapid and Hance rapid. They recaptured only 3 fish and were unable to estimate the population of adults in this reach. Of the 351 unique humpback chub PIT tagged between Lava Chuar rapid and Hance rapid since 1991, 47 were recaptured in the LCR, 18 in the LCR inflow aggregation, and 4 between Lava Chuar rapid and Hance rapid. In addition, 28 humpback chub tagged in the LCR were later recaptured between Lava Chuar rapid and Hance rapid. Many humpback chub captured in this area were smaller than 200 mm, suggesting emigration of young fish from the LCR. Humpback chub are not thought to spawn in this area, but likely migrate to the LCR to spawn. A single ripe female, however, was captured in this aggregation upstream of Tanner rapid in 2004.

Bright Angel Creek Inflow Aggregation

The first humpback chub identified from the Grand Canyon were reported in the early 1940s from the vicinity of Bright Angel Creek, including the holotype used to describe the species (Miller, 1946). Valdez and Ryel (1995) defined this inflow aggregation from the base of 83-Mile rapid to just upstream of Salt Creek rapid associated with Bright Angel and Clear Creeks. They captured only eight adult humpback chub in this reach and were unable to generate a closed population estimate. Only 25 humpback chub that ranged in length from 54 to 357 mm TL (mean = 211 mm) were captured from 1990 to 2014 (table 4C, fig. 8C). Mean annual hoop net and trammel net CPUEs at this aggregation were generally low, and no temporal changes in CPUEs were apparent. Flannelmouth sucker and brown trout (*Salmo trutta*) dominated the catch at this aggregation (1990–2014) (table 4C). Bright Angel Creek sustains reproducing populations of rainbow trout, brown trout, and flannelmouth sucker (Maddux and others, 1987; Valdez and Ryel, 1995; Weiss and others, 1998). A single ripe male humpback chub (TL = 324 mm) was captured in May 1992 at RM 83.9 very near or at the Clear Creek inflow, and five tuberculate males were captured between 1991 and 1993 (table 6).

Humpback chub originally captured in the Bright Angel Creek inflow aggregation were not recaptured in the same location. Seven humpback chub tagged at the Bright Angel Creek inflow were subsequently recaptured, six at the LCR or LCR inflow and one at Middle Granite Gorge (table 3). Catch per unit effort at Bright Angel Creek inflow was low during all Periods (figs. 4, 5). We conclude from this evidence that this group of fish is not persistent and have eliminated this aggregation from further consideration.

Shinumo Creek Inflow Aggregation

The Shinumo Creek inflow aggregation was originally defined from the base of Bass rapid to the top of Shinumo rapid, from RM 108.1–108.6. Based on captures of humpback chub in the GCMRC database, we redefined the aggregation as extending from RM 107.8 to 110.0 as in Martin and Whitis (2007). Valdez and Ryel (1995) attributed this aggregation to the presence of Shinumo Creek, a cool-water tributary. Researchers have historically pointed to Shinumo Creek as being a potential spawning tributary for humpback chub (Suttkus and Clemmer, 1977; Valdez and others, 2000). An approximately 120-m-long section of the creek, which has been identified as a potential spawning area, is located downstream of a natural fish barrier. Humpback chub smaller than 100 mm TL were collected between 1991 and 2014 from Shinumo Creek very near its confluence (fig. 8D), but their source is unknown.

Valdez and Ryel (1995) generated a closed population estimate of 57 (31–149, 95 percent CI) adult humpback chub based on capture of 27 adults and 6 recaptures. Between 2009 and 2013, the U.S. Fish and Wildlife Service and the National Park Service moved 1,102 age 1 and age 2 humpback chub from the LCR to Shinumo Creek as part of a translocation effort. Approximately 8 percent of humpback chub translocated to Shinumo Creek were subsequently captured in the Colorado River or in Shinumo Creek downstream of the barrier falls. Humpback chub showed relatively high apparent site fidelity to the Shinumo Creek inflow aggregation; 139 individuals tagged in this location (including translocated fish) were subsequently recaptured in the same aggregation (table 3).

Although translocated humpback chub do show high apparent site fidelity, some move considerable distances, including returning to the LCR. One fish translocated to Shinumo Creek in 2009 was captured at RM 128.2 (Middle Granite Gorge aggregation) in 2010, one fish translocated in 2009 was detected at a PIT-tag antenna in March 2012 in the LCR, and one fish translocated in 2010 was detected at a PIT-tag antenna in the LCR in November 2013.

Speckled dace (40 percent), flannelmouth sucker (29 percent), and humpback chub (11 percent) were the most common native species captured in this area (table 4D). Large numbers of speckled dace were captured by hoop net below the first falls in Shinumo Creek, whereas most humpback chub were captured in the main-stem Colorado River near Shinumo Creek.

The aggregation at Shinumo Creek appears to have increased since translocations began in 2009, owing in large part to some of the 1,102 fish translocated to the creek upstream of the barrier falls moving downstream to the Colorado River. Modeled CPUE with trammel and hoop nets increased during Period 3, largely owing to capture of translocated humpback chub (fig. 7). Eight ripe male humpback chub were collected in this aggregation, and several tuberculate and colored fish were also captured, suggesting that fish are in reproductive condition (table 6). A large debris flow in Shinumo Creek in 2015 scoured the stream channel and eliminated most of the fish from the system, including the translocated humpback chub (Brian Healy, Grand Canyon National Park, oral commun., January 2016).

Stephen Aisle Aggregation

The Stephen Aisle aggregation was defined by Valdez and Ryel (1995) as distributed from below Garnet Canyon to Lower Blacktail Camp. Valdez and Ryel (1995) suggested that the occurrence of an aggregation in Stephen Aisle was because this reach of river represents one of the first stretches of river containing large eddy complexes and slower water velocities below the Inner Gorge, and it encompasses the vicinity of Elves Chasm Creek. The aggregation was defined based on capture of 7 juvenile and 17 adult humpback chub from 1990–93 (Valdez and Ryel, 1995). They were unable to estimate the abundance of humpback chub in this aggregation. During 2002 to 2014, humpback chub in this aggregation ranged in size from 48 to 394 mm TL (mean = 239 mm) (fig. 8E). Adult flannelmouth sucker made up the majority (64 percent) of the fish captured in Stephen Aisle during 1990–2014, followed by rainbow trout (11 percent) and humpback chub (9 percent) (table 4E).

Since 1991, 98 humpback chub were PIT tagged in the Stephen Aisle aggregation, and only one was recaptured there. In addition, one humpback chub each was recaptured in the LCR, Shinumo Creek inflow, and Middle Granite Gorge aggregations (table 3). No ripe male or female humpback chub have been collected in this aggregation, although one tuberculate male and one male showing spawning colors were captured in 1991 and 1992, respectively (table 6). Modeled CPUE of humpback chub in trammel and hoop nets increased during Period 3 (figs. 4, 5).

Middle Granite Gorge Aggregation

More humpback chub were caught in Middle Granite Gorge than in any other aggregation except the LCR inflow (Table 4F). The Middle Granite Gorge aggregation, described by Valdez and Ryel (1995) from below Fossil rapid to Specter rapid, contained an estimated 98 adult humpback chub, based on mark-recapture studies from 1990 to 1993 (table 1). Most chub tagged in the Middle Granite Gorge aggregation were recaptured in Middle Granite Gorge. Two chub moved to Stephen Aisle, two fish moved to the Shinumo Creek inflow aggregation, eight to the LCR, and one to the LCR inflow aggregation (table 3). Of special note, 2 ripe male humpback chub were captured at this aggregation in September 2010 (215 and 236 mm TL) in a single baited hoop net with 47 other humpback chub (mean TL = 246, range 168 to 368 mm) on the downriver edge of a gravel debris fan located on river right at RM 128.2. The next highest catch of adults (≥200 mm) in a single baited hoop net in the main-stem Colorado River was 29 fish just upstream of the LCR confluence during September 2014. Although no ripe female humpback chub have been captured in this aggregation, approximately 11 percent of the male chub captured were ripe, and tuberculate males and females were captured, suggesting that fish are in reproductive condition (table 6).

Flannelmouth sucker (46 percent), humpback chub (22 percent), and rainbow trout (14 percent) were the most common species captured by trammel nets and hoop nets in the Middle Granite Gorge aggregation (table 4F). Humpback chub were captured in all years the aggregation was sampled, and a relatively wide size range of chub was caught (range = 50 to 405 mm TL, mean = 248 mm) (fig. 8F). Modeled CPUE of humpback chub ≥200 mm TL in hoop nets and trammel nets increased at this aggregation during Period 3 (figs. 4, 5).

Havasu Creek Inflow Aggregation

Valdez and Ryel (1995) captured only seven adult humpback chub in this aggregation between 1990 and 1993 and were not able to generate a population estimate. They defined this aggregation as extending from about Last Chance Camp to the mouth of Havasu Creek, RM 156.2 to 157.2 in Martin and Whittis (2007). We redefined the aggregation as extending from RM 155.8 to 160 based on capture of 176 humpback chub from 1990–2014. Valdez and others (2000) identified Havasu Creek as a preferred tributary stream in Grand Canyon for establishment of a second spawning population of humpback chub. Humpback chub have been captured in the mouth of Havasu Creek since at least the late 1990s (Gorman and others, 2005). For example, 45 humpback chub were captured in the mouth of Havasu Creek during the months of June and September in 1998 and 1999 (mean TL 185 mm, TL range 138–388 mm). Trammell and others (2012) documented naturally occurring humpback chub approximately 3 miles upstream from the Colorado River in 2011. Fall spawning of flannelmouth sucker on gravel beds at the Havasu Creek outflow was documented by Douglas and Douglas (2000).

Flannelmouth sucker and speckled dace were the most abundant fish captured at this aggregation (table 4G), owing to high catches in the mouth of Havasu Creek, especially when flannelmouth sucker were ascending Havasu Creek presumably for spawning (Douglas and Douglas, 2000). Flannelmouth sucker made up 63 percent of the catch and humpback chub 6 percent of the catch. Humpback chub ranged in size from 123 to 440 mm TL (mean = 268 mm TL) (fig. 8G). An increasing trend in CPUE across time periods for both hoop and trammel nets suggests increases in abundance at this aggregation. The increasing trend appears to be the result of an expansion of humpback chub downriver (below Havasu rapid) and from translocated fish (figs. 4–6).

A total of 1,492 humpback chub, including 1,350 translocated individuals, were PIT tagged in Havasu Creek or in the Havasu Creek inflow aggregation (table 3). Eight chub moved from the Havasu inflow aggregation to the LCR or LCR inflow aggregation, and three chub also moved from the LCR to the Havasu Creek inflow aggregation (table 3). Seventy-three fish tagged in the Havasu Creek inflow aggregation were subsequently recaptured, and 64 of these were recaptured within the same aggregation. During June 2011, seven previously untagged humpback chub (mean = 257 mm TL) were captured in Havasu Creek just prior to a translocation release, and in 2013, two untagged juvenile chub (121 and 127 mm TL) were captured, suggesting that humpback chub spawned in Havasu Creek (Trammell and others, 2012; National Park Service, unpub. data January 2016). During 2013, 14 of 30 humpback chub captured in the Havasu Creek inflow aggregation had been previously translocated to Havasu Creek. Although no ripe humpback chub were captured at the Havasu Creek inflow aggregation, both colored and tuberculated males and females have been collected, again suggesting that fish are in reproductive condition (table 6). A series of low falls occur in the lower end of Havasu Creek, but these are evidently not a barrier to movement, based on the recapture of fish in this stream.

Pumpkin Spring Aggregation

The Pumpkin Spring aggregation was described as a short stretch of river from the base of Little Bastard rapid (RM 212.5) to a short distance below Pumpkin Spring eddy. Based on capture of six adult humpback chub and two recaptures, five adult humpback chub were estimated to make up this aggregation. Valdez and Ryel (1995) and Ackerman (2008) sampled below the defined Pumpkin Spring aggregation area to about RM 214 but captured very few humpback chub. We extended the lower boundary of this aggregation to RM 216 (Three Springs Canyon) based on captures of 35 adult (≥200 mm TL) humpback chub between RM 213.2 and 216 from 2006 to 2014.

Between 1990 and 2014, 92 humpback chub were captured, ranging in length from 42 to 381 mm TL (mean = 173 mm TL) (fig. 8H). Relative abundance of humpback chub ≥200 mm TL increased during 2010–14, although there was very low hoop netting effort in this aggregation prior to 2010 (fig. 4, table 4H). Despite the low effort prior to 2010, the modeled CPUE shows an increase during the most recent time period (2010–13). Forty-one humpback chub have been implanted with PIT tags at this aggregation since 1991. Three of these fish have been recaptured within the aggregation (table 3), and none have been recaptured in other aggregations. Flannelmouth sucker (56 percent) and speckled dace (30 percent) dominated the catch at the Pumpkin Spring aggregation (table 4H).

Humpback Chub Not Associated With Aggregations

The Colorado River through Marble and Grand Canyons has been sampled extensively with hoop nets, trammel nets, electrofishing, and seines since the late 1970s. We compiled humpback chub catch data to examine distribution of humpback chub in areas not associated with defined aggregations. During aggregation sampling trips, 3,046 humpback chub were captured at aggregations during more than 107,000 net hours of effort. In contrast, only 102 were captured in areas not associated with revised aggregations during approximately 30,000 net hours of effort (tables 4I, 4J). Our analysis of CPUE for both hoop and trammel net catches suggests that at some locations, CPUE of humpback chub not associated with aggregations may be similar to the CPUE at known aggregations. Continued sampling of both aggregations and non-aggregation locations will provide valuable information to discern the distribution and relative abundance of humpback chub. The capture of 105 adult chub near RM 34.5 in 2013 and 2014 illustrates the importance of periodic sampling outside of known aggregations, including tributaries; this new capture information has allowed us to extend the boundaries of several aggregations, including the 30-Mile aggregation.

Summary and Conclusions

Most Marble and Grand Canyon aggregations of humpback chub originally described by Valdez and Ryel (1995) appear to have increased in relative abundance since the 1990s. Based on trammel net and hoop net CPUE data, humpback chub numbers increased at most aggregations compared to previous estimates. These increases were particularly visible in the post-2009 time period (Period 3).

The LCR inflow aggregation displayed a pattern similar to the findings of Coggins and Walters (2009) and Van Haverbeke and others (2013). That is, the LCR inflow aggregation experienced a decline in adult humpback chub abundance sometime between Periods 1 and 2 (1994 to 2001). This decline was subsequently followed by a significant post-2006 increase in adult abundance. Interestingly, other main-stem aggregations did not show a decline between Periods 1 and 2 but displayed uniformly depressed levels until Period 3.

Because many factors were in play, we cannot offer definitive answers as to why relative abundance of adult humpback chub increased during Period 3. However, the LCR experienced relatively good production of age-0 chub during the 2003 to 2005 timeframe, and these fish appeared to recruit reasonably well into the larger size classes (Van Haverbeke and others, 2013). Main-stem water temperatures were unusually warm during 2003 to 2005 (Voichik and Wright, 2007), which potentially led to increased growth rates of juvenile chub (Clarkson and Childs, 2000) and presumably higher survival rates. The 2003 to 2006 time period was also accompanied by mechanical removal of salmonids in the LCR aggregation (Coggins and others, 2011; Yard and others, 2011), as well as a systemwide decline in trout abundance (Makinster and others, 2010). Because juvenile humpback chub may take several years to grow into adulthood in the main stem (Coggins and Pine, 2010), the opportunities afforded for increased growth and survival during 2002 to 2006 may have manifested as increases in adult humpback chub relative abundance during 2010 to 2014.

In addition, small humpback chub (<100 mm TL) have been commonly collected in areas not associated with aggregations (fig. 8B). During recent years, main-stem water temperature has frequently exceeded 16 °C at Middle Granite Gorge during summer months and has exceeded 16 °C at Pumpkin Spring during summer months approximately 50 percent of the time (Voichick and Wright, 2007; Wright and others, 2008). These conditions have likely allowed for greater survival of YOY chub and perhaps main-stem spawning by adults (Valdez and others, 2000). In 2014, for example, 66 likely YOY humpback chub (mean TL 55 mm, range TL 36–89 mm) were captured in western Grand Canyon between RM 213 and 244 as part of this project. Because only three likely YOY humpback chub were captured between the LCR (RM 61.5) and RM 212, this suggested that local main-stem spawning had occurred in western Grand Canyon. Main-stem water temperatures were 16 to 20 ºC from June to September in 2014 in western Grand Canyon, and fresh gravels emitted from tributary fans may have functioned as spawning habitat.

Sampling humpback chub aggregations by trammel net and hoop net provides information on relative abundance, size distribution, and movement of humpback chub in areas of the main-stem Colorado River that otherwise might not be sampled. Sampling of aggregations also provides the opportunity to mark and recapture humpback chub with PIT tags systemwide. This has proven to be a critical tool in monitoring the status and trends of these disjunct groups of fish because results from this and previous studies show few of these fish move to the LCR inflow aggregation, thus are not included in population estimates generated using current methods (Van Haverbeke and others, 2013; Yackulic and others, 2014). Sampling Shinumo and Havasu Creek inflows also provides important information concerning the fate of humpback chub translocated to those tributaries. Data from these efforts have allowed us to quantify increases in humpback chub relative abundance at these aggregations and to determine that increases are due in part to translocation of approximately 2,000 fish since 2009 and possibly to warmer river temperatures.

The 30-Mile aggregation is of special interest to managers because there is strong evidence of main-stem reproduction by humpback chub at this location (Valdez and Masslich, 1999; Andersen and others, 2010). Suttkus and others (1976) reported collecting young or small humpback chub at RM 44, and Carothers and Minckley (1981) reported humpback chub at Tiger Wash. In 1993 and 1994, age-0 humpback chub were captured in a backwater at RM 44.5 (Eminence Fault), and in 1994, age-1 humpback chub were captured in this same locality (Arizona Game and Fish Department, 1996). Andersen and others (2010) captured presumed age-0 and age-1 humpback chub in 2006 and 2007 in backwaters between RM 30 and 56.5. These findings suggest some overwinter survival of fish thought to have originated near RM 30. Collection of adult humpback chub at previously unsampled areas near RM 35 suggests that the 30-Mile aggregation is larger than previously thought or has expanded in range, despite the high abundance of rainbow trout in Marble Canyon. Adult humpback chub were captured between RM 30 and 35 during each year sampled between 2000 and 2014, indicating high persistence of adult fish in this area.

The LCR aggregation represents the majority of humpback chub found in the Colorado River downstream of Glen Canyon Dam. Based on movement of PIT-tagged humpback chub between the LCR inflow aggregation and the Lava Chuar to Hance aggregation and size of fish captured, we believe the Lava Chuar to Hance aggregation represents a geographic extension of the LCR aggregation and not a disjunct group of fish. By our broader definition this aggregation, it would extend from RM 57 to 77.1, or from downstream of Kwagunt rapid to the top of Hance rapid.

Extremely low catches of humpback chub near the Bright Angel Creek inflow, as well as movement of fish from the Bright Angel Creek inflow aggregation to the LCR, suggest that this area does not currently support a disjunct aggregation of humpback chub. It is likely, however, that the area supported humpback chub in the past (see Miller, 1946) and perhaps could do so in the future. Electrofishing catch rates of brown trout have increased in the main-stem Colorado River near the confluence of Bright Angel Creek since 2006 (Makinster and others, 2010). Brown trout in the Colorado River are highly piscivorous (Yard and others, 2011), and it has been postulated that they limit humpback chub and other native fish near Bright Angel Creek. The National Park Service has been experimentally removing rainbow trout and brown trout from Bright Angel Creek as a potential management tool to benefit native fishes (Omana-Smith and others, 2012).

The Shinumo Creek inflow aggregation was originally defined as a very short reach (120 m) of the main-stem Colorado River. Recapture data from tagged humpback chub suggest expansion of the area of the aggregation upstream to RM 107.8 and downstream to RM 110 is warranted. This expansion is due in part to some of the humpback chub that have been translocated to Shinumo Creek since 2009, emigrating and dispersing into the main-stem Colorado River near the confluence of this tributary.

The Stephen Aisle aggregation may represent a disjunct group of humpback chub or could represent an area these fish simply traverse. It is rare to recapture humpback chub previously tagged in this aggregation. Because of few recaptures of fish tagged in this aggregation and the absence of gravid males or females, we are hesitant to define this location as a disjunct humpback chub aggregation. We do, however, recommend continued sampling in the area to better understand its use by humpback chub. Alternatively, the Stephen Aisle aggregation may be an extension of the Middle Granite Gorge aggregation that may become more evident as the numbers of tagged fish in these areas increase.

Catches near the Middle Granite Gorge aggregation were primarily in the same area described by Valdez and Ryel (1995), thus we do not propose to change the range of this aggregation. Over the duration of our study, humpback chub catches in the Middle Granite Gorge aggregation were second only to those in the LCR inflow aggregation. Humpback chub relative abundance at this aggregation increased during Period 3 (2010–13). In 2010, hoop net CPUE was strongly influenced by a single net with an unusually large catch of humpback chub (49 fish). Large catches of adult humpback chub in single nets are very uncommon except in the LCR during spawning season. It is possible that a gravid female humpback chub was present in this net and other fish were attracted to it by pheromones released by the gravid fish (Sorensen and Stacey, 2004).

The original characterization of the Havasu Creek inflow aggregation was based on the capture of only a small number of adult humpback chub directly upstream of the Havasu inflow. Catches at this site remained low during monitoring efforts in the early to mid-2000s. Translocations of humpback chub into Havasu Creek by the National Park Service since 2009 have resulted in dramatic increases in abundance in this adjoining aggregation. Initial captures of humpback chub and recaptures of previously tagged fish have consistently occurred over a broader range than the original definition of this aggregation, thus we recommend increasing its breadth such that it extends from RM 155.8 to 160, or inclusive of a small reach of river downstream of the

Havasu Creek inflow. As observed at the Shinumo Creek inflow aggregation, expansion here is due in part to some translocated humpback chub emigrating downstream and dispersing into the Colorado River. The survival and persistence of translocated humpback chub in both the Shinumo Creek and Havasu Creek inflow aggregations as well as increases in abundance at these sites suggest translocations can play an important role in the maintenance and expansion of humpback chub populations in Grand Canyon.

As with several other sites, we propose to enlarge the range of the Pumpkin Spring aggregation, based on catches of untagged and tagged humpback chub. The upstream extent of the aggregation would remain at RM 212.5, while the downstream boundary would be extended to RM 216.

Continued sampling of the aggregations is needed to provide critical information regarding the status and trends of this key component of the Grand Canyon humpback chub population. The intensity and frequency of future sampling should be determined by identifying what information is needed by managers and decision makers and at what level of precision. If there is interest in estimating capture probabilities to generate survival and population estimates within individual aggregations, then sampling should be structured to achieve that objective by scheduling more trips and attempting to generate population estimates using mark-recapture methodologies at aggregations where catches might support an estimate (for example, 30-Mile, Middle Granite Gorge, and Shinumo Creek inflow). Although thoroughly investigating capture probability (p) values for individual aggregations may be enticing to pursue, it may not provide reliable abundance estimates because of the low numbers of fish captured in the smaller aggregations. In addition, from a conservation standpoint, care should be taken to balance the level of effort required to answer questions of management interest with concerns of handling small populations of endangered species. If there is interest in determining if aggregations house humpback chub that are reproductively active and successfully producing offspring that are recruiting in the main-stem Colorado River, separate from the LCR population, efforts might be better directed at sampling when fish are likely to be gravid and in spawning condition (June and July; Valdez and Ryel 1995). Additionally, otolith microchemistry of young of the year chub offers a promising approach to discern whether fish are successfully spawning and recruiting in the main-stem Colorado River.

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References Cited

Ackerman, M.W., 2008, 2006 native fish monitoring activities in the Colorado River, Grand Canyon: SWCA Environmental Consultants, report to Grand Canyon Monitoring and Research Center, cooperative agreement 04WRAG0011, 77 p.

Andersen, M.E., Ackerman, M.W., Hilwig, K.D., Fuller, A.E., and Alley, P.D., 2010, Evidence of young humpback chub overwintering in the main stem Colorado River, Marble Canyon, Arizona, USA: The Open Fish Science Journal, v. 3, doi:10.2174/1874401X01003010042, p. 42–50, accessed August 26, 2010, at http://www.bentham.org/open/tofishsj/articles/V003/42TOFISHSJ.pdf.

Arizona Game and Fish Department, 1996, Ecology of Grand Canyon backwaters—final report: submitted to Bureau of Reclamation, Glen Canyon Environmental Studies, cooperative agreement no. 9-FC-40-07940, 155 p.

Belknap, B., and Belknap-Evans, L., 1989, Belknap's waterproof Grand Canyon river guide—all new color edition: Evergreen, Colo., Westwater Books, 120 p.

Bolker, B.M., 2008, Ecological models and data in R: Princeton University Press, 408 p.

Burnham, K.P., and Anderson, D.R., 2002, Model selection and multimodel inference—a practical information-theoretic approach (2d ed.): New York, Springer Science+Business Media, Inc., 488 p.

Carothers, S.W., and Minckley, C.O., 1981, A survey of the fishes, aquatic invertebrates and aquatic plants of the Colorado River and selected tributaries from Lees Ferry to Separation Rapids: Museum of Northern Arizona, sumitted to U.S. Department of the Interior Water and Power Resources Service, contract no. 7-07-30-X0026, 401 p.

Clarkson, R.W., and Childs, M.R., 2000, Temperature effects of hypolimnial-release dams on early life stages of Colorado River Basin big-river fishes: Copeia, v. 2000, no. 2, p. 402–412, accessed August 26, 2010, at http://www.jstor.org/stable/1448187.

Coggins, L.G., Jr., Pine, W.E., III, Walters, C.J., and Martell, S.J.D., 2006a, Age-structured mark-recapture analysis—a virtual population-analysis-based model for analyzing age-structured capture-recapture data: North American Journal of Fisheries Management, v. 26, no. 1, p. 201–205, accessed July 19, 2012, at http://www.usbr.gov/uc/rm/amp/twg/mtgs/06may24/Attach_06h.pdf.

Coggins, L.G., Jr., Pine, W.E., III, Walters, C.J., Van Haverbeke, D.R., Ward, D., and Johnstone, H.C., 2006b, Abundance trends and status of the Little Colorado River population of humpback chub: North American Journal of Fisheries Management, v. 26, no. 1, doi: 10.1577M05-075.1, p. 233–245, accessed July 19, 2011, at http://www.usbr.gov/uc/rm/amp/twg/mtgs/06may24/Attach_06f.pdf.

Coggins, L.G., Jr., and Walters, C.J., 2009, Abundance trends and status of the Little Colorado River population of humpback chub—an update considering data from 1989–2008: U.S. Geological Survey Open-File Report 2009–1075, 18 p., accessed February 1, 2010, at http://pubs.usgs.gov/of/2009/1075/.

Douglas, M.E., and Marsh, P.C., 1996, Population estimates/population movements of *Gila cypha*, an endangered cyprinid fish in the Grand Canyon region of Arizona: Copeia, v. 1996, no. 1, p. 15–28, accessed February 10, 2010, at http://www.jstor.org/stable/1446938.

Douglas, M.R., and Douglas, M.E., 2000, Late season reproduction by big-river Catostomidae in Grand Canyon (Arizona): Copeia, v. 2000, no. 1, p. 238–244, accessed February 10, 2010 at http://www.jstor.org/stable/pdfplus/1448256.pdf.

Douglas, M.R., and Douglas, M.E., 2010, Molecular approaches to stream fish ecology: American Fisheries Society Symposium 73, p. 157–195.
Finch, C., Pine, W.E., III, Yackulic, C.B., Dodrill, M.J., Yard, M.D., Gerig, B.S., Coggins, L.G., Jr., and Korman, J., 2015, Assessing juvenile native fish demographic responses to a steady flow experiment in a large regulated river: River Research and Applications, v. 32, no. 4, p. 763–775, http://dx.doi.org/10.1002/rra.2893.
Gorman, O.T., Bramblett, R.G., Hervin, R.M., Van Haverbeke, D.R., and Stone, D.M., 2005, Distribution and abundance of native and non-native fishes of the Colorado River ecosystem in Grand Canyon, Arizona, *in* Brouder, M.J., Springer, C.L., and Leon, S.C., eds., Restoring natural function and native fish within a modified riverine environment: U.S. Fish and Wildlife Service, p. 78–94, accessed June 11, 2014, at https://www.usbr.gov/uc/rm/amp/amwg/mtgs/07aug29/Attach_12b.pdf.
Hamman, R.L., 1982, Spawning and culture of humpback chub: The Progressive Fish-Culturist, v. 44, no. 4, p. 213–216, accessed November 9, 2012, at http://dx.doi.org/10.1577/1548-8659(1982)44[213:SACOHC]2.0.CO;2.
Hunt, T.A., Ward, D.L., Propper, C.R., and Gibb, A.C., 2012, Effects of capture by trammel net on Colorado River native fishes: Journal of Fish and Wildlife Management, v. 3, no. 1, p. 133–141, accessed June 20, 2012, at http://www.fwspubs.org/doi/abs/10.3996/122011-JFWM-070.
Huntoon, P.W., 1981, Fault controlled ground-water circulation under the Colorado River, Marble Canyon, Arizona: Ground Water, v. 19, no. 1, p. 20–27. [Also available at http://dx.doi.org/10.1111/j.1745-6584.1981.tb03433.x.]
Kaeding, L.R., and Zimmerman, M.A., 1983, Life history and ecology of the humpback chub in the Little Colorado and Colorado Rivers of the Grand Canyon: Transactions of the American Fisheries Society, v. 112, no. 5, p. 577–594, accessed August 24, 2011, at http://www.tandfonline.com/doi/abs/10.1577/1548-8659%281983%29112%3C577%3ALHAEOT%3E2.0.CO%3B2.
Kegerries, R., Albrecht, B., Rogers, R., Gilbert, E.,, Brandenburg, W.H., Barkalow, A.L., Platania, S.P., McKinstry, M., Healy, B., Stolberg, J., Omana Smith, E., Nelson, C. and Harrison, M., 2015, Razorback sucker Xyrauchen texanus research and monitoring in the Colorado River inflow area of Lake Mead and the lower Grand Canyon, Arizona and Nevada: Final report prepared by BIO-WEST, Inc., for U.S. Bureau of Reclamation, Upper Colorado Region, 162 p.
Lindén, A., and Mäntyniemi, S., 2011, Using the negative binomial distribution to model overdispersion in ecological count data: Ecology, v. 92, no. 7, doi:10.1890/10-1831.1, p. 1414–1421, accessed March 13, 2015, at http://dx.doi.org/10.1890/10-1831.1.
Maddux, H.R., Kubly, D.M., deVos, J.C., Jr., Persons, W.R., Staedicke, R., and Wright, R.L., 1987, Effects of varied flow regimes on aquatic resources of Glen and Grand Canyons—final report: Arizona Game and Fish Department, unpublished report submitted to Bureau of Reclamation, Glen Canyon Environmental Studies, contract no. 4-AG-40-01810, 291 p. [Available from National Technical Information Service as NTIS Report PB88-183439/AS.]
Makinster, A.S., Persons, W.R., and Avery, L.A., 2011, Status and trends of the rainbow trout population in the Lees Ferry Reach of the Colorado River downstream from Glen Canyon Dam, Arizona, 1991–2009: U.S. Geological Survey Scientific Investigations Report 2011–5015, 17 p., accessed June 13, 2011, at http://pubs.usgs.gov/sir/2011/5015/.
Makinster, A.S., Persons, W.R., Avery, L.A., and Bunch, A.J., 2010, Colorado River fish monitoring in Grand Canyon, Arizona—2000 to 2009 summary: U.S. Geological Survey Open-File Report 2010–1246, 26 p., accessed November 5, 2010, at http://pubs.usgs.gov/of/2010/1246/.

Marsh, P.C., 1985, Effect of incubation temperature on survival of embryos of native Colorado River fishes: Southwestern Naturalist, v. 30, no. 1, p. 129–140, accessed August 18, 2010, at http://www.jstor.org/stable/3670666.

Marsh, P.C., and Douglas, M.E., 1997, Predation by introduced fishes on endangered humpback chub and other native species in the Little Colorado River, Arizona: Transactions of the American Fisheries Society, v. 126, no. 2, p. 343–346, http://dx.doi.org/10.1577/1548-8659(1997)126<0343:PBIFOE>2.3.CO;2.

Martin, T., and Whitis, D., 2007, Guide to the Colorado River in the Grand Canyon—Lees Ferry to South Cove (3d ed.): Flagstaff, Ariz., Vishnu Temple Press, 108 p.

Miller, R.R., 1946, *Gila cypha*, a remarkable new species of cyprinid fish from the Colorado River in Grand Canyon, Arizona: Journal of the Washington Academy of Sciences, v. 36, no. 12, p. 409–415.

Minckley, C.O., 1996, Observations on the biology of the humpback chub in the Colorado River Basin, 1980–1990: Flagstaff, Northern Arizona University, Ph.D. dissertation, 218 p., accessed March 10, 2015, at http://www.nativefishlab.net/library/textpdf/21260.pdf.

Minckley, W.L., 1991, Native fishes of the Grand Canyon region—an obituary?, *in* Marzolf, G.R., and Committee to Review the Glen Canyon Environmental Studies Water Science and Technology Board, eds., Colorado River ecology and dam management, Washington, D.C., May 24–25, 1990, Proceedings of a Symposium: National Academy Press, p. 124–177.

Omana-Smith, E.C., Healy, B.D., Leibfried, W.C., and Whiting. D.P., 2012, Bright Angel Creek Trout Reduction Project; winter 2010–2011 report: National Park Service, Natural Resource Technical Report NPS/GRCA/NRTR-2012/646, Published report 2191593, 45 p.

Paukert, C.P., Coggins, L.G., Jr., and Flaccus, C.E., 2006, Distribution and movement of humpback chub in the Colorado River, Grand Canyon, based on recaptures: Transactions of the American Fisheries Society, v. 135, no. 2, p. 539–544.

Persons, W.R., Ward, D.L., and Avery, L.A., 2013, Standardized methods for Grand Canyon fisheries research 2015 (ver. 1.1, January 2015): U.S. Geological Survey, Techniques and Methods, book 2, chapter A12, 19 p., accessed March 15, 2015, at http://pubs.usgs.gov/tm/tm2a12/.

R Core Development Team, 2014, R—A language and environment for statistical computing: R Foundation for Statistical Computing, accessed at http://www.R-project.org/.

Rogowski, D.L., and Wolters, P.N., 2014, Colorado River fish monitoring in Grand Canyon, Arizona—2013 annual report: Arizona Game and Fish Department, Colorado River Research Office, draft submitted to U.S. Geological Survey, Grand Canyon Monitoring and Research Center, cooperative agreement no. G10AC00147, 51 p.

Schmidt, J.C., Webb, R.H., Valdez, R.A., Marzolf, G.R., and Stevens, L.E., 1998, Science and values in river restoration in the Grand Canyon: BioScience, v. 48, no. 9, p. 735–747, accessed August 17, 2010, at http://www.jstor.org/stable/1313336.

Sorensen, P.W., and Stacey, N.E., 2004, Brief review of fish pheromones and discussion of their possible uses in the control of non-indigenous teleost fishes: New Zealand Journal of Marine and Freshwater Research, v. 38, no. 3, doi: 10.1080/00288330.2004.9517248, p. 399–417, accessed October 5, 2010, at http://www.informaworld.com/smpp/content~db=all~content=a920473219.

Stanford, J.A., and Ward, J.V., 1991, Limnology of Lake Powell and the chemistry of the Colorado River, *in* Committee to Review the Glen Canyon Environmental Studies Water Science and Technology Board, ed., Colorado River ecology and dam management, Washington D.C., May 24–25, 1990, Proceedings: National Academy Press, p. 75–101.

Stevens, L.E., 1990, The Colorado River in Grand Canyon—a comprehensive guide to its natural and human history (3d printing, 3d ed.): Flagstaff, Ariz., Red Lake Books, 115 p.

Suttkus, R.D. and Clemmer, G.H., 1977, The humpback chub, Gila cypha, in the Grand Cayon area of the Colorado River: Occasional Papers, Tulane University, Museum of Natural History, 30 p.

Suttkus, R.D., Clemmer, G.H., Jones, C., and Shoop, C.R., 1976, Survey of the fishes, mammals and herpetofauna of the Colorado River in Grand Canyon, Colorado River Research Program final report, Research Series contribution no. 34: Grand Canyon National Park, Technical report no. 5, 48 p., accessed August 11, 2010, at http://www.riversimulator.org/Resources/NPS/GCresearch/1976no5animals.pdf.

Trammell, M., Healy, B., Omana Smith, E., and Sponholtz, P.J., 2012, Humpback chub translocation to Havasu Creek, Grand Canyon National Park—implementation and monitoring plan: National Park Service, Grand Canyon Park, natural resource report NPS/GRCA/NRR—2012/586, 26 p.

U.S. Fish and Wildlife Service, 2002, Humpback chub (Gila cypha) recovery goals [amendment and supplement to the Humpback Chub Recovery Plan]: U.S. Fish and Wildlife Service, Mountain-Prairie Region (6), 71 p.

U.S. Fish and Wildlife Service, 2011, Humpback chub (*Gila cypha*) 5-Year review—summary and evaluation: U.S. Fish and Wildlife Service Upper Colorado River Endangered Fish Recovery Program, 25 p.

U.S. Department of the Interior, 1995, Operation of Glen Canyon Dam—final environmental impact statement, Colorado River storage project, Arizona: Bureau of Reclamation, Upper Colorado Regional Office, 337 p., accessed November 18, 2010, at http://www.usbr.gov/uc/library/envdocs/eis/gc/pdfs/Cov-con/cov-con.pdf.

Valdez, R.A., Carothers, S.W., Douglas, M.E., Douglas, M., Ryel, R.J., Bestgen, K.R., and Wegner, D.L., 2000, Final research and implementation plan for establishing a second population of humpback chub in Grand Canyon: U.S. Department of the Interior, Grand Canyon Monitoring and Research Center, 56 p.

Valdez, R.A., and Masslich, W.J., 1999, Evidence of reproduction by humpback chub in a warm spring of the Colorado River in Grand Canyon, Arizona: Southwestern Naturalist, v. 44, no. 3, p. 384–387, accessed March 24, 2010, at http://www.jstor.org/stable/30055237.

Valdez, R.A., and Ryel, R.J., 1995, Life history and ecology of the humpback chub (*Gila cypha*) in the Colorado River, Grand Canyon, Arizona—final report: BIO/WEST, Inc., submitted to Bureau of Reclamation, contract no. 0-CS-40-09110, technical report no. TR-250-08, 328 p.

Valdez, R.A., and Ryel, R.J., 1997, Life history and ecology of the humpback chub in the Colorado River, Grand Canyon, Arizona, *in* van Riper, C., III, and Deshler, E.T., eds., Third Biennial Conference on the Colorado Plateau, Flagstaff, Ariz., October 17–20, 1995: National Park Service Transactions and Proceedings Series NPS/NRNAU/NRTP-97/12, p. 3–31.

Van Haverbeke, D.R., Stone, D.M., Coggins, L.G., and Pillow, M.J., 2013, Long-term monitoring of an endangered desert fish and factors influencing population dynamics: Journal of Fish and Wildlife Management, v. 4, no. 1, doi:10.3996/082012-JFWM-071, p. 163–177, http://dx.doi.org/10.3996/082012-JFWM-071.

Vernieu, W.S., 2009, Physical and chemical data for water in Lake Powell and from Glen Canyon Dam releases, Utah-Arizona, 1964–2008: U.S. Geological Survey Data Series 471, 23 p., accessed February 1, 2010, at http://pubs.usgs.gov/ds/471/.

Voichick, N., and Wright, S.A., 2007, Water-temperature data for the Colorado River and tributaries between Glen Canyon Dam and Spencer Canyon, northern Arizona, 1988–2005: U.S.

Geological Survey Data Survey Series 251, 24 p., accessed July 19, 2011, at http://pubs.usgs.gov/ds/2007/251/.

Webb, R.H., Pringle, P.T., and Rink, G.R., 1989, Debris flows from tributaries of the Colorado River, Grand Canyon National Park, Arizona: U.S. Geological Survey Professional Paper 1492, 39 p., accessed February 4, 2013, at http://pubs.usgs.gov/pp/1492/report.pdf.

Weiss, S.J., Otis, E.O., and Maughan, O.E., 1998, Spawning ecology of flannelmouth sucker, *Catostomus lattipinnis* (Catostomidae), in two small tributaries of the lower Colorado River: Environmental Biology of Fishes, v. 52, no. 4, p. 419–433. [Also available at http://dx.doi.org/10.1023/A:1007497513762.]

Wright, S.A., Anderson, C.R., and Voichick, N., 2008, A simplified water temperature model for the Colorado River below Glen Canyon Dam: River Research and Applications, v. 25, no. 6, p. 675–686. [Also available at http://dx.doi.org/10.1002/rra.1179.]

Yackulic, C.B., Yard, M.D., Korman, J., and Van Haverbeke, D.R., 2014, A quantitative life history of endangered humpback chub that spawn in the Little Colorado River—variation in movement, growth, and survival: Ecology and Evolution, v. 4, no. 7, p. 1006–1018, http://dx.doi.org/10.1002/ece3.990.

Yard, M.D., Coggins, L.G., Baxter, C.V., Bennett, G.E., and Korman, J., 2011, Trout piscivory in the Colorado River, Grand Canyon—effects of turbidity, temperature, and fish prey availability: Transactions of the American Fisheries Society, v. 140, no. 2, doi:10.1080/00028487.2011.572011, p. 471–486, accessed April 19, 2011, at http://www.tandfonline.com/doi/abs/10.1080/00028487.2011.572011.

Table 1. Original and revised locations of nine main-stem humpback chub aggregations, including river mile boundaries, estimates of adult abundance (N), and 95 percent confidence interval estimated by Valdez and Ryel (1995).

[Revised boundaries are indicated as bolded river miles and based on Martin and Whitis (2007)]

Aggregation	Aggregation boundaries[1]	Redefined aggregation boundaries	N	95% confidence interval
30-Mile	29.8–31.3	29.8–36.3	52	24–136
Little Colorado River inflow	57.0–65.4	57.0–77.2	3,482	2,682–4,281
Lava Chuar to Hance	65.7–76.3	--	--	--
Bright Angel Creek inflow	83.8–92.2	--	--	--
Shinumo Creek inflow	108.1–108.6	107.8–110	57	31–149
Stephen Aisle	114.9–120.1	--	--	--
Middle Granite Gorge	126.1–129.0	125.0–129.7	98	74–153
Havasu Creek inflow	155.8–156.7	155.8–159.2	13	5–70
Pumpkin Spring	212.5–213.2	212.5–216.0	5	4–16

[1]Defined by Valdez and Ryel (1995)

Table 2. Sampling dates; number of days sampled; mean, minimum, and maximum 15-minute discharge values; range in discharge in ft^3/s; and mean water temperature (°C) during each sampling trip measured at the U.S. Geological Survey Grand Canyon gage (http://waterdata.usgs.gov/az/nwis/uv?site_no=09402500) during humpback chub aggregation surveys, 2002–14.

Year	Start date	End date	Trip duration in days	Mean discharge	Minimum discharge	Maximum discharge	Range in discharge	Mean temperature at RM 61
2002	12–Sep–02	24–Sep–02	12	10,103	6,670	14,400	7,730	13.6
2003	14–Jun–03	30–Jun–03	16	14,787	10,500	19,100	8,600	14.0
2004	12–Jun–04	28–Jun–04	16	14,057	10,200	17,700	7,500	13.1
2006	3–Jun–06	19–Jun–06	16	14,103	10,613	17,634	7,021	13.4
2010	11–Sep–10	27–Sep–10	16	8,854	8,410	11,200	2,790	14.1
2011	9–Sep–11	24–Sep–11	15	17,001	16,200	19,300	3,100	15.6
2012	7–Sep–12	24–Sep–12	17	8,835	8,250	13,100	4,850	13.7
2013	20–Jul–13	5–Aug–13	16	15,353	10,400	22,000	11,600	13.6
2013	7–Sep–13	23–Sep–13	16	11,745	7,590	19,100	11,510	14.1
2014	19–Jul–14	3–Aug–14	15	13,754	10,600	17,300	6,700	14.6
2014	6–Sep–14	21–Sep–14	15	10,827	7,070	13,800	6,730	15.3

Table 3. Tag and recapture locations with river miles in parentheses for humpback chub recaptured 14+ days after tagging, 1991 to 2014.

[Numbers in bold represent fish captured and recaptured in the same location (for example, apparent site fidelity). Numbers above the diagonal indicate downstream movement, whereas numbers below the diagonal indicate upstream movement. Includes fish translocated to Shinumo Creek and Havasu Creek. Total recaptures column includes fish recaptured more than once, but individual fish are only counted once within the same aggregation]

		Location recaptured										
Location tagged	Number tagged	30-Mile (RM 29.8–31.3)	Little Colorado River inflow (RM 57–77.2)	Little Colorado River	Bright Angel Creek inflow (RM 83.8–92.2)	Shinumo Creek inflow (RM 107.8–110.0)	Stephen Aisle (RM 114.9–121.0)	Middle Granite Gorge (RM 125.0–129.0)	Havasu Creek inflow (RM 155.8–160)	Pumpkin Spring (RM 212.5–215.1) .	Total recaptures	Percentage of fish recaptured in same river reach as captured
30-Mile (RM 29.8–31.3)	162	**43**	0	1	0	0	0	0	0	0	44	97.7%
Little Colorado River inflow (RM 57–77.2)	6,250	7	**1,417**	2,449	0	0	1	1	1	0	3,876	36.6%
Little Colorado River	48,941	4	1,815	**21,413**	1	1	1	1	3	0	23,239	92.1%
Bright Angel Creek inflow (RM 83.8–92.2)	33	0	3	5	**0**	0	0	1	0	0	9	0.0%
Shinumo Creek inflow (RM 107.8–110.0)	1,233	0	2	8	0	**139**	3	6	0	0	158	88.0%
Stephen Aisle (RM 114.9–121.0)	98	0	0	1	0	1	**1**	1	0	0	4	25.0%
Middle Granite Gorge (RM 125.0–129.0)	370	0	1	8	0	2	2	**68**	0	0	81	84.0%
Havasu Creek inflow (RM 155.8–160)	1,492	0	3	5	0	0	0	1	**64**	0	73	87.7%
Pumpkin Spring (RM 212.5–215.1)	41	0	0	0	0	0	0	0	0	**3**	3	100.0%
Total	58,620	54	3,241	23,890	1	143	8	79	68	3	27,487	

Table 4. Number of fish captured and hours fished by hoop net and trammel net at each aggregation (A–H) and totaled for all sites (I–J), 1990–2014.

[River miles (RM) sampled are given for each aggregation in parenthesis. Species are listed in order of total abundance at each aggregation]

A. 30-Mile (29.8–36.3)

Species	1990–93	2002	2003	2004	2006	2010	2011	2012	2013	2014	Total
Rainbow trout	215	64	35	59	6	67	79	160	704	146	1,535
Flannelmouth sucker	9	--	5	5	4	22	16	18	51	319	449
Humpback chub	19	5	3	3	--	9	16	3	41	88	187
Bluehead sucker	1	--	--	--	1	--	--	1	2	1	6
Common carp	7	--	--	--	--	--	--	--	--	--	7
Brown trout	--	--	1	--	--	--	--	--	1	--	2
Total	251	69	44	67	11	98	111	182	799	554	2,186
Hoop net hours		450	1,394	1,274	590	376	494	462	3,484	2,993	11,517
Trammel net hours	232	45	117	110	53	56	55	43	193	73	977
Total net hours	232	495	1,511	1,384	643	432	549	505	3,677	3,066	12,494

B. Little Colorado River inflow (57–77.2)

Species	1990-93	2002	2003	2004	2006	2010	2011	2012	2013	2014	Total
Humpback chub	1,099	27	7	33	105	112	239	103	20	222	1,967
Flannelmouth sucker	591	2	1	12	173	185	107	92	17	226	1,406
Rainbow trout	1,040	18	9	8	19	81	87	19	9	22	1,312
Bluehead sucker	109	17	--	--	55	15	42	10	3	11	262
Fathead minnow	--	2	--	--	33	1	10	1	--	1	48
Brown trout	24	--	--	1	1	--	--	--	--	--	26
Common carp	20	1	--	--	1	--	1	--	--	--	23
Channel catfish	19	--	--	--	--	--	--	--	--	--	19
Speckled dace	1	--	--	1	11	--	--	1	--	--	14
Black bullhead	1	--	--	1	1	1	--	2	--	--	6
Flannelmouth razorback hybrid	3	--	--	--	--	--	--	--	--	--	3
Plains killifish	--	2	--	--	--	--	--	--	--	--	2
Total	2,907	69	17	56	399	395	486	228	49	482	5,088
Hoop net hours	2	1,225	603	590	2,873	1,237	2,009	2,509	2,053	2,230	15,331
Trammel net hours	4,158	171	58	60	235	187	152	29	--	27	5,077
Total net hours	4,160	1,396	661	650	3,108	1,424	2,161	2,538	2,053	2,257	20,407

C. Bright Angel Creek inflow (83.8–92.2)

Species	1990–93	2002	2003	2004	2006	2010	2011	2012	2013	2014	Total
Flannelmouth sucker	135	--	4	--	4	18	4	--	7	99	271
Brown trout	151	--	19	5	1	4	2	--	--	--	182
Rainbow trout	75	--	11	5	--	11	1	1	6	--	110
Bluehead sucker	16	--	1	1	3	20	4	--	--	--	45
Humpback chub	8	--	2	2	6	1	2	--	1	3	25
Speckled dace	--	--	--	--	2	16	4	--	--	--	22
Common carp	2	--	1	--	--	2	--	--	--	--	5
Fathead minnow	--	--	--	--	2	--	--	--	--	--	2
Flannelmouth razorback hybrid	1	--	--	--	--	--	--	--	--	--	1
Channel catfish	--	--	1	--	--	--	--	--	--	--	1
Total	253	--	35	13	14	54	13	1	7	3	393
Hoop net hours	186	--	569	292	628	376	570	34	1,115	543	4,314
Trammel net hours	631	--	57	19	56	59	20	--	25	--	867
Total net hours	817	--	626	311	684	435	590	34	1,141	543	5,181

D. Shinumo Creek inflow (107.8–110.0)

Species	1990–93	2002	2003	2004	2006	2010	2011	2012	2013	2014	Total
Speckled dace	--	--	6	--	3	264	--	471	--	--	744
Flannelmouth sucker	32	--	5	6	13	27	27	309	15	96	530
Rainbow trout	112	1	47	11	--	37	12	8	1	6	235
Humpback chub	24	2	20	6	2	41	51	33	11	7	197
Bluehead sucker	24	1	1	--	3	14	9	16	2	--	70
Brown trout	14	--	10	2	1	--	--	--	--	--	27
Fathead minnow	--	--	--	--	--	1	--	18	--	--	19
Common carp	6	1	3	--	2	1	1	3	--	1	18
Total	212	5	92	25	24	385	100	858	29	110	1,840
Hoop net hours	278	609	2,195	1,436	628	1,042	1,532	3,509	252	861	12,341
Trammel net hours	937	27	178	115	59	57	46	--	22	--	1,440
Total net hours	1,215	635	2,373	1,551	687	1,099	1,578	3,509	274	861	13,781

E. Stephen Aisle (114.9–121.0)

Species	1990–93	2002	2003	2004	2006	2010	2011	2012	2013	2014	Total
Flannelmouth sucker	17	--	--	15	41	117	50	30	79	301	650
Rainbow trout	37	2	--	14	5	29	9	1	10	9	116
Humpback chub	12	--	--	5	11	19	11	3	11	15	87
Bluehead sucker	4	5	--	2	8	29	18	--	1	--	67
Speckled dace	--	--	--	--	25	4	--	--	2	1	32
Common carp	11	1	--	2	2	2	1	4	--	3	26
Fathead minnow	--	--	--	--	10	3	1	1	1	--	16
Brown trout	3	--	--	9	1	1	1	--	1	--	16
Flannelmouth razorback hybrid	--	--	--	--	--	--	--	--	--	2	2
Channel catfish	--	--	--	--	1	--	--	--	--	--	1
Black bullhead	--	--	--	--	--	--	1	--	--	--	1
Total	84	8	--	47	104	204	92	39	105	331	1,014
Hoop net hours	--	641	--	1,408	1,300	1,307	1,832	704	2,536	1,384	11,112
Trammel net hours	456	56	--	118	111	120	103	7	--	--	972
Total net hours	456	697	--	1,526	1,412	1,427	1,935	711	2,536	1,384	12,084

F. Middle Granite Gorge (125.0–129.7)

Species	1990–93	2002	2003	2004	2006	2010	2011	2012	2013	2014	Total
Flannelmouth sucker	35	1	15	17	51	101	30	99	134	191	674
Humpback chub	112	10	29	17	13	73	8	33	6	11	312
Rainbow trout	33	1	54	18	--	47	9	27	7	6	202
Bluehead sucker	12	2	6	3	2	18	41	8	1	--	93
Speckled dace	--	--	1	--	49	20	3	1	2	1	77
Common carp	35	1	3	--	2	--	--	2	2	3	48
Brown trout	7	2	13	9	--	3	--	--	--	--	34
Fathead minnow	--	--	--	--	6	1	--	--	--	--	7
Channel catfish	--	--	--	1	--	1	--	--	--	--	2
Green sunfish	--	--	--	1	--	--	--	--	--	--	1
Total	234	17	121	66	123	264	91	170	153		1,451
Hoop net hours	--	645	3,105	3,137	1,431	1,292	1,663	1,579	2,331	1,019	16,201
Trammel net hours	1,270	65	2,436	208	116	117	86	80	17	--	4,393
Total net hours	1,270	709	5,540	3,345	1,547	1,409	1,749	1,659	2,347	1,019	20,594

G. Havasu Creek inflow (155.8–160)

Species	1990–93	2002	2003	2004	2006	2010	2011	2012	2013	2014	Total
Flannelmouth sucker	132	3	29	17	32	206	118	347	687	174	1,745
Speckled dace	7	1	5	--	51	189	85	27	1	1	367
Bluehead sucker	184	--	3	1	6	27	16	7	5	--	249
Humpback chub	6	5	4	2	1	18	50	35	46	9	176
Rainbow trout	11	--	19	13	1	62	14	15	18	7	160
Common carp	21	2	2	4	--	1	--	2	6	3	41
Channel catfish	--	--	2	1	3	2	--	--	--	--	8
Fathead minnow	--	--	--	--	5	1	1	--	--	--	7
Striped bass	1	--	--	1	--	--	--	--	--	--	2
Brown trout	--	--	1	--	--	1	--	--	--	--	2
Red shiner	--	--	--	--	1	--	--	--	--	--	1
Total	362	11	65	39	100	507	284	433	763	194	2,758
Hoop net hours	111	608	2,479	2,202	950	1,255	1,401	1,448	2,368	478	13,300
Trammel net hours	795	57	147	149	73	110	55	36	34	--	1,457
Total net hours	906	665	2,626	2,351	1,024	1,365	1,456	1,485	2,402	478	14,758

H. Pumpkin Spring (212.5–216.0)

Species	1990–93	2002	2003	2004	2006	2010	2011	2012	2013	2014	Total
Flannelmouth sucker	18	2	--	--	11	72	60	245	248	384	1,040
Speckled dace	--	2	--	--	2	151	39	54	13	284	545
Humpback chub	6	--	--	--	2	18	10	9	5	42	92
Common carp	33	3	--	--	3	--	--	9	3	5	56
Fathead minnow	--	--	--	--	--	19	18	1	--	7	45
Channel catfish	23	3	--	--	8	1	1	--	--	--	36
Bluehead sucker	1	--	--	--	--	7	2	1	--	1	12
Striped bass	3	--	--	--	5	--	--	--	--	--	8
Rainbow trout	4	--	--	--	--	--	--	--	--	3	7
Black bullhead	--	--	--	--	3	--	--	--	--	1	4
Flannelmouth razorback hybrid	--	--	--	--	--	--	--	1	--	--	1
Total	88	10	--	--	34	268	130	320	269	727	1,846
Hoop net hours	--	623	--	--	557	342	703	2,043	1,804	1,235	7,308
Trammel net hours	622	57	--	--	56	57	43	--	--	--	836
Total net hours	622	681	--	--	613	399	746	2,043	1,804	1,235	8,144

I. Total at all aggregations

Species	1990–93	2002	2003	2004	2006	2010	2011	2012	2013	2014	Total
Flannelmouth sucker	971	8	59	72	329	748	412	1,140	1,238	1,790	6,767
Rainbow trout	1,527	86	175	128	31	334	211	231	755	199	3,677
Humpback chub	1,289	49	65	68	140	291	387	219	141	397	3,046
Speckled dace	8	3	12	1	143	644	131	554	18	287	1,801
Bluehead sucker	354	25	11	7	78	130	132	43	14	13	807
Brown trout	199	2	44	26	4	9	3	--	2	--	289
Common carp	135	9	9	6	10	6	3	20	11	15	224
Fathead minnow	--	2	--	--	56	26	30	21	1	8	144
Channel catfish	42	3	3	2	12	4	1	--	--	--	67
Black bullhead	4	--	--	1	5	--	--	--	--	1	11
Striped bass	1	--	--	1	4	1	1	2	--	--	10
Plains killifish	4	--	--	--	--	--	--	1	--	2	7
Flannelmouth razorback hybrid	--	2	--	--	--	--	--	--	--	--	2
Unidentified sucker	--	--	--	--	--	--	--	--	--	1	1
Red shiner	--	--	--	--	--	--	--	--	1	--	1
Green sunfish	--	--	--	--	1	--	--	--	--	--	1
Total	4,534	189	378	312	813	2,193	1,311	2,231	2,181	2,713	16,855
Hoop net hours	606	4,801	10,345	10,339	8,957	7,226	10,205	12,290	15,943	10,742	91,454
Trammel net hours	9,106	477	2,993	779	759	763	560	195	290	99	16,022
Total net hours	9,711	5,278	13,338	11,118	9,716	7,990	10,764	12,485	16,234	10,842	107,476

J. Total at locations other than aggregations

Species	1990–93	2002	2003	2004	2006	2010	2011	2012	2013	2014	Total
Flannelmouth sucker	298	6	26	18	18	157	105	24	567	1,635	2,854
Rainbow trout	508	30	3	10	1	113	28	50	155	161	1,059
Speckled dace	20	2	15	33	42	142	52	10	11	512	839
Common carp	253	6	9	4	--	17	--	--	4	4	297
Channel catfish	177	1	4	4	--	1	--	--	--	--	187
Bluehead sucker	140	21	1	1	--	2	6	--	11	2	184
Humpback chub	5	8	2	--	1	5	3	1	19	58	102
Red shiner	--	--	--	--	--	72	5	--	--	1	78
Striped bass	40	--	--	--	--	1	--	--	--	--	41
Fathead minnow	--	2	--	--	6	8	9	--	--	11	36
Brown trout	8	11	--	--	--	--	--	--	1	--	20
Unidentified sucker	--	--	--	--	--	--	--	--	--	15	15
Black bullhead	3	--	--	--	--	--	--	--	--	--	3
Walleye	2	--	--	--	--	--	--	--	--	--	2
Threadfin shad	1	--	--	--	--	--	--	--	--	--	1
Largemouth bass	1	--	--	--	--	--	--	--	--	--	1
Black crappie	1	--	--	--	--	--	--	--	--	--	1
Total	1,457	87	60	70	68	518	208	85	768	2,399	5,720
Hoop net hours	929	1,981	1,452	1,102	624	845	969	1,378	6,377	7,158	22,816
Trammel net hours	5,850	225	152	151	41	135	63	6	226	53	6,902
Total net hours	6,779	2,206	1,604	1,253	665	981	1,032	1,384	6,603	7,210	29,717

Table 5. Alternative models of adult humpback chub catch.

[ΔAICc, Akaike information criterion corrected for small sample sizes relative to the model with the smallest AICc; K, number of parameters]

Model	ΔAICc	K
Gear + Period + Location – Non-Aggregation + LCR Inflow:Period	0	15
Gear + Period + Location + LCR Inflow:Period	0.9	23
Gear + Period + Location – Non-Aggregation	5.06	13
Gear + Period + Location	5.13	21
Gear + Year + Location – Non-Aggregation	11.44	23
Gear + Year + Location	13.73	31
Gear + Period + Aggregation + LCR Inflow	19.21	7
Gear + Year + Aggregation + LCR Inflow	28.09	17
Gear + Period + Aggregation	33.84	6
Gear + Year + Aggregation	41.36	16
Gear + Location	65.56	19
Gear + Location – Non-Aggregation	67.26	11
Gear + Aggregation + LCR Inflow	75.29	5
Gear + Aggregation	81.07	4
Gear + Period + LCR Inflow	116.97	6
Gear + Year + LCR Inflow	133.51	16
Gear + LCR Inflow	174.51	4
Gear + Period	178.16	5
Gear + Year	192.01	15

Table 6. Number and percent of humpback chub classified by sexual condition and secondary sexual characteristics by location of capture with river miles in parentheses, 1977 to 2014.

[Please note that various investigators made visual determinations of these morphologic features and may have made slightly different determinations; also not all investigators consistently collected this information; and the information varied with season. R = Ripe: Extrudes gametes with gentle pressure. S = Spent: fish appears to have released gametes. NR = Not ripe: no gametes extruded. U = Undetermined. C = Color: Orange color at base of pelvic and pectoral fins and on belly. T = Tuberculate: Tubercles present. B= Both colored and tuberculated]

Aggregation	Female							Total number of females	Percent of ripe females
	Sexual condition				Sexual characteristics				
	R	S	NR	U	C	T	B		
30-Mile (RM 29.8–36.3)	4	1	40	31		8	2	76	5.3%
Little Colorado River inflow (RM 57.0–77.2)	7	8	196	1,072	35	22	1	1,283	0.5%
Little Colorado River	402	335	17,178	7,941	2,019	410	110	25,856	1.6%
Bright Angel Creek inflow (RM 83.8–92.2)			1	2				3	0.0%
Shinumo Creek inflow (RM 107.8–110.0)			35	32	6	1	1	67	0.0%
Stephen Aisle (RM 114.9–121.0)			11	13				24	0.0%
Middle Granite Gorge (RM 125.0–129.7)			12	83	2	3		95	0.0%
Havasu Creek inflow (RM 155.8–159.2)			20	22	1	2		42	0.0%
Pumpkin Spring (RM 212.5–216.0)	1		4	3				8	12.5%

Aggregation	Male							Total number of males	Percent of ripe males
	Sexual condition				Sexual characteristics				
	R	S	NR	U	C	T	B		
30-Mile (RM 29.8–36.3)	11		41	27	2	11	2	79	13.9%
Little Colorado River inflow (RM 57.0–77.2)	25	2	139	965	28	81		1,131	2.2%
Little Colorado River	7,560	29	13,415	6,934	2,122	3,755	2,363	27,938	27.1%
Bright Angel Creek inflow (RM 83.8–92.2)	1			7		5		8	12.5%
Shinumo Creek inflow (RM 107.8–110.0)	8		52	22	23	4	6	82	9.8%
Stephen Aisle (RM 114.9–121.0)			3	11	1	1		14	0.0%
Middle Granite Gorge (RM 125.0–129.7)	11		4	85		8		100	11.0%
Havasu Creek inflow (RM 155.8–159.2)			9	25	1	4		34	0.0%
Pumpkin Spring (RM 212.5–216.0)			3	1	1			4	0.0%

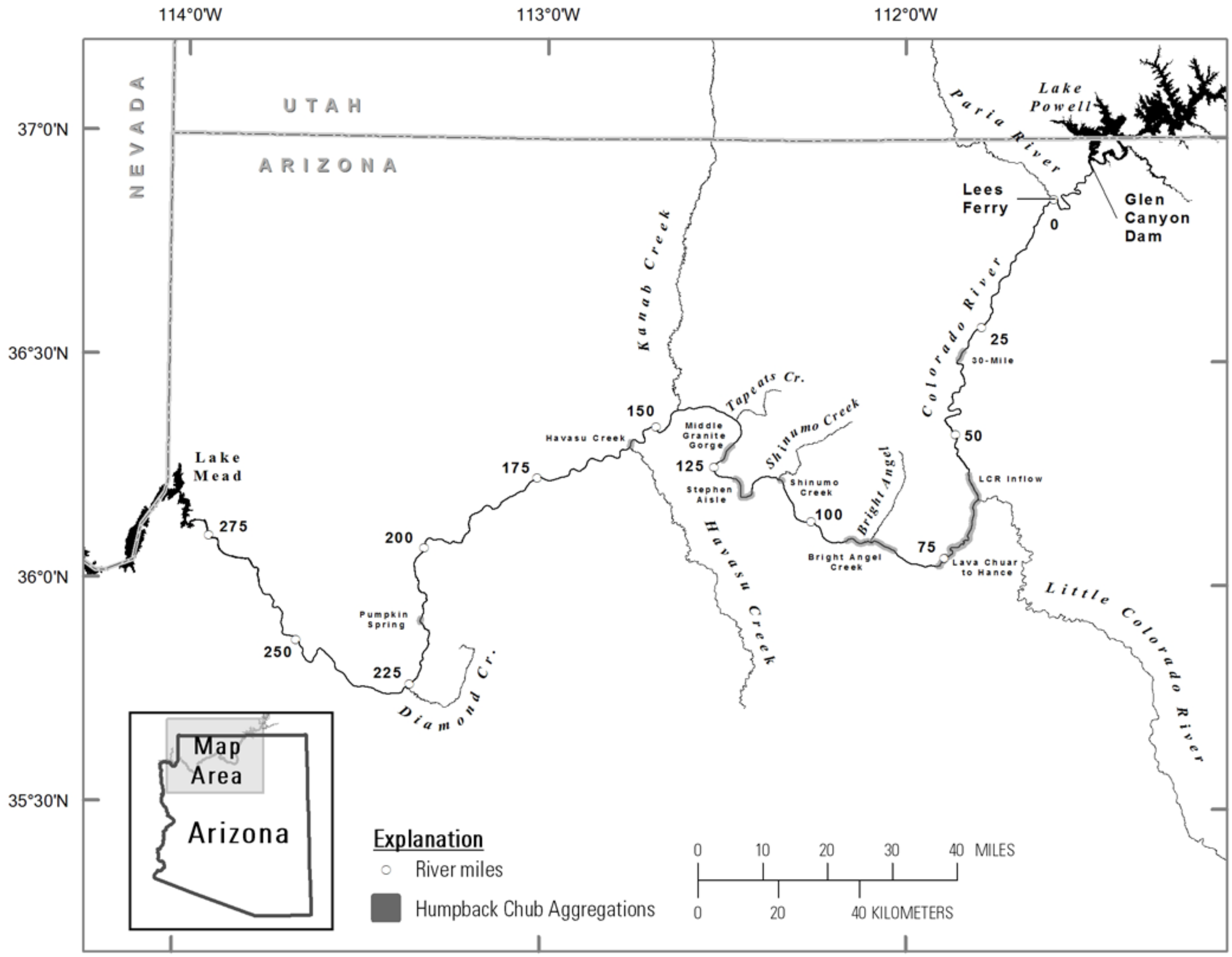

Figure 1. Map of study area identifying Glen Canyon Dam, the Little Colorado River, and the original nine humpback chub aggregation locations.

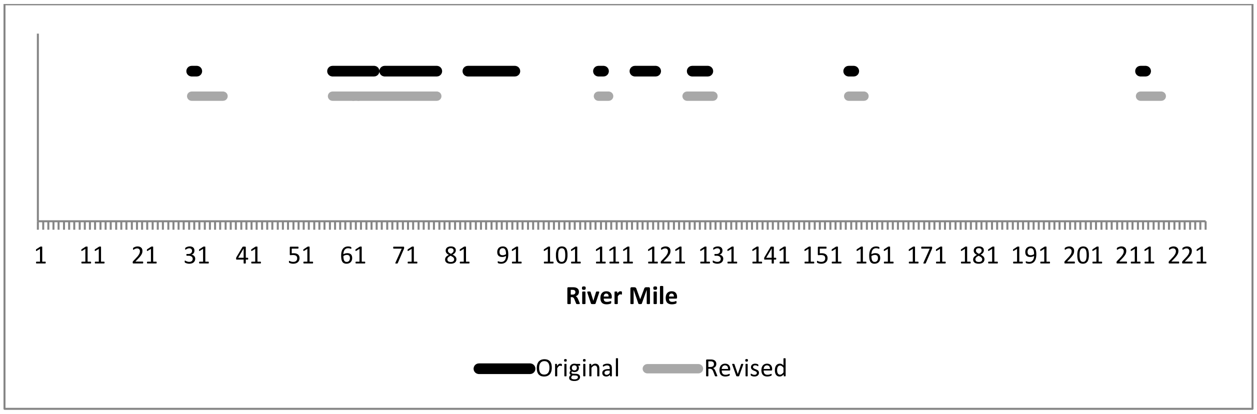

Figure 2. Original (black bars) and revised (gray bars) aggregation boundaries. Original from Valdez and Ryel (1995), revised from this study.

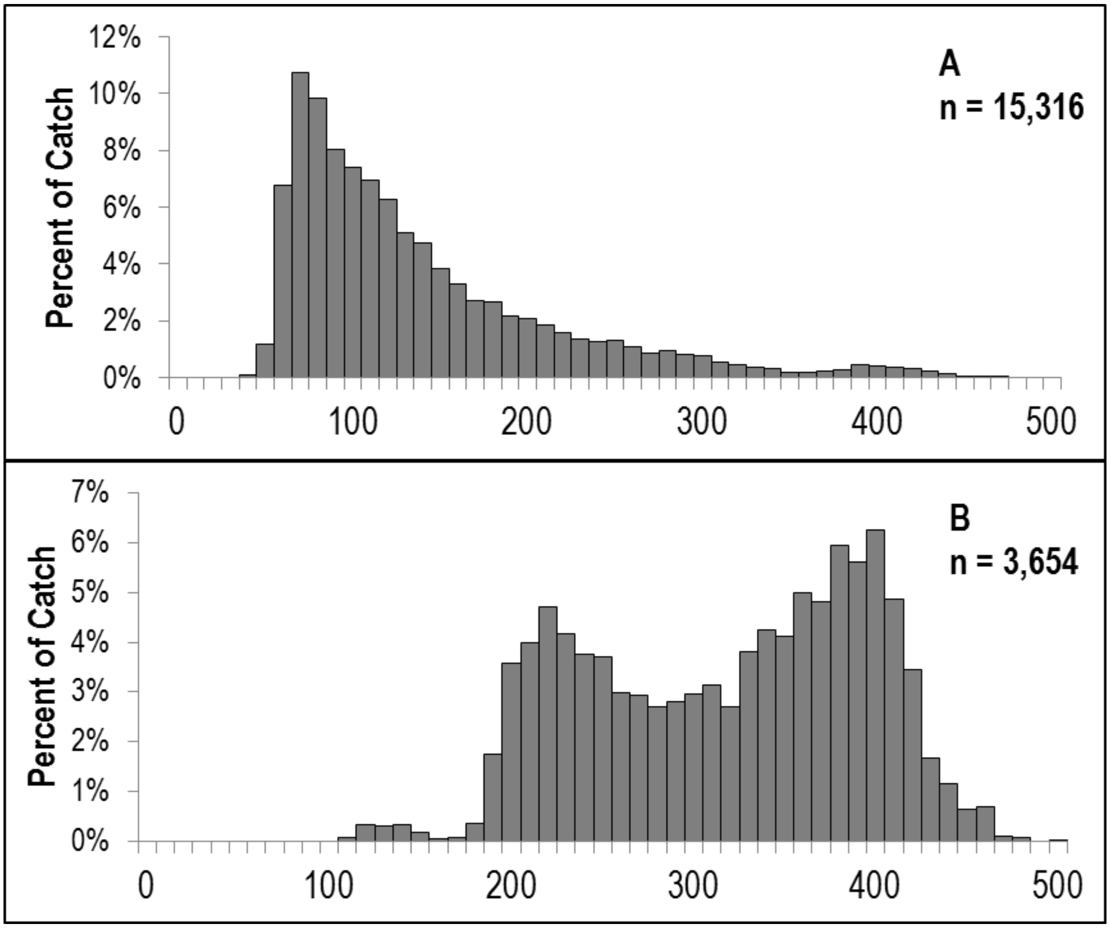

Figure 3. Length-frequency distribution of humpback chub captured by hoop nets (panel A) and trammel nets (panel B) in the Colorado River between Lees Ferry and Lake Mead from 1980 to 2014.

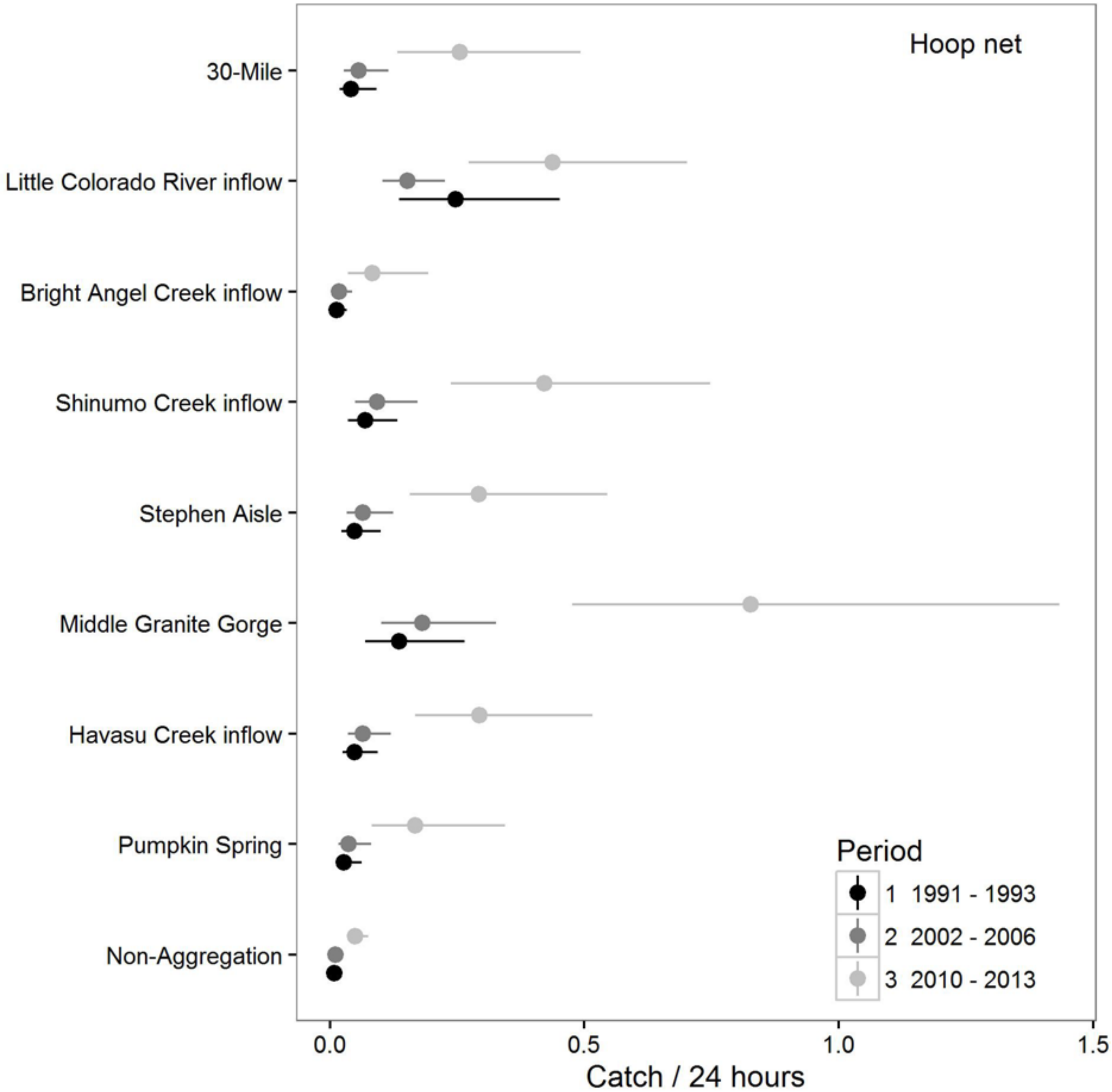

Figure 4. Predicted catch of adult humpback chub per 24 hours for hoop nets during three time periods (Period 1, 1991–93, in black; Period 2, 2002–6, in gray; Period 3, 2010–13, in light gray). Error bars represent 95 percent confidence intervals. “Non-Aggregation” includes all locations not previously defined as an aggregation.

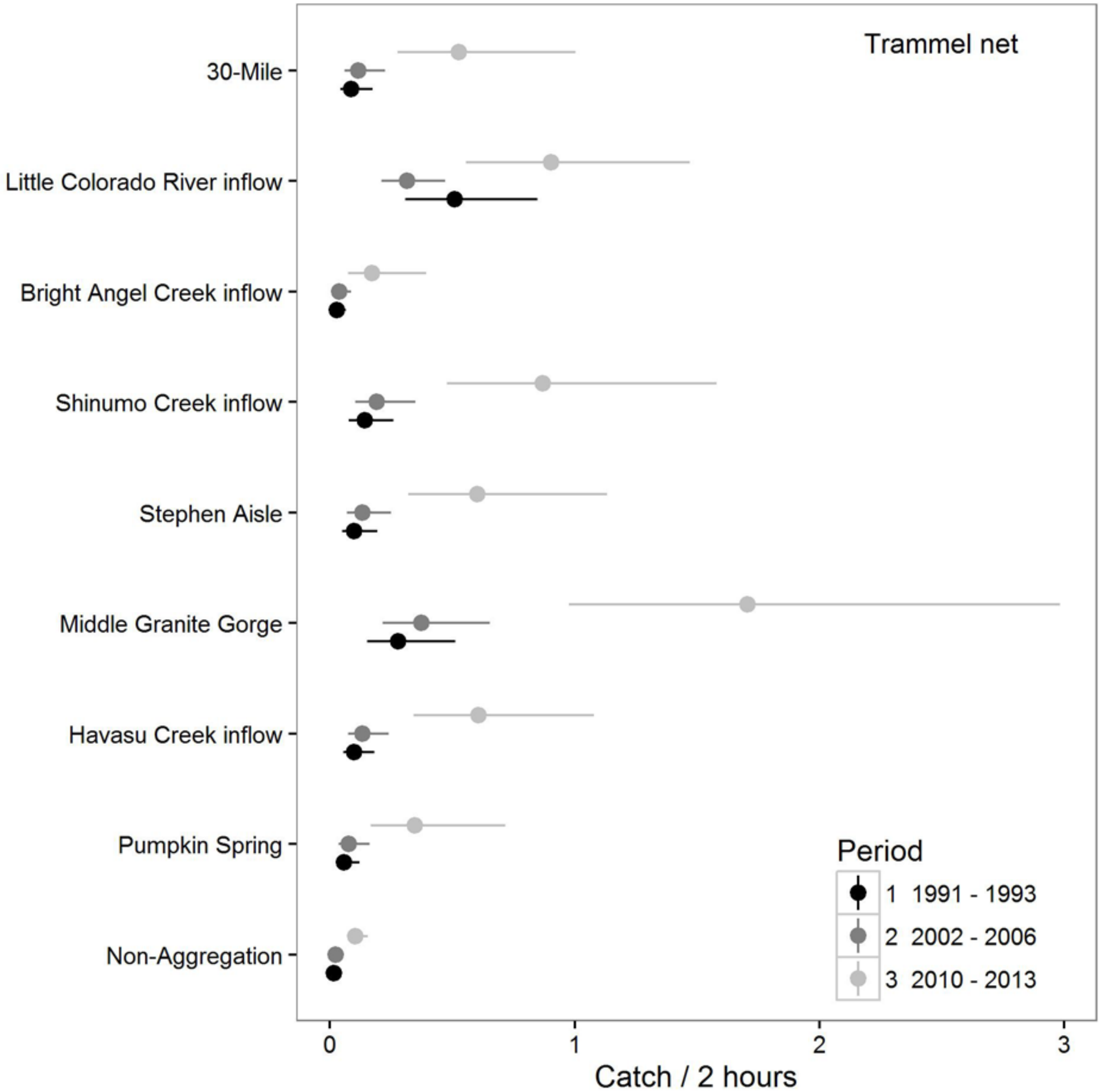

Figure 5. Predicted catch of adult humpback chub per 2 hours for trammel nets during three time periods (Period 1, 1991–93, in black; Period 2, 2002–6, in gray; Period 3, 2010–13, in light gray). Error bars represent 95 percent confidence intervals. “Non-Aggregation” includes all locations not previously defined as an aggregation.

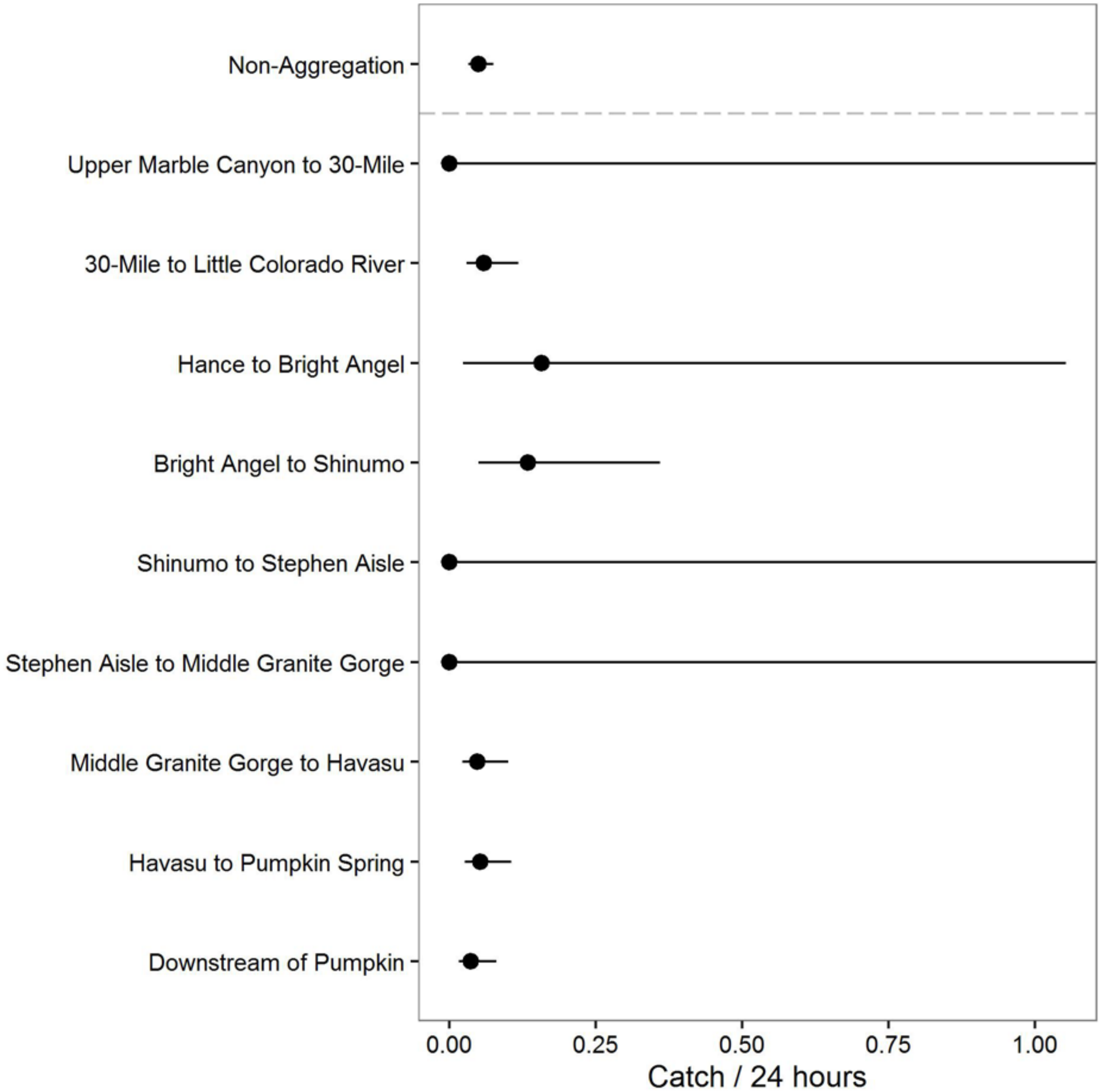

Figure 6. Pridicted catch of adult humpback chub per 24 hours comparing the terms “Location – Non-Aggregation” and “Location” from the two most highly supported models (table 5). The estimates are shown for a common gear (hoop nets) and time period (Period 3) to facilitate comparison. The term “Location – Non-Aggregation” groups all non-aggregation locations together forming one estimate (above horizontal dashed line). The term “Location” estimates each river location seperately. Unbounded estimates are due to sections of river with low or no catches of adult humback chub.

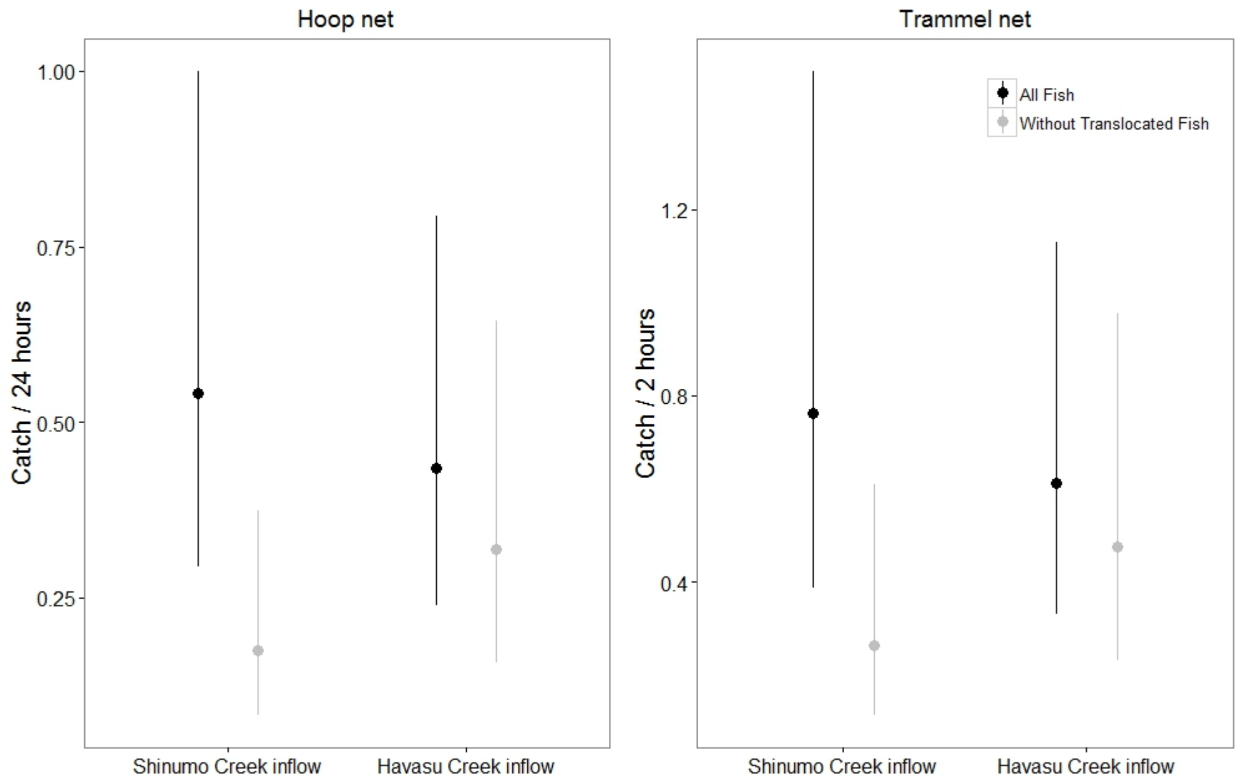

Figure 7. Comparison of predicted catch rates for hoop nets (catch/24 hours) and trammel nets (catch/2 hours), showing the effect of translocated fish at Shinumo Creek and Havasu Creek inflow aggregations. Point estimates and 95 percent confidence intervals for both hoop and trammel are from a generalized linear model (negative binomial errors) fit with all fish (black points and error bars) and fit without translocated fish (gray points and error bars).

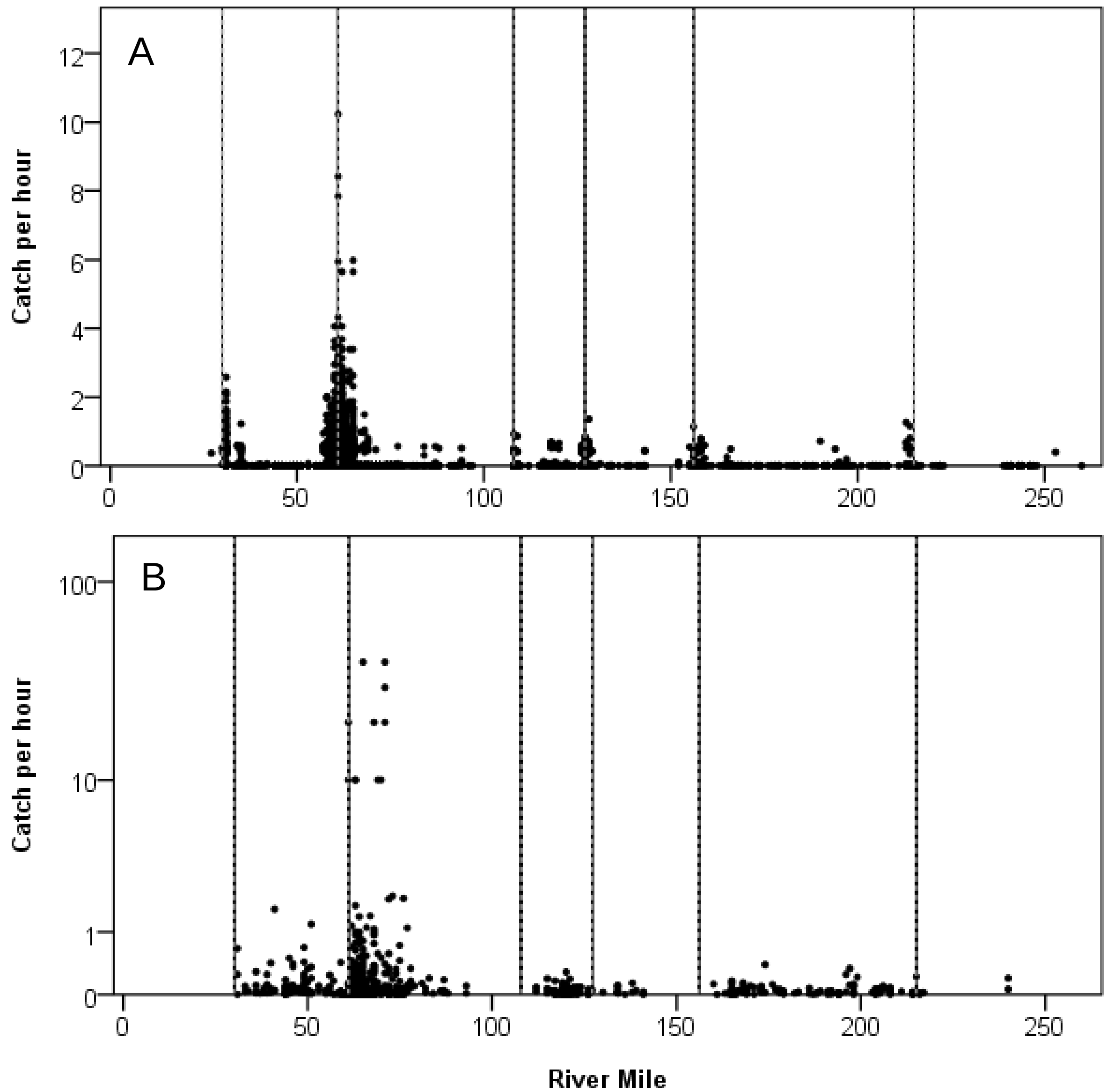

Figure 8. Catch per unit effort (fish/hour) of humpback chub ≥300 millimeters (mm) total length (TL) (panel A) captured by trammel net, and catch per unit effort (fish/hour) of humpback chub ≤100 mm TL (panel B) captured by hoop net by river mile main-stem Colorado River, 1981 to 2014. Note the y-axis of panel B is log scale. Vertical lines represent upstream boundary of aggregations and approximate river miles (RM) at 30-Mile (RM 30), Little Colorado River (RM 61), Shinumo Creek (RM 108), Middle Granite Gorge (RM 127), Havasu Creek (RM 157), and Pumpkin Springs (RM 213). Each point represents an individual sample.

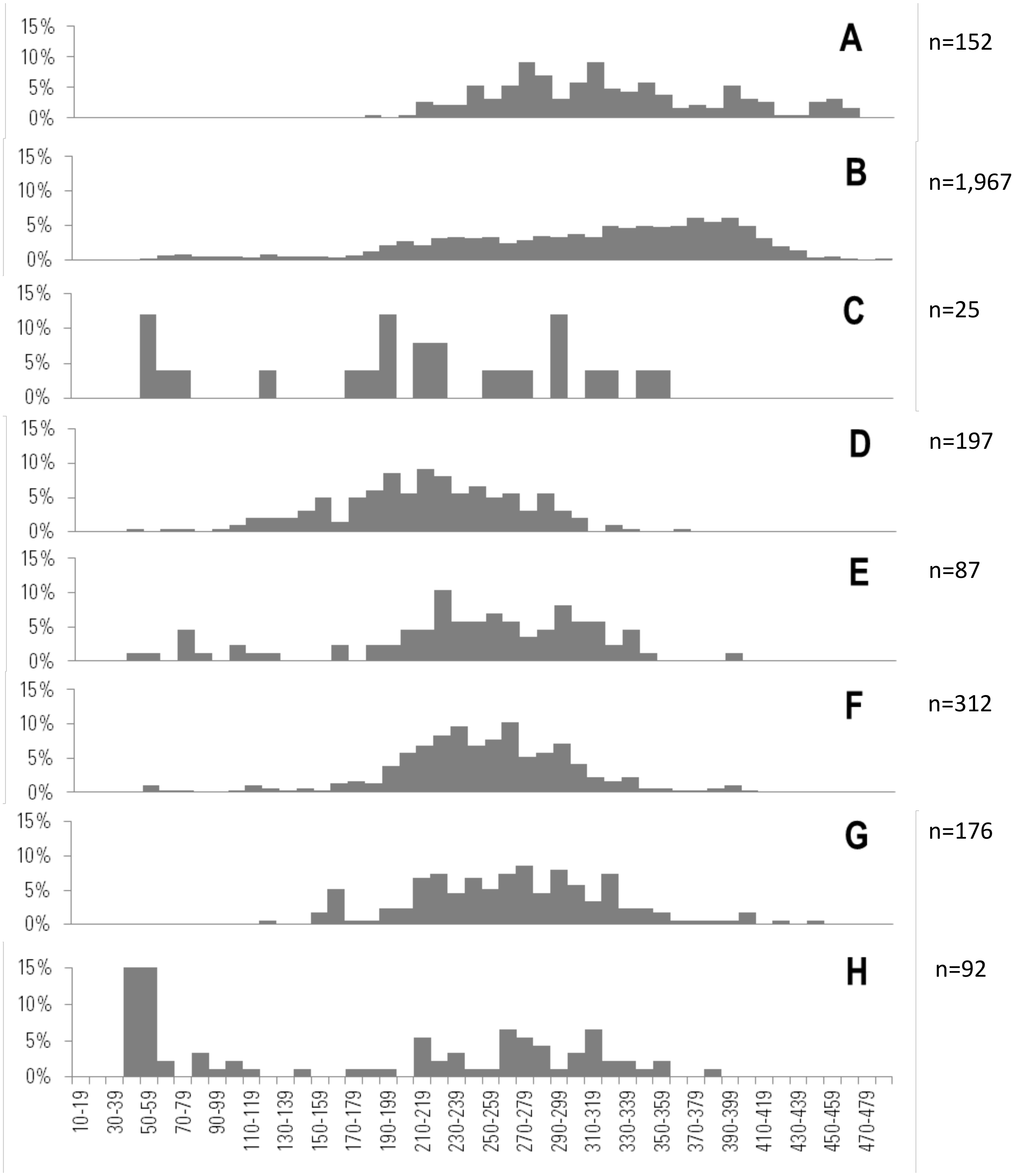

Figure 9. Frequency of humpback chub captures by size class at each aggregation on the Colorado River between Lees Ferry and Lake Mead, 1990 to 2014 aggregation sampling trips. Number of fish captured may include individual fish captured more than once. Panel A, 30-Mile (river mile [RM] 29.8–36.3); panel B, Little Colorado River inflow (RM 57–77.2); panel C, Bright Angel Creek inflow (RM 83.8–92.2); panel D, Shinumo Creek inflow (RM 107.8–110.0); panel E, Stephen Aisle (RM 114.9–121.0); panel F, Middle Granite Gorge (RM 125.0–129.7); panel G, Havasu Creek inflow (RM 155.8–159.2); panel H, Pumpkin Spring (RM 212.5–216.0).