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Mark-Recapture and Fish Monitoring Activities in the Little Colorado River in Grand Canyon from 2000 to 2015

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Little Colorado River in lower Coyote reach, May 2015. Photograph by David Van Haverbeke.

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Abstract

Since 2000, monitoring using hoop nets has been conducted in the lower 13.57 river kilometers (rkm) of the Little Colorado River (LCR) to estimate abundance and track trends in abundance of the endangered humpback chub (*Gila cypha*), and to monitor other fishes. These monitoring activities occurred during the spring and fall seasons. The LCR continues to be dominated by native fish species, comprising 91 percent of fish captures since 2000. Closed Chapman Petersen mark-recapture methods and catch per unit effort data were used to estimate either absolute or relative abundances of humpback chub of various size classes. Between 2000 and 2006, adult humpback chub (≥200 mm) maintained stable but low abundances of <3,000 individuals during the spring and fall seasons. From 2007 to 2014, abundance of adult humpback chub significantly increased, and remained at elevated levels throughout this period (~4,000 to 7,000 individuals). In 2015, both the spring and fall abundances of adult chub in the LCR significantly declined for reasons unknown. Spring abundance estimates of sub-adult humpback chub (150-199 mm) were more variable than adults, but have also increased since 2006, with annual abundances ≥1,000 fish since 2007. Smaller size classes of humpback chub (<150 mm) displayed significant annual variation, thought to be related to the LCR hydrograph.

Robust design models in Program MARK provided the same population trend as provided by closed Chapman Petersen population estimations. In addition, robust models suggested that the mean annual apparent survival of humpback chub ≥200 mm was 77%.

Bluehead sucker (*Catostomus discobolus*) and flannelmouth sucker (*C. latipinnis*) were monitored using catch per unit effort. Relative catches of both native sucker species significantly increased during the post-2006 timeframe, but have since declined.

Reasons for the post-2006 increases of humpback chub, bluehead sucker, and flannelmouth sucker are thought to be related to several factors, including warmer mainstem Colorado River water temperatures since 2003, and mechanical removal of nonnative fish in the mainstem Colorado River during 2003-2006.

Finally, annual monitoring has been conducted since 2006 to monitor humpback chub that have been translocated to above 13.57 rkm in the LCR. Annual estimates of adult humpback chub above Chute Falls (>14.1 rkm) have ranged from 1-143, and annual estimates of adult chub immediately below Chute Falls (13.57-14 rkm) have ranged from 16-435.

Introduction

With completion of the EIS on Operations of Glen Canyon Dam (USBR 1996), the Glen Canyon Dam Adaptive Management Program was initiated. The Adaptive Management Work Group (AMWG) within the program is responsible for defining management objectives associated with resources downstream from Glen Canyon Dam, and provides recommendations about development of long-term monitoring programs to assess those resources. The U.S. Geological Survey Grand Canyon Monitoring and Research Center (GCMRC) is responsible for developing and implementing long-term monitoring programs and fulfilling the needs of the AMWG. Assessing the status of the humpback chub (*Gila cypha*) is particularly important because it is listed as a federally endangered species (U.S. Office of the Federal Register 32:48 [1967]:4001).

Because of the above needs, GCMRC and U.S. Fish and Wildlife Service (USFWS) initiated a program in fall 2000 to conduct long-term monitoring of humpback chub in the Little Colorado River (LCR). Between 2000 and 2015, USFWS obtained closed mark-recapture population abundance estimates of humpback chub ≥150 mm in the lower 13.57 river kilometers (rkm) of the LCR during the spring spawning season and during the fall season (e.g., Van Haverbeke 2010, Van Haverbeke et al. 2013). The spring mark-recapture effort is aimed to coincide with the peak of humpback chub spawning in the LCR and provides an annual estimate of the spring spawning abundance. The fall mark-recapture efforts provide data more representative of humpback chub overwintering in the LCR, particularly those in the juvenile and sub-adult life stages. Additionally, the fall mark-recapture efforts temporally expand marks and recaptures of humpback chub in the LCR, thereby strengthening other open or multi-state models (e.g., Coggins et al. 2006, Coggins and Walters 2009, Yackulic et al. 2014).

In addition to estimating abundance and population trends of sub-adult and adult humpback chub ≥150 mm, there is interest in tracking abundance of smaller size classes of humpback chub <150 mm. This interest stems from a desire to further understand recruitment dynamics of humpback chub (e.g., Coggins and Walters 2009). This information is also used to estimate the portion of age 0 chub that are annually removed for translocations to Shinumo and Havasu creeks (NPS 2013, Trammel et al. 2012) and for maintenance of a refuge population of humpback chub at the Southwest Native Aquatic Research and Recovery Center (SNARRC).

Finally, in addition to the ongoing monitoring in the lower 13.57 rkm of the LCR, between 2006 and 2015 humpback chub monitoring has occurred upstream of rkm 13.57 in the LCR (Van Haverbeke 2010, Van Haverbeke et al. 2013). The purpose for this monitoring has been two-fold. First, this portion of the LCR (rkm 13.57 to ~17.7) became of interest after a series of translocations initiated in 2003 moved juvenile humpback chub from the lower reaches of the LCR (rkm 1.15 to 9.85) to upstream of a natural travertine structure called Chute Falls. Chute Falls is located at rkm 14.1 and translocated chub were released at rkm 16.2. Monitoring efforts upstream of Chute Falls provide annual population estimates of these translocated chub as they grow into adulthood. Second, there is a small reach of river (rkm 13.57 to 14.1) that is not included during our mark-recapture efforts downstream of rkm 13.57. This is a section of river in which chub naturally occur, and also a section of river in which many of the translocated chub occupy as they eventually disperse downstream.

Previous Investigations

Early studies on humpback chub in Grand Canyon began in the 1970s and focused on morphology, life history, and ecology (Suttkus and Clemmer 1977, Kaeding and Zimmerman 1983, Minckley 1996). In Grand Canyon, humpback chub are potadromous, with adults typically migrating from nearby areas in the Colorado River to the LCR to spawn during spring (Douglas and Marsh 1996, Gorman and Stone 1999). Young humpback chub rear in the LCR and many remain in the LCR until early adulthood (Douglas and Marsh 1996, Gorman and Stone 1999) unless they emigrate or are transported out of the LCR by seasonal flood events (Valdez and Ryel 1995). In addition to the LCR population, there are several smaller “aggregations” of humpback chub inhabiting the mainstem Colorado River in Grand Canyon (Valdez and Ryel 1995). With few exceptions, post-dam mainstem reproduction in other aggregations is absent (but see Valdez and Masslich 1999, Andersen et al. 2010) and exchange of individuals from these aggregations to the LCR is limited (Paukert et al. 2006).

Since emplacement of Glen Canyon Dam, the Colorado River throughout Grand Canyon has been predominately characterized by cold hypolimnetic release waters (Wright et al. 2009) that negatively affect humpback chub by lengthening the egg incubation period, decreasing egg and larval survival, and slowing growth at all life stages (Hamman 1982, Clarkson and Childs 2000, Robinson and Childs 2001, Coggins and Pine 2010). These factors are considered to have caused range contraction and decreases in abundances of humpback chub in Grand Canyon (Kaeding and Zimmerman 1983, Douglas and Marsh 1996, USFWS 2002). Because of the need to conserve and recover this relict species, several studies have focused on estimating population abundance of the LCR population (Douglas and Marsh 1996, Coggins et al. 2006, Coggins and Walters 2009, Van Haverbeke et al. 2013).

Purpose and Objectives

The purpose of this report is to summarize humpback chub mark-recapture studies in the LCR from 2000 through 2015 and evaluate the status and trends of humpback chub during those years. Population variables evaluated for the study include closed population estimates, length frequency distributions, and external parasites of humpback chub during the spring and fall seasons. In addition, data are presented on relative abundance (catch per unit effort) of smaller size classes of humpback chub (<150 mm), as well as flannelmouth sucker (*Catostomus latipinnis*) and bluehead sucker (*C. discobolus*) ≥150 mm. The specific objectives of this report are:

1. Present closed Chapman-modified Peterson (Chapman Petersen) abundance estimates of humpback chub ≥150 mm and ≥200 mm in the lower 13.57 rkm of the LCR during the spring and fall seasons. In addition, present spring abundance estimates of humpback chub ≥150 mm and ≥200 mm obtained using robust design models in Program MARK (White and Burnham 1999).

2. Present Chapman Petersen abundance estimates of age 0 humpback chub (40-99 mm) in the lower 13.57 rkm of the LCR during the fall season.

3. Present Chapman Peterson abundance estimates of humpback chub in the LCR between rkm 13.57 and 14.1 and between rkm 14.1 to 17.7 (Chute Falls reaches).

4. Present additional information related to physical parameters of the LCR, length frequency distributions of native fishes, species composition, and parasites.

5. Present 2015 annual data alongside previous data to provide data continuity.

For additional detailed information about monitoring activities, readers should consult Pillow (2015) concerning the spring 2015 mark-recapture trips; Stone (2015) concerning the 2015 Chute Falls monitoring trip; and Stone and Pillow (2015) concerning the fall 2015 mark-recapture trips. Stone and Pillow (2015) also provide details on the 2015 translocation of humpback chub to Chute Falls.

Methods

Trips and Participating Personnel

Between September 2000 and October 2015, 62 field trips were conducted to perform 31 mark-recapture efforts to estimate abundance of humpback chub ≥150 mm and ≥200 mm in the lower 13.57 rkm of the LCR. A mark-recapture event occurred each spring (generally during April and May), and each fall (generally during September and October). In addition, between 2006 and 2015, fourteen trips were conducted to estimate

abundances of humpback chub upstream of rkm 13.57 in the LCR (Chute Falls reaches). These trips occurred during May and June. Personnel on the above mentioned trips included USFWS staff from the Arizona Fish and Wildlife Conservation Office, USFWS volunteers, and collaborative staff from the Arizona Game and Fish Department, Grand Canyon National Park, and GCMRC.

During 2015, four trips were conducted: 14-23 April, 19-28 May, 22 September-1 October (September trip), and 23 October-1 November (October trip). The May trip included collection of ~315 larval humpback chub in the lower portions of the LCR that were sent to SNARRC, and also monitoring in the Chute Falls reaches. The October trip included capture and translocation of 303 juvenile humpback chub from the lower 13.57 km of the LCR to upstream of Chute Falls (Stone and Pillow 2015).

Study Area

Work during the spring and fall mark-recapture trips in the lower 13.57 rkm of the LCR was conducted downstream of a large travertine structure called Lower Atomizer Falls, with the confluence of the LCR and the mainstem Colorado River designated as rkm 0 (Figure 1). During these trips, the LCR was divided into three contiguous reaches (Boulders, Coyote, and Salt). Each reach was divided into three subreaches (Table 1).

During the Chute Falls trip, the LCR upstream of rkm 13.57 was divided into a lower reach from the top of Lower Atomizer Falls (rkm 13.57) to the base of Chute Falls (rkm 14.1), and an upper reach from the top of Chute Falls (rkm 14.1) to rkm 17.7 (Figure 1, Table 1).

Gear and Effort

During spring and fall trips in the lower 13.57 rkm of the LCR, unbaited hoop nets (0.5 - 0.6 m diameter, 1.0 m length, 6 mm [1/4”] mesh, with a single 0.1 m throat) were used to sample fishes. During 2001 and 2002, nets were baited with AquaMax Grower 600 for Carnivorous Species (Purina Mills, Inc., Brentwood, MO). With few exceptions, ~540 net sets were deployed during each monitoring trip. Each “net set” consisted of a hoop net being deployed in the river for ~24 hours, after which it was checked for fish. This resulted in ~180 net sets being deployed per reach (i.e., Boulders, Coyote, and Salt reaches). Each reach was divided into three subreaches, and within each subreach, ~20 nets were set for three 24-hour periods. This design results in a stratified netting effort that is spatially and temporally uniform among sampling trips across years (Figures 1 and 2). Exceptions to the above were five trips during 2001 and 2002, when nets were set for four 24-hour periods rather than three. Minor variation also occurred because helicopter logistics occasionally resulted in slightly shortened trips (e.g., spring 2006, and fall 2011, 2013, 2014 mark trips). Between fall 2000 and fall 2015, a total of 33,068 hoop net sets were deployed during spring and fall trips combined yielding 789,113 hours of fishing effort. With exclusion of the five

higher effort trips in 2001 and 2002, average hoop netting effort among spring trips was 12,619 hrs per trip (SE = 431), and among fall trips was 12,230 hrs per trip (SE = 1,152). During spring 2015, 540 hoop net sets were deployed during the April trip and 541 hoop net sets were deployed during the May trip, yielding 12,856 and 12,582 hours of effort, respectively. During fall 2015, 540 hoop net sets were deployed during the September trip and 533 hoop net sets were deployed during the October trip, yielding 12,661 and 12,306 hours of effort, respectively.

During the Chute Falls monitoring trips, hoop nets were baited near their cod ends by attaching nylon mesh bags (30 x 30 cm, 6 mm mesh) filled with ~160 g AquaMax Grower 600 for Carnivorous Species (Purina Mills Inc., Brentwood, MO). This was done to increase fish captures in order to more closely track translocated fish (Stone 2005). Typically, the reach between Lower Atomizer Falls (rkm 13.57) and the base of Chute Falls (rkm 14.1) was sampled with 17 hoop nets, and the reach upstream of Chute Falls to rkm 17.7 fished with 33 hoop nets, all of which were run for three 24-hr periods. During 2006-2009, Chute Falls monitoring entailed two trips per year (a marking trip and a recapture trip), but years 2010-2015 included only annual marking trips. Sampling effort (hours of hoop netting) was uniform across trips, both in the lower reach (Lower Atomizer to Chute Falls, rkm 13.57-14.1) and in the upper reach (Chute Falls to rkm 17.7, Figure 3). Average trip effort in the lower reach was 1,140 hours (SE = 30), and average trip effort in the upper reach was 2,351 hours (SE = 34). During 2015, 51 net sets were deployed in the lower reach yielding 1,120 hours of effort, and 99 net sets were deployed in the upper reach yielding 2,254 hours of effort.

On all LCR monitoring trips, nets were positioned in habitat suspected to catch humpback chub, and were frequently repositioned or moved if the catch was poor and if an alternative site was available. Nets were spread throughout each subreach within constraints of river hydrology and depth. Most nets were set near shore, but some were set further midstream if access allowed. Each net was checked and emptied of fish daily. Net locations on all sampling trips above were recorded as distance (rkm) upstream of the confluence.

Fish Handling and Data Collection

Data collected from fish included species, total and fork length (mm), sex, sexual condition (ripe, not ripe, gravid), and sexual characteristics (tuberculate, spawning colors). Speckled dace and non-native fish were generally measured only for total length. Humpback chub and other fish were visually checked for the presence of the external copepod parasite (*Lernaea cyprinacea*), but the internal Asian fish tapeworm *(Bothriocephalus acheilognathi*) was not monitored. All fish lengths reported refer to total length.

Humpback chub, flannelmouth sucker, and bluehead sucker ≥150 mm were scanned for a Passive Integrated Transponder (PIT) tag (Biomark Inc., Boise, ID), and if lacking a tag were PIT tagged. From 2000 through 2002, 400 kHz PIT tags were used. Thereafter, 134 kHz PIT tags were used and fish containing a 400 kHz tags were retagged with a 134 kHz tag. From 2000 to 2003 and from 2009 onward humpback chub ≥100 mm were PIT tagged. From 2012 through 2015 some humpback chub as small as 65 mm TL were PIT tagged, but generally chub below 80 mm were not PIT tagged. From 2000 through spring 2003, most fish were weighed (g). Methods for collection of fish data followed the Standardized Methods for Grand Canyon Fisheries Research 2012 (Persons et al. 2013) with the following additions:

1. Humpback chub ≥100 mm in the Chute Falls monitoring efforts were PIT tagged from 2006 onward.

2. From 2010 onward during September marking trips in the lower 13.57 rkm of the LCR, humpback chub 40-99 mm received a red Visible Implant Elastomer (VIE) tag (Northwest Marine Technology, Shaw Island, WA), and humpback chub 40-99 mm during the October recapture trips received a blue VIE tag. Tag placement was trip specific (e.g., below, anterior, or posterior to dorsal fins, and left or right side of dorsal fins). Secondary VIE tags were inserted (generally on opercles or on top of head) for size strata marks (e.g., 40-60 mm, 60-80 mm).

Water Quality

Measured water quality parameters for the spring and fall trips included turbidity readings (nephelometric turbidity units, NTUs) collected near Salt Camp (rkm 10.4). Generally, three or more turbidity readings were taken with a Hach 2100P Turbidimeter (Loveland, CO) and averaged. During Chute Falls trips, these measurements were taken at Translocation Camp (rkm 16.2). Provisional data (mean daily discharges in cubic feet per second; cfs) were downloaded (http://waterdata.usgs.gov/az/nwis/uv?site_no=09402000) for USGS gage station 0940200 located on the LCR near Cameron, Arizona.

Closed Mark-Recapture

Between 2000 and 2015, closed Chapman Petersen mark-recapture efforts were conducted during the spring and fall to estimate abundance of humpback chub ≥150 mm in the lower 13.57 rkm of the LCR. During 2000, no spring mark-recapture effort occurred. Like Douglas and Marsh (1996), our approach was to obtain closed abundance estimates of humpback chub ≥150 mm via fishing the lower 13.57 rkm of the LCR with hoop nets. However, our efforts only provide abundance estimates during the spring and fall seasons of each year rather than on a monthly basis as in Douglas and Marsh (1996). This is because Douglas and Marsh (1996) conducted monthly sampling whereas this study only collected data four times per year. Nevertheless, within a

given set of months, and within a given size class of fish (≥150 mm), our abundance estimates are comparable to Douglas and Marsh (1996).

The target population for determining abundance estimates was all humpback chub ≥150 mm, with the exceptions mentioned above (e.g., humpback chub ≥100 mm from 2010 onward, and humpback chub ≥40 mm during fall trips 2010 onward). We first examined our data to define the sampled population. Bernard and Hansen (1992) suggest setting the lower boundary of the sampled population equal to the length of the smallest fish recaptured. However, we allowed for growth and measurement error that could have occurred between the marking and recapture events (generally ~10 mm). We did not truncate the upper length end of our abundance estimates, because the types of hoop nets used in our study have been shown to capture large humpback chub (Gorman and Stone 1999, Stone and Gorman 2006).

The closed Chapman modified Petersen two-sample mark-recapture model (Seber 2002) was used to estimate abundance. Using the Chapman Peterson model requires only two trips (i.e., a marking trip and a recapture trip) to generate abundance estimates, and therefore requires less handling of fish. In addition, data gathered to produce the Chapman Petersen estimates can be incorporated into open and multi-state models (e.g., Coggins et al. 2006, Coggins and Walters 2009, Yackulic et al. 2014, Dzul et al. 2014, Van Haverbeke et al. 2015). Assumptions necessary for unbiased estimates of abundance using the Chapman Petersen estimator are:

1. The population is closed with no additions (i.e., recruitment, immigration) or losses (i.e., mortality, emigration) between marking and recapture events
2. All individuals in the target population have an equal probability of capture. Specifically:
    a. Marked individuals mix completely with unmarked individuals prior to the recapture event.
    b. Marking does not affect capture probability during the recapture event (i.e., animals are not 'trap-happy' or 'trap-shy').
3. Marks (tags) are not lost between the mark and recapture events.
4. All marked individuals captured can be recognized from unmarked individuals.

The first assumption, addressing population closure, could potentially be violated in this system because humpback chub in the LCR have access to the mainstem Colorado River. This assumption has a higher probability of being violated during the spring than during the fall mark-recapture events. Humpback chub movement and migration is known to occur during the springtime (Kaeding and Zimmerman 1983, Douglas and Marsh 1996), but is thought to be much lower during the fall and winter months (Douglas and Marsh 1996). We minimized potential

for violating this assumption by allowing less than a month to elapse between mark and recapture events. It was also assumed that growth-related recruitment was minimal because of the short time span between the mark and recapture events. Finally, all fish captured during the mark-recapture efforts were handled with care according to protocols (Persons et al. 2013) to minimize injury or stress to fish.

If the humpback chub population experiences only losses between mark and recapture events, the Chapman Petersen estimator will be unbiased and pertain to population abundance during the marking event. Conversely, if the humpback chub population experiences only additions, population estimates will be unbiased and pertain to abundance during the recapture event. However, if both additions and losses occur, there is no possible correction and the estimator will overestimate abundance (Otis et al. 1978, Seber 1982). For further explanation about population estimation, and measures taken to minimize assumption violation during these studies, see Van Haverbeke et al. (2013).

Population estimation using capture probability

From 2010 onward, capture probability (*p*) rather than the Chapman Petersen estimator was used to estimate abundance of adult humpback chub in the Chute Falls reaches. This was because there were fewer humpback chub in the Chute Falls reaches after 2009 and the expected numbers of recaptured fish may have been too low for mark-recapture to function properly. Instead, annual catch of adult chub in each reach from 2010–2015 was divided by *p* data derived from the Chapman Petersen efforts during 2006–2009. Capture probabilities were calculated as $p = R/C$, where C = total number of unique adult humpback chub captured during a recapture trip, and R = number of adult humpback marked (tagged) during a mark trip and subsequently recaptured during the recapture trip. Capture probability values in the upper reach (above Chute Falls) between 2006 and 2009 ranged from 0.58 - 0.91 (mean = 0.67, SE = 0.27, n = 4). Capture probability values in the lower reach (13.57-14.1 km) between 2006 and 2009 ranged from 0.53 - 0.74 (mean = 0.67, SE = 0.20, n = 4). Population estimation from 2010–2015 was performed by dividing the annual trip catch of adult humpback chub within each reach by the four individual capture probabilities for adult humpback within each reach. Confidence intervals were constructed from the variance in the abundance estimates. Because hoop netting effort and turbidity conditions that can influence catch rates (see Stone 2010) during 2010-2015 were nearly identical to those of 2006–2009, we considered it reasonable to assume that detection values were similar between the two time periods.

Catch per Unit Effort

Catch per unit effort (CPUE) was used to monitor relative trends in smaller size classes of humpback chub <150 mm, and for flannelmouth and bluehead suckers ≥150 mm. This was because humpback chub <150 mm

were not PIT tagged during all years of this study, and because in several years numbers of recaptured suckers were insufficient for population estimation. In the LCR, catch rates of these fish in hoop nets can be significantly affected by high turbidities resulting from flood events (Stone 2010). To minimize this effect, we calculated CPUEs using only data gathered during the second spring trips (May or June) of each year, and only from October trips during the fall. During these trips, LCR conditions were generally at base flow and low turbidities. For spring 2015, we calculated CPUE from days when NTU was < 54 (n = 5 days). For fall 2015, we obtained CPUEs from the blue water September trip, because turbidities were high during the entire October trip. Because nets were set very close to 24 hours each, all CPUEs in this report are expressed as number of fish captured per net set (Stone 2010).

Program MARK: Spring Humpback Chub Abundance Estimation (rkm 0-13.57)

One of our goals in this report was to generate spring abundance estimates of humpback chub ≥150 mm and ≥200 mm within the robust design framework (Pollack 1982) using Program MARK (White and Burnham 1999, Cooch and White 2011). In conducting modeling exercises in MARK, it is generally desirable to run a Goodness of Fit (GOF) test with the data at hand to confirm that the starting (general) model adequately fits the data, and to provide indications about survival and capture probability assumption violations (Cooch and White 2011, Chapter 5). Unfortunately, there are no GOF tests in the closed capture-recapture or robust design frameworks (Cooch and White 2011). As a result, it has been suggested to test GOF within the less parameterized Cormack-Jolly-Seber (CJS, Lebreton et al. 1992) framework (E. Cooch and G. White, pers. com.). To do this, we condensed the capture histories of unique humpback chub ≥150 mm captured during the spring mark-recapture events (2001-2015) in the LCR into a CJS format to run a general time dependent CJS model. The bootstrap GOF approach in MARK (Cooch and White 2011, Chapter 5) was used to generate $\hat{c}$ (c-hat is an estimate of lack of fit of the model to the data, or a measure of over-dispersion in the data). A $\hat{c}$ of 1 indicates perfect fit, while $\hat{c}$ values of >1 indicate some lack of fit. As a 'rule of thumb', $\hat{c}$ values of <3 are relatively safe (Lebreton et al. 1992, pp. 84-85). A measure of $\hat{c}$ was obtained by dividing the observed model deviance by the simulated deviance, yielding $\hat{c}$ = 1.41. This same procedure was run for humpback chub ≥200 mm, yielding $\hat{c}$ = 1.26. A qualifier for this is that the $\hat{c}$ values were computed from the CJS model, but robust design models can account for temporary emigration and individual heterogeneity that may contribute to the estimate of $\hat{c}$ obtained with the CJS model (G. White, pers. com.). Because our $\hat{c}$ values were >1, model selection values were adjusted in MARK (Cooch and White 2011, p. 5-36), resulting in AICc values being transformed to QAICc values.

Once GOF was tested in the CJS format, we used the robust design (Pollack 1982, Figure 4) in Program MARK (Cooch and White 2011, Chapter 15) to compare estimates of abundance generated with MARK with those

generated with closed Chapman Petersen methods (Van Haverbeke et al. 2013). Robust design capture histories were built in SPSS (version 22; IBM Corp.) for humpback chub ≥150 mm and for chub ≥200 mm, and included 30 encounter occasions between 2001 and 2015 (two secondary trapping occasions per 15 primary trapping occasions). Fish captured during our spring marking events (generally April trips) were considered the first secondary trapping occasions, while fish captured during our spring recapture events (generally May trips) were considered the second secondary trapping occasions. Capture histories included only chub captured in the lower 13.57 km of the LCR. Since there were several tag types captured during these years (e.g., Floy tags, Carlin tags, 400 kHz and 134.2 kHz PIT tags), we linked tag types if fish were subsequently recaptured. Some of this tag linking was done after retrieval of data from the GCMRC database.

We built a subset of nested robust design models (full likelihood *p* and *c*) in MARK to answer questions about optimal model structure. Full likelihood *p* and *c* models are those of Otis et al. (1978), with abundance in the likelihood (Cooch and White 2011, p. 14-3). These subset models were ranked by Akaike Information Criterion adjusted for small sample size (AICc, Cooch and White 2011, p. 4-33). All models were built using the Parameter Index Matrix (PIM) feature in MARK. Models included the following 'standard' models described in Otis et al. (1978): M_o (capture probabilities constant), M_t (capture probabilities vary with time), and M_b (capture probabilities vary by behavioral response to capture). Variations of these models were also run (e.g., survival parameter held constant, but capture probabilities allowed to vary by time, etc.).

The robust design framework provides estimates of abundance (N), survival (S), capture probabilities (*p* and *c*), and gamma parameters for temporary emigration (γ") and the return rate of temporary immigrants (1-γ'). For the purposes of this report, we were interested only in abundance and survival. The top QAICc ranking model was a fully time dependent M_t Markovian model. This model was then constrained in order that the survival and gamma parameters became fully identifiable. This was done by applying the constraints to the gamma parameters $\gamma'_k = \gamma'_{k-1}$ and $\gamma''_k = \gamma''_{k-1}$ (Cooch and White 2011, p. 15-17). Before presenting final parameter estimates, the top QAICc models were run through Markov Chain Monte Carlo (MCMC) parameter estimation using the logit link in MARK (Cooch and White 2011, pp. 10-39 to 10-46). This procedure refines parameter estimation, particularly if parameters are near 0 or 1. To generate MCMC parameter estimates, we used 4000 "tuning" samples, 1000 "burn in" samples and stored 50,000 samples. We used the default prior mean of 0 and standard deviation of 1.75 for beta.

Results –rkm 0-13.57

Physical Parameters

Turbidity and Flow

Turbidities encountered during 2000-2015 fall mark-recapture events were generally much higher than those of 2001-2015 spring mark-recapture events in the lower 13.57 rkm (Figure 5). This is because monsoonal flooding events during September tend to cause far higher turbidities than spring runoff flows of April. Average trip turbidities encountered during the spring ranged from 4 to 6,343 NTUs (mean = 560 NTUs, N = 30 trips). With the exception of 2005 and 2015, turbidity was low (4 to 50 NTUs, mean = 18 NTUs) on all spring recapture trips. Turbidity tended to be higher during spring mark trips because of snow run-off, and tended to be low during the spring recapture trips when the LCR generally returned to base flows (Figure 6). Average trip turbidities during the fall ranged from 5 to 75,956 NTUs (mean = 14,775 NTUs, N = 32 trips). Turbidity tended to be high during the fall mark trips because of monsoonal flooding, and low during the fall recapture trips when the LCR generally returned to base flows (Figure 6). For 2015, average trip turbidity during the spring trips was 690 NTUs (SE = 918), and for the fall trips was 16,587 NTUs (SE =23,389).

Species Composition

Humpback chub have generally dominated hoop net catches in the lower 13.57 rkm of the LCR since fall 2000 (Figure 7). Bluehead sucker displayed high variance in percent species composition because of highly variable annual catches. Native fish have comprised 91% of all fish captured since fall 2000. Fathead minnow (*Pimephales promelas*) were generally the dominant nonnative fish captured, comprising 6.5% of catch since 2000. Catches of fathead minnow were variable and thought to result either from downstream transport of fish caused by floods in the LCR (Stone et al. 2007), or from extended periods of base flows during which local populations may have expanded. Other nonnative fish captured since 2000, listed in order of decreasing catch, included common carp (*Cyprinus carpio*), black bullhead (*Ameiurus melas*), channel catfish (*Ictalurus punctatus*), red shiner (*Cyprinella lutrensis*), plains killifish (*Fundulus zebrinis)*, rainbow trout (*Oncorhynchus mykiss*), brown trout (*Salmo trutta*), and green sunfish (*Lepomis cyanellus*). A few fish thought to be razorback sucker (*Xyrauchen texanus*) and flannelmouth sucker hybrids have been captured since 2000, and these fish are treated as flannelmouth sucker for this report. Such hybrids were infrequently captured during monitoring efforts in the early 1990s (Douglas and Marsh 1998). Presumably under-represented in hoop net catches were adult channel catfish and adult common

carp, which seldom enter our nets but are seen by field crews and captured by angling. In 2015, humpback chub again dominated trip catches (72% of captures), followed by speckled dace (13%), flannelmouth sucker (9%), and bluehead sucker (5%). Native fish comprised 99% of fish captures.

Length Frequency Distributions

Humpback Chub

Humpback chub in the lower 13.57 rkm of the LCR show a widely distributed population structure, with all size classes represented and recruitment of young fish apparent (Figure 8-A). Cumulatively since 2001, the spring season shows sizeable production of age 1 fish in the roughly 80-130 mm size class. Some smaller humpback chub can also be seen, representing the oncoming age 0 cohorts born each spring. This smaller group of humpback chub may be under-represented since fish <40 mm escape the hoop nets. Humpback chub in the 130-300 mm size class also show good representation, indicating multiple age classes. Most of these fish are likely in the 2-15 year age classes (see Figure 4 in Coggins and Pine 2010). Finally, fewer individuals were observed above 300 mm, but of these fish some individuals measured ~470-480 mm in length. Since 2001, captures have included 3,683 chub ≥ 300 mm.

During the fall in the lower 13.57 rkm of the LCR, there is also indication of a healthy population structure for humpback chub, with multiple size class representation (Figure 8-B). Cumulatively since 2000, there has been sizeable production of age 0 humpback chub. These fish hatch during the spring seasons, and most are still <100 mm by fall (Figure 8-B). There is another mode of fish centered at ~145-150 mm. This mode may largely represent the age 1 cohort that were 80-130 mm the previous spring (Figure 8-A). Noticeably fewer fish are captured in the ~200-300 mm size class during the fall compared to spring, since many of these fish presumably vacate the LCR after the spring spawning season. Finally, captures of the largest of humpback chub >300 mm are fewer during the fall season, with 800 captured since 2000.

Bluehead sucker

Bluehead sucker also show signs of a healthy population structure in the lower 13.57 rkm of the LCR, with adult fish as well as recruiting young fish present (Figure 9-A). Cumulatively from 2001-2014, the spring season displays a sizeable group of presumed age 0 fish (mode at 65-70 mm), and another group of sub-adult/adult fish (mode ~240 mm). By fall, both size groups remain, but the mode for small fish is somewhat larger (110 mm; Figure 9-B). Catches of bluehead sucker are ~10-fold lower during the fall season compared to spring season (Figure 9),

strongly suggesting that most adult bluehead suckers seen in the LCR are migratory between the mainstem and the LCR.

Flannelmouth Sucker

Cumulatively (2001-2014), flannelmouth sucker show distinct size class patterns during the spring (Figure 10-A), with representatives from the age 0 (<80 mm) and 1 cohorts (~80-150 mm) being most distinguishable (i.e., older cohorts tend to blur). Like bluehead suckers, the spring age 0 size class of flannelmouth suckers is more pronounced compared to humpback chub, possibly because they spawn earlier than chub. By fall, the age 0 cohorts of both sucker species (Figures 9-B and 10-B) tend to be very diminished compared to humpback chub (Figure 8-B).

Parasites

Percent occurrence of the external parasite (*Lernaea cyprinacea*) on humpback chub during spring trips was generally lower compared to fall trips, with infestation rate representing the percent of chub captured observed carrying the parasite (Figure 11). Infestation rates during spring trips averaged 1.9% (range 0.05% to 8%), while those on fall trips averaged 7.6% (range 0.08% to 35%). The highest infestation rate was during fall 2009 at 35%. Typically, only one or two parasites are seen on individual humpback chub in the LCR, although numbers are sometimes higher. Very infrequently, this parasite is seen on other species of native and nonnative fish (e.g., flannelmouth, bluehead, dace, fathead minnows), again typically at low frequencies with only one or two parasites per fish. For 2015, infestation rates were very low (0.2%) during both spring and fall seasons.

Population Abundance Estimation (rkm 0-13.57)

Adult and sub-adult humpback chub

Following the decline in sub-adult (150-199) and adult (≥200 mm) humpback chub abundance documented in the early-mid 90s (Coggins et al. 2006), mark-recapture abundance estimates in the LCR remained at reduced but stable levels during the early-mid 2000s (Figure 12). After 2006, abundance of humpback chub in the LCR during the spring and fall seasons significantly increased. Since this increase, the spring abundances of humpback chub ≥150 mm and ≥200 mm remained at elevated levels until 2015 (Figure 12). For spring 2015, the abundance estimate of humpback chub ≥150 mm was 3,999 (SE = 314), of which an estimated 3,078 (SE = 246) were ≥200 mm. For fall 2015, the abundance estimate of humpback chub ≥150 mm was 2,664 (SE = 255), of which an estimated 1,628 (SE = 134) were ≥200 mm.

With the exception of 2015, since 2007 the spring abundance estimates for humpback chub in the 150-199 mm size class have all been >1,000 fish (Figure 13). The mean spring estimate for humpback chub in the sub-adult category (150-199 mm) from 2007-2015 was 1,767 fish (SE = 665). For spring 2015, the abundance estimate for humpback chub in the 150-199 mm size class was 921 (SE = 84).

Juvenile (age 1 and age 0) humpback chub

Mark-recapture estimates of humpback chub in the age 1 size class (100-149 mm) during the spring season were conducted in 2001, 2002 and 2009-2015, and have ranged between 761 and 11,619 fish (Figure 14-A). For spring 2015, the abundance estimate for humpback chub in this size class was 2,760 (SE = 543). CPUE in years 2001-2015 ranged between 0.14 and 3.5 fish per 24-hour net set (mean = 1.6) during the spring recapture trips (Figure 14-A). For spring 2015, CPUE for age 1 humpback chub was 0.795 fish per net set during the low turbidity (<55 NTUs) days of the recapture trip (N = 5 days). Several years (2001, 2003, 2005, 2007 and 2010) can be characterized as years with low relative abundance. Four of these years (2001, 2003, 2007 and 2010) correspond to the low age 0 CPUEs of the previous fall (Figure 14-B). The age 1 mark-recapture estimates show good correlation with the age 1 CPUE calculations (r^2 = 0.75, N = 9 years).

Annual Chapman Petersen efforts using VIE tagging to estimate abundance of humpback chub in the age 0 size class (40-99 mm) in the LCR began in fall 2010 and have continued through fall 2015. Between fall 2010 and fall 2015, abundance estimates of the fall age 0 cohorts ranged between 3,479 and 10,511 fish (Figure 14-B). For 2015, we obtained an estimate of 5,374 (SE = 1,514) humpback chub in this size class. CPUE in years 2000-2015 has ranged between 0.05 and 3.0 fish per 24-hour net set (mean = 1.4) during October trips (Figure 14-B). For fall 2015, CPUE for age 0 humpback chub was 2.12 fish per net set during the mark trip. Unfortunately, the age 0 mark-recapture estimates show poor correlation with the age 0 CPUE calculations (r^2 = 0.07, N = 6 years).

Bluehead and flannelmouth sucker

Bluehead sucker and flannelmouth sucker relative abundance trends in the LCR were described using CPUE data from spring recapture trips when turbidities were low (Figure 15). Similar to humpback chub, bluehead and flannelmouth suckers underwent a post-2006 period of significant increase, although this increase was noticeably less for flannelmouth sucker. From 2009-2011, bluehead sucker then significantly declined, somewhat increased again from 2012 to 2014, and declined to pre-2006 levels in 2015. Flannelmouth sucker have also been trending downward since 2010 (Figure 15). For May 2015, CPUE was 0.21 (SE=0.08) for bluehead sucker and 0.27 (SE = 0.05) for flannelmouth sucker.

Program MARK Spring Humpback Chub Abundance Estimation (rkm 0-13.57)

Robust design models were run in Program MARK to generate abundance estimates of humpback chub ≥150 mm and ≥200 mm in the LCR. The top ranking QAICc model was a fully time dependent Markovian model. The abundance estimates generated in MARK were compared to the closed Chapman Petersen estimates (Figure 16). There was no significant difference in any given year between the closed Chapman Petersen abundance estimates and those generated by MARK (Figures 16 A&B). Mean apparent (2001-2014) survival of humpback chub ≥200 mm was 0.77 (range 0.60 - 0.91, SE = 0.09), as estimated within a CJS framework.

Results Chute Falls (rkm 13.57 to 17.7)

Physical Parameters

Turbidity and Flow

Excluding two sampling days during 2015, average trip turbidities during the 2006-2015 Chute Falls monitoring trips were consistently low, ranging from 0.9-6.9 NTUs (mean = 3.6 NTUs, N = 14 trips), and were accompanied by base flows. For the 2015 trip, average turbidity in the Chute Falls reach was 1.2 NTUs (SE = 0.5) during the first 6 days of sampling, after which a small spate substantially increased turbidity to an average of 2,967 NTUs (SE = 1,553) during the last two days of sampling. Average daily afternoon water temperature at 16.2 km was 20.7 ^{o}C.

Length Frequency Distributions and Catch

Length frequencies demonstrate that humpback chub translocated to upstream of Chute Falls can remain upstream of Chute Falls and grow to adulthood (Figure 17-A). Most fish were ~80-130 mm at the time of their translocation. Immediately downstream of Chute Falls, a sizeable number of humpback chub fall into the approximately 110-160 mm size class (Figure 17-B). Some of these fish represent humpback chub that vacated habitat upstream of Chute Falls after translocation, and some were likely the result of spawning in this reach, or in the reach above Chute Falls. Interestingly, the long term mode (2006-2014) of small humpback chub during May/June immediately downstream of Chute Falls is ~140 mm (Figure 17-B), while the long term mode (2001-2014) of small fish downstream of rkm 13.57 during May/June is ~110 mm (Figure 8-A), suggesting that growth of small humpback chub is higher upstream of lower Atomizer Falls (above rkm 13.57).

Parasites

Similar to spring trips in the lower 13.57 rkm, infestation rates of *Lernaea cyprinacea* on humpback chub in the Chute Falls reaches tended to be low, ranging from 0% to 6% (mean = 0.9%). The highest infestation rate was 6% in 2009. During 2015, infestation rate was 0.02%, with only 1 infested fish.

Population Abundance Estimation

Upstream of Chute Falls, there was a period of decline (2007-2008) in adult humpback chub ≥200 mm that followed no translocations occurring in 2006 and 2007 (Figure 18-A). Translocations resumed again in 2008 and this was followed by a higher abundance of adults by 2009. A prolonged spring flood in early 2010 (Figure 6) is thought to have resulted in a near absence of humpback chub upstream of rkm 13.57 during summer of 2010 (Figures 18-A and 18-B). Translocations continued during 2010-2014, again resulting in an increase in abundance of adult humpback chub upstream of Chute Falls through 2015 (Figure 18-A). On 1 November 2015, another 303 humpback chub were translocated to upstream of Chute Falls (Stone and Pillow 2015). Importantly, the abundance estimates calculated with mark-recapture (2006-2009) and those calculated using *p* data for 2006-2009 were highly correlated (r^2 = 0.93, n = 8), and did not differ significantly during any given year (see Figures 18-A and 18-B), lending credibility to the post 2010 abundance estimates that were derived using *p* data. An exception is that the estimates for chub in the upper reach for 2015 may be biased low because turbidities were high during two sampling days in this reach (i.e., catches could have dropped with higher turbidity [Stone 2010], thus lowering the abundance estimates). For 2015, it was estimated that there were 247 humpback chub ≥100 mm (SE = 55) in the upper reach, and 435 ≥100 mm (SE = 80) in the lower reach. Of these, it was estimated that there were 29 humpback chub ≥200 mm (SE = 6) in the upper reach, and 177 ≥200 mm in the lower reach (SE = 30).

Discussion

Lower 13.57 rkm of the LCR

Population estimates of humpback chub indicate that sometime between the early 1990s and 2000, the abundance of adult humpback chub (≥200 mm) underwent a decline in the LCR (Coggins et al. 2006). This was followed by a period of relatively low but stable abundance between 2000 and 2006, and by a 2007-2014 period of significantly increased abundance levels (Van Haverbeke et al. 2013). The post-2006 increase in humpback chub ≥150 mm and ≥200 mm is visible during both spring and fall seasons, but it is more apparent during spring months

(Figures 12-A and 12-B). The significant decline in the 2011 spring abundance of humpback chub ≥150 mm (Figure 12-A) may be a result of relative low production of age 0 fish during 2009 as suggested by Figure 14-B.

Spring 2015 saw a significantly lowering of abundance of humpback chub ≥150 mm and ≥200 mm compared to the previous several years. This decline was also seen during the fall LCR sampling of 2015. The cause of this decline is unknown. During the September 2014 monitoring trip the LCR experienced a monsoon flood accompanied by unusually high turbidities (recorded turbidity reached a peak of ~190,000 NTUs). This event caused some fish to perish and is described in a report by Stone and Pillow (2014). However, it is unlikely that this flood alone could have caused a decrease in the population by spring 2015 of nearly 4,000 chub ≥150 mm. For example, after this flood subsided, we captured of 678 chub ≥150 mm during October 2014 with an estimated capture probability of 0.17. This alone would indicate there were still ~3,900 chub ≥150 mm still alive in the LCR system during October 2014. There is some indication based on unusually high CPUEs in the mainstem Colorado River near the LCR that chub may have emigrated into the mainstem (M. Dodrill, pers. com.), and may not have returned into the LCR during spring 2015 because of poor condition factors possibly caused by depressed food resources (C. Yackulic, pers. com.).

There is considerable annual variation in spring abundance estimates of sub-adult humpback chub 150-199 mm (Figure 13). This is expected because annual variation in the sub-adult size class correlates with preceding annual variation of chub in the 100-149 mm size class (Van Haverbeke et al. 2013). Since 2008 there have been only three years (2008, 2011 and 2015) in which the lower 95% confidence interval of the spring abundance estimate dropped below 910 fish (Figure 13). This is important for two reasons. First, the Biological Opinion associated with mechanical removal of trout (USFWS 2011) implemented a set of triggers under which mechanical removal of trout would resume. One of the measures listed that could help trigger mechanical removal was if the adult abundance of humpback chub drops below 7,000 fish (based on the Age Structured Mark-Recapture Model, Coggins and Walters 2009), and if the lower 95% confidence interval of humpback chub in the 150-199 mm size category drops below 910 fish in any 3 of 5 years extending retrospectively since 2008. Our closed estimates of the 150-199 size class only account for chub in the LCR, but indicate this trigger has not been met. Second, to help meet the recovery criteria for humpback chub, the Recovery Goals (USFWS 2002) called for mean estimated recruitment of age 3 (150–199 mm) naturally produced fish to equal or exceed mean annual adult mortality. Mean annual adult mortality rate has been estimated at 0.13 and the adult population size has been estimated at ~7,650 individuals (Coggins and Walters 2009). Using these numbers as a base guideline, this translates into 995 sub-adult (150-199 mm) humpback chub needed annually to compensate for adult mortality. Spring population estimates for humpback chub in the 150-199 mm size class from 2007 to 2015 have averaged

1,767 fish (SE = 665). Hence, our results also indicate that that the Recovery Goal guideline for sub-adult production is being met.

Concerning juvenile humpback chub <150 mm, both mark-recapture and CPUE indices suggest high annual variability in abundance of the fall 40-99 mm size class (age 0) and the spring 100-149 mm (largely age 1) size class of humpback chub (Figures 14-B and 14-A, respectively). Since 2010, sizes of fall age 0 cohorts (40-99 mm) have ranged from 3,479 to 10,511 fish. One reason for estimating this parameter is to gain insight into what percentage of the age 0 cohort is being harvested (cropped) each year for the Shinumo and Havasu creek translocations and for the establishment of a refuge at SNARRC. As in 2014, this year, chub cropped for translocation outside of the LCR were harvested as larval fish (<30 mm), thus helping to alleviate concerns about potential overharvesting (Pine et al. 2013).

Relative abundance (CPUE) of bluehead sucker and flannelmouth sucker ≥150 mm significantly increased in the post-2006 timeframe during the spring spawning season (Figure 15), with bluehead suckers reaching peak abundance in 2008 and flannelmouth sucker reaching peak abundance in 2010. The two sucker species have since undergone declines in relative abundance. Bluehead sucker catches have been about 10-fold lower during the fall season, suggesting mass annual emigration for this species to the mainstem. Alternatively, during fall sampling trips, bluehead sucker could be seeking refuge in shallow fast water habitat where hoop nets are not usually deployed. Finally, because few age 0 suckers are captured in the fall season, this may indicate that both sucker species tend to drift as larvae and emigrate from the LCR before the onset of the fall season (see Robinson et al. 1998).

Chute Falls (rkm 13.57-17.7)

Since 2003, ~2,969 juvenile humpback chub have been translocated from the lower reaches of the LCR to upstream of Chute Falls. Since 2003, humpback chub have been found to grow to adulthood in the upper reach, although not all translocated fish have stayed upstream of Chute Falls. Many have either moved into the lower Chute Falls reach, moved further downriver (downstream of Lower Atomizer Falls), or moved into the mainstem Colorado River. Between summer of 2009 and summer 2010, nearly all humpback chub vacated both the upper and lower Chute Falls reaches (Figure 18), as well as the upper portion of Salt reach (12.3 to 13.57 km). It is thought that this was a result of a prolonged spring flood during 2010 that deposited a heavy sand load in the upper reaches of the LCR, filling in much of the available deep pool habitat. This phenomenon may explain why there were no humpback chub upstream of Chute Falls prior to the translocation efforts. High environmental stochasticity in this section of river may over-ride low colonization rates. Since 2003, only six chub have been documented

ascending Chute Falls on their own accord. With the re-commencement of translocation activities in 2010, humpback chub have again been found to remain and grow to adulthood in the upper and lower reaches of Chute Falls.

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Table 1. List of reaches, subreaches, and river kilometers within each subreach; Little Colorado River.

Sub-reach	Reach	River km (range)
	Boulders	
Confluence-Jump Off Rock		0.0-1.8
Jump Off Rock-Powell Pool		1.8-3.0
Powell Pool-5.0 rkm		3.0-5.0
	Coyote	
5.0 rkm - White Spot (Kachina Falls)		5.0-6.5
White Spot-Redbud Canyon		6.5-8.0
Redbud Canyon-House Rock		8.0-9.6
	Salt	
House Rock-Hell Hole		9.6-11.2
Hell Hole-Triple Drop		11.2-12.3
Triple Drop-Lower Atomizer Falls		12.3-13.57
	Chute Falls	
Lower Atomizer Falls-Chute Falls		13.57-14.1
Chute Falls-17.7 rkm		14.1-17.7

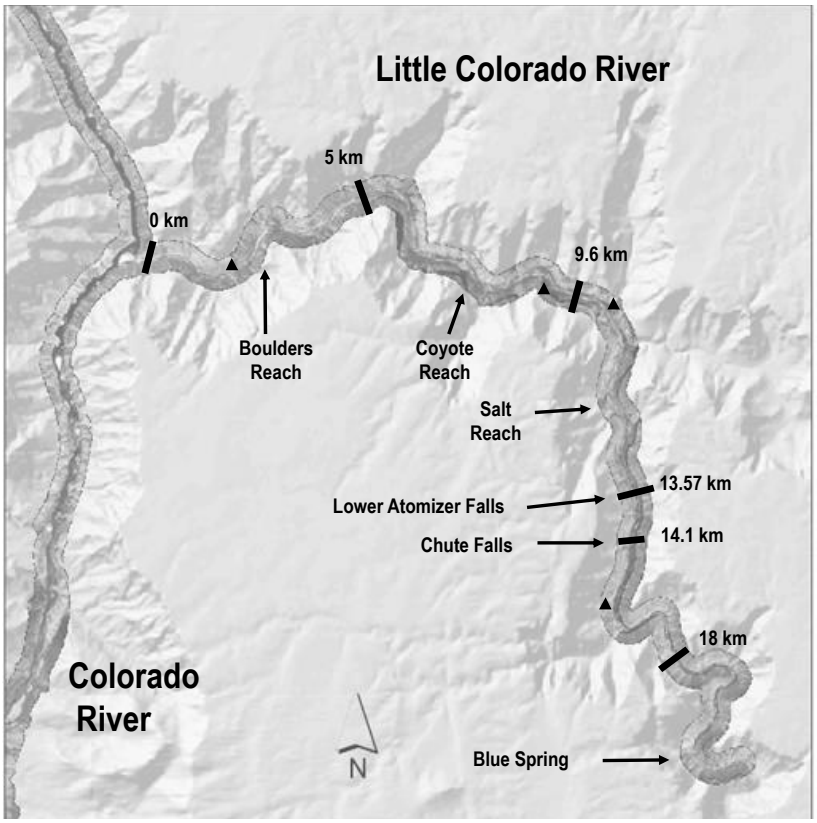


Figure 1. Map of study areas, showing Boulders (river km [rkm] 0 to 5), Coyote (rkm 5 to 9.6) and Salt (rkm 9.6 to 13.57) reaches, and lower Chute Falls (rkm 13.57 to 14.1) and upper Chute Falls (rkm 14.1 to 17.7) reaches; Little Colorado River. Camps are designated by triangles.

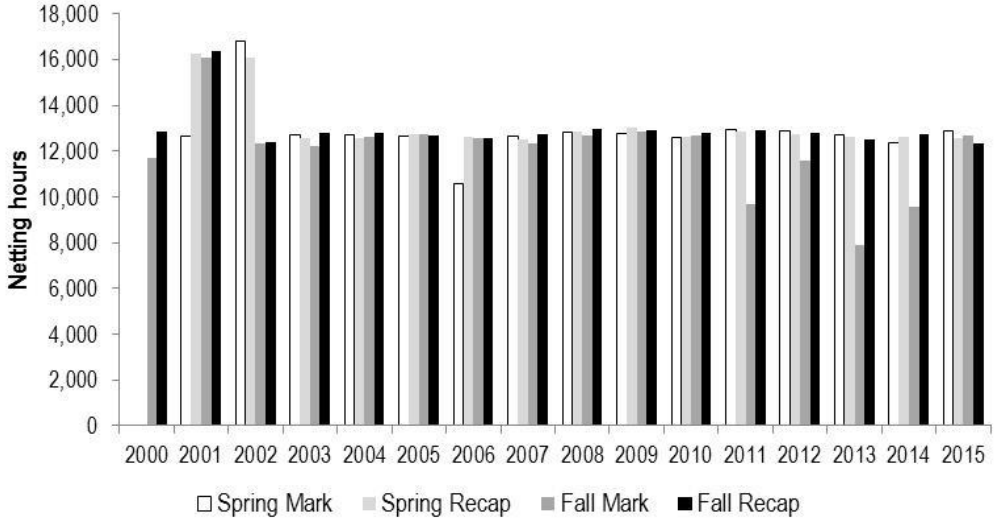


Figure 2. Hoop net sampling effort (hours) across all spring and fall monitoring trips 2000 to 2015 in lower 13.57 river km of the Little Colorado River.

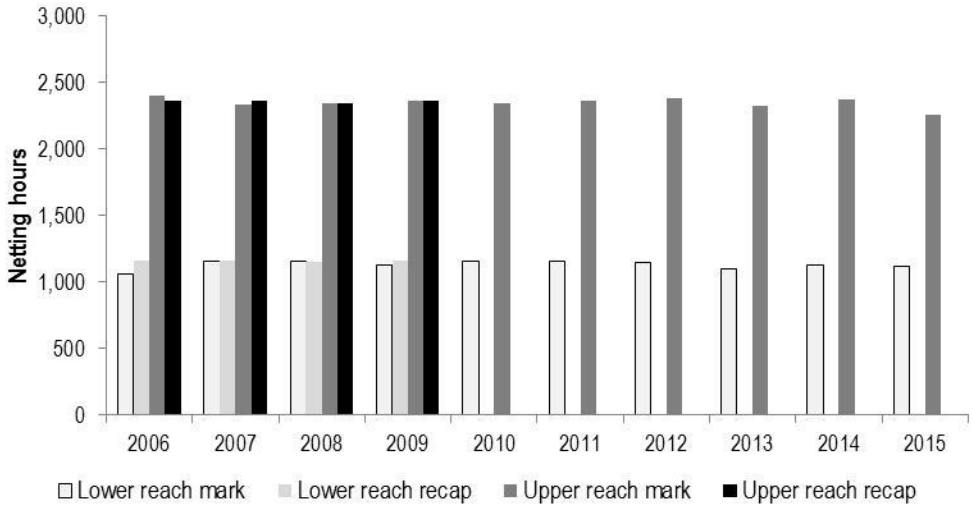


Figure 3. Hoop netting effort (hours) in the upper and lower Chute Falls reaches during monitoring efforts between 2006 and 2015, Little Colorado River. Note: Lower reach extended from Lower Atomizer Falls (river km 13.57) to Chute Falls (river km 14.1). Upper reach extended from top of Chute Falls (river km 14.1) to river km 17.7. Both reaches included a mark and recapture event from 2006-2009, but thereafter only included one marking trip per year.

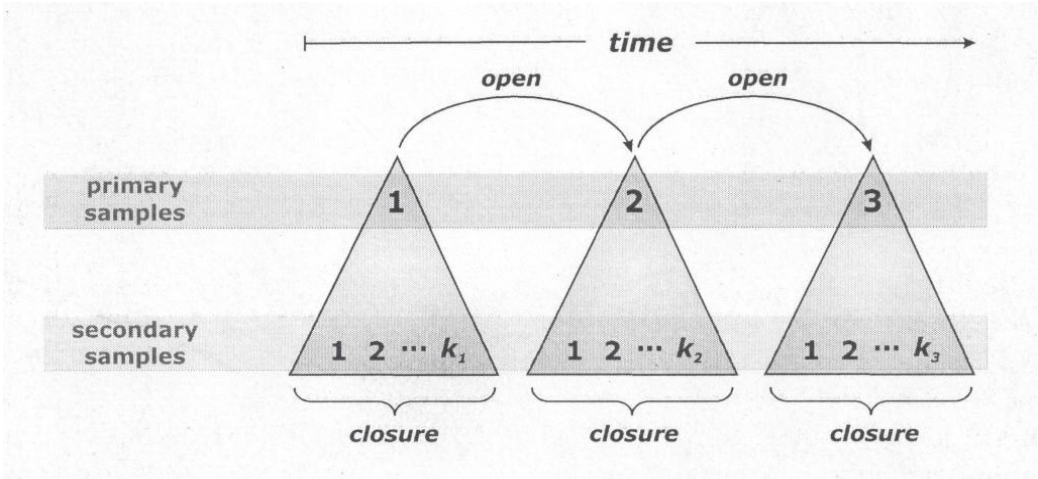


Figure 4. Basic structure of 'classical' Pollack's robust design. For this study, we had two secondary sample occasions. Schematic from Cooch and White (2011).

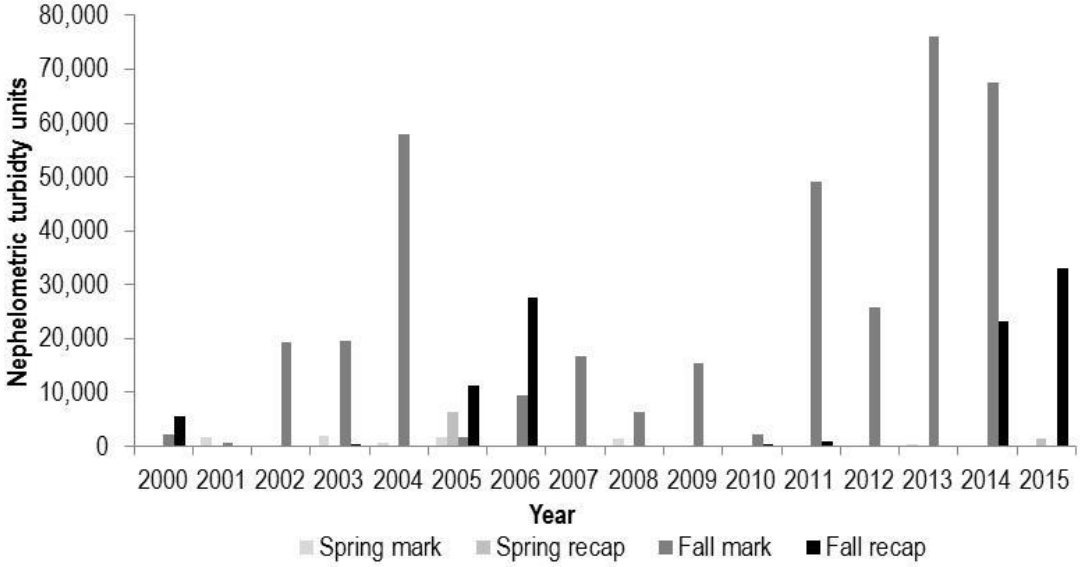


Figure 5. Average trip turbidities (nephelometric turbidity units, NTU) during spring and fall mark-recapture trips in the Little Colorado River, 2000-2015. Note, daily turbidity readings were taken on each trip. "Missing" bars represent low trip turbidities (most < 50 NTUs), not missing data.

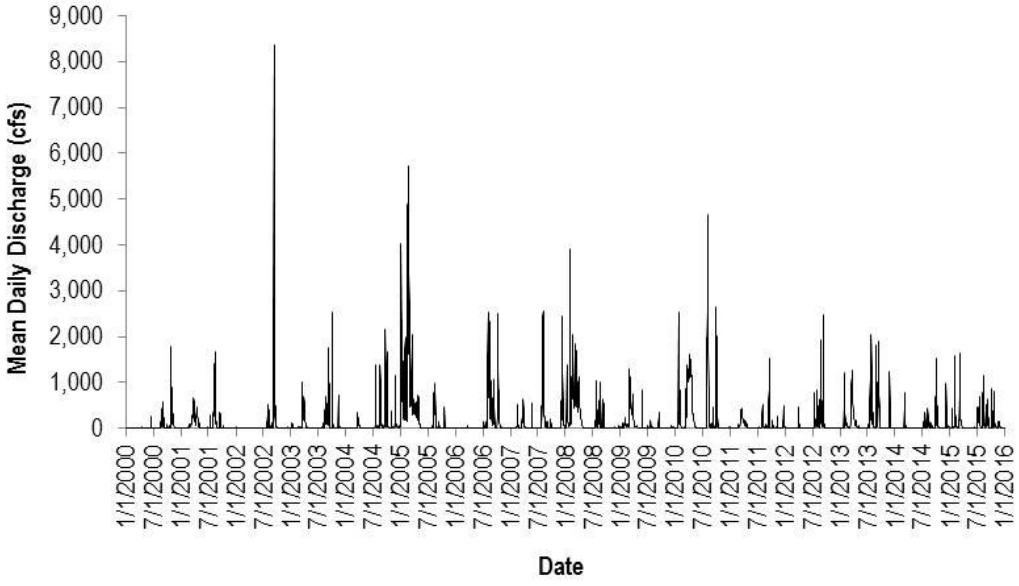


Figure 6. Provisional mean daily discharge (cubic feet/second; cfs) from USGS gage station 0940200; Little Colorado River (LCR), Arizona, January 2000 – January 2016.

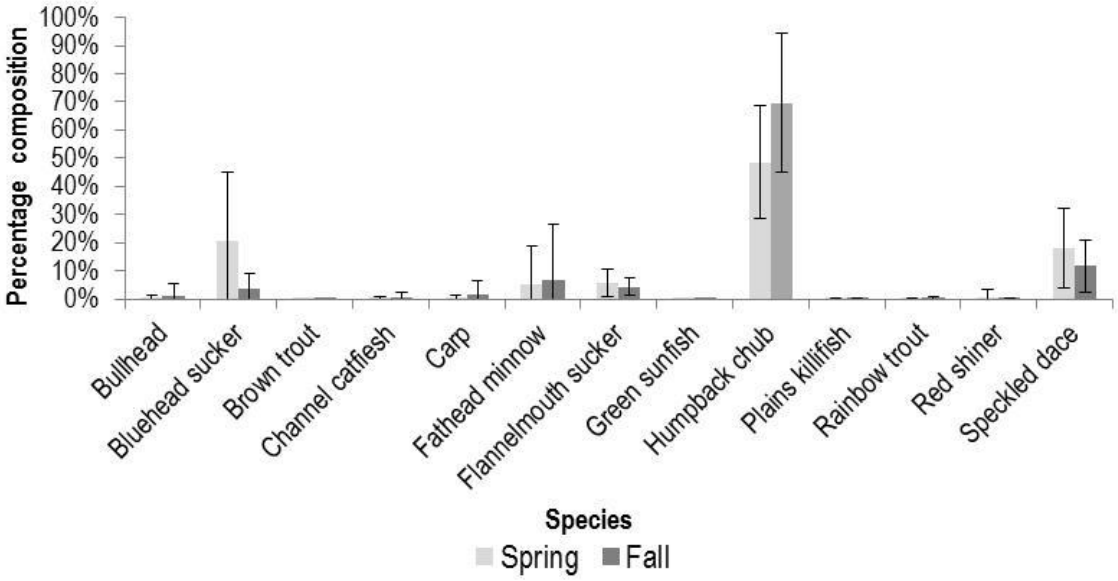
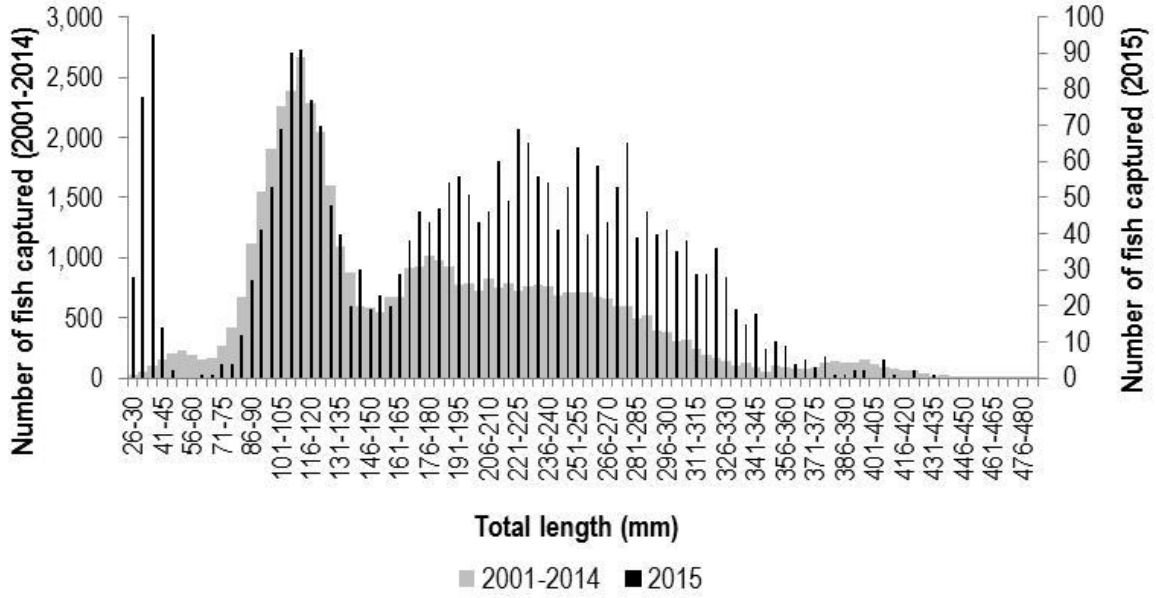


Figure 7. Spring and fall species composition (±95% CI) of fish captured in hoop nets between fall 2000 and fall 2015; Little Colorado River (N = 179,441 fish).

A.



B.

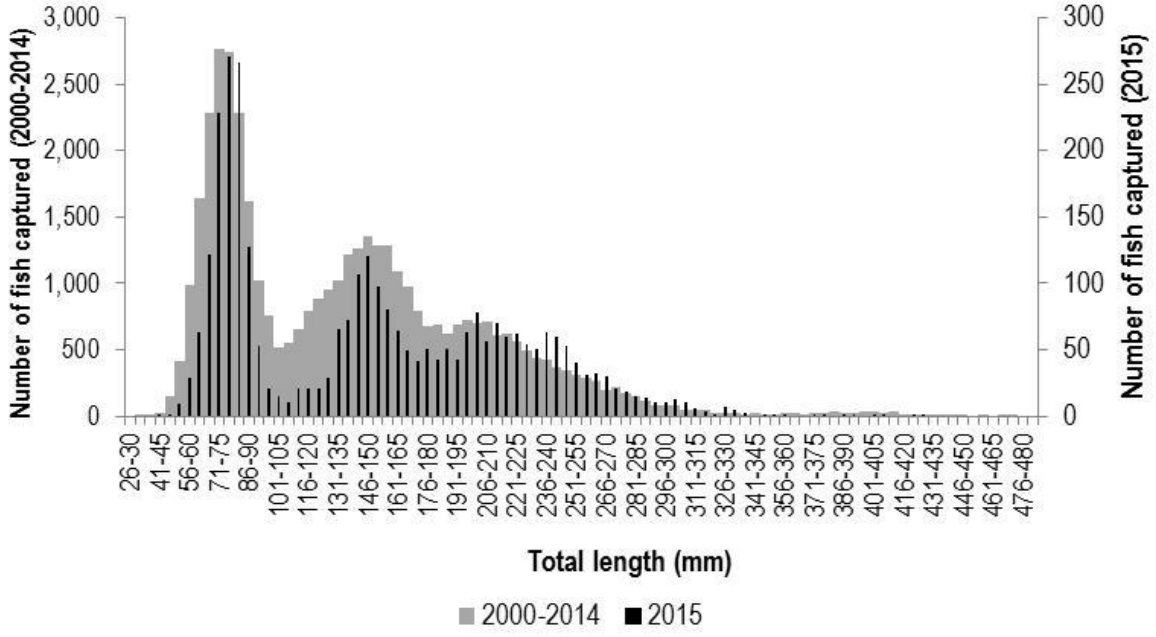
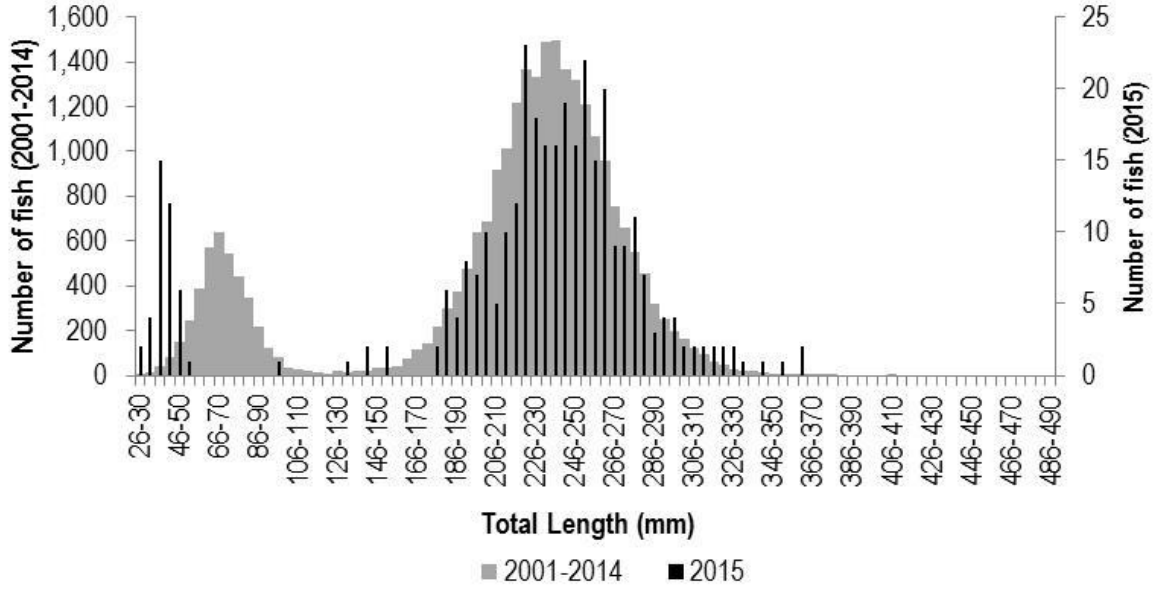


Figure 8. Length frequency distributions of humpback chub captured in the Little Colorado River (river km 0-13.57) during (A) spring 2001-2014 and 2015 and (B) fall 2000-2014 and 2015.

A.



B.

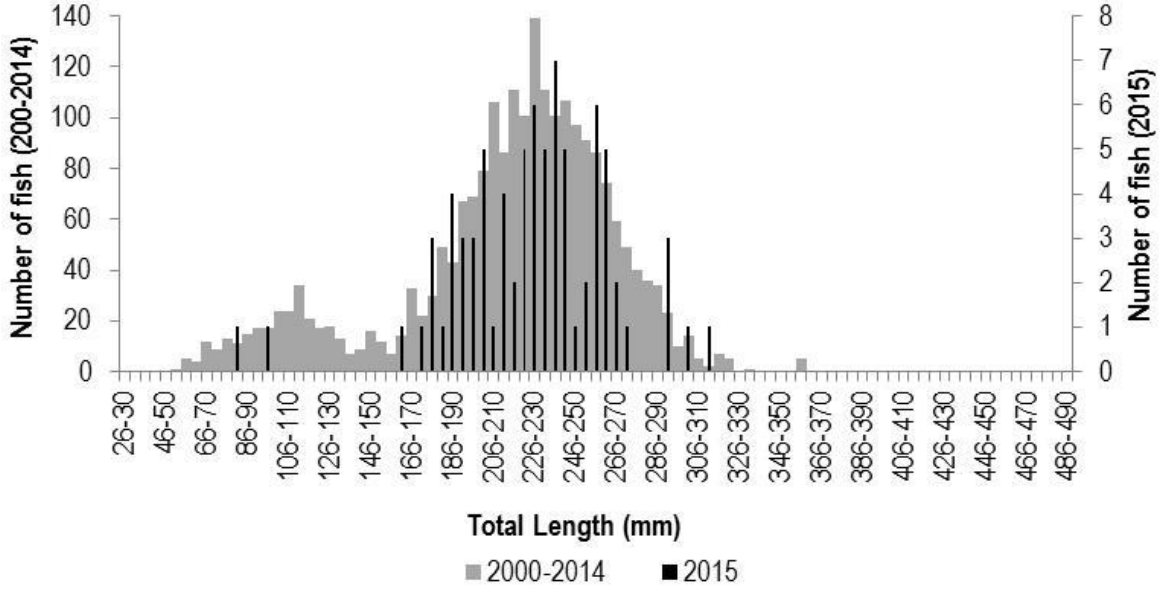
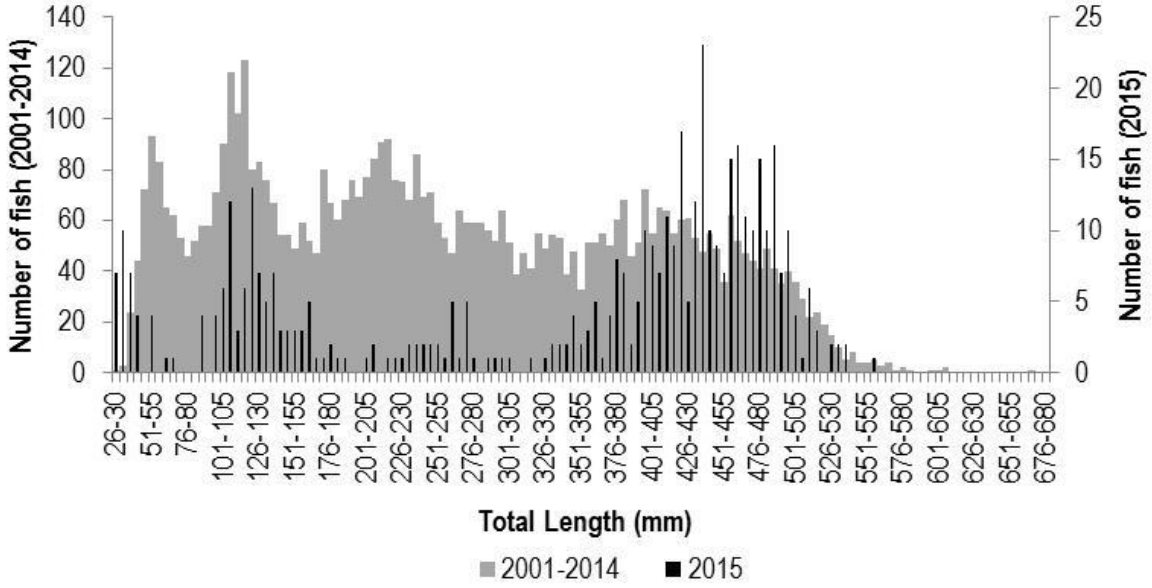


Figure 9. Length frequency distributions of bluehead suckers captured in the Little Colorado River (river km 0-13.57) during (A) spring 2001-2014 and 2015 and (B) fall 2000-2014 and 2015.

A.



B.

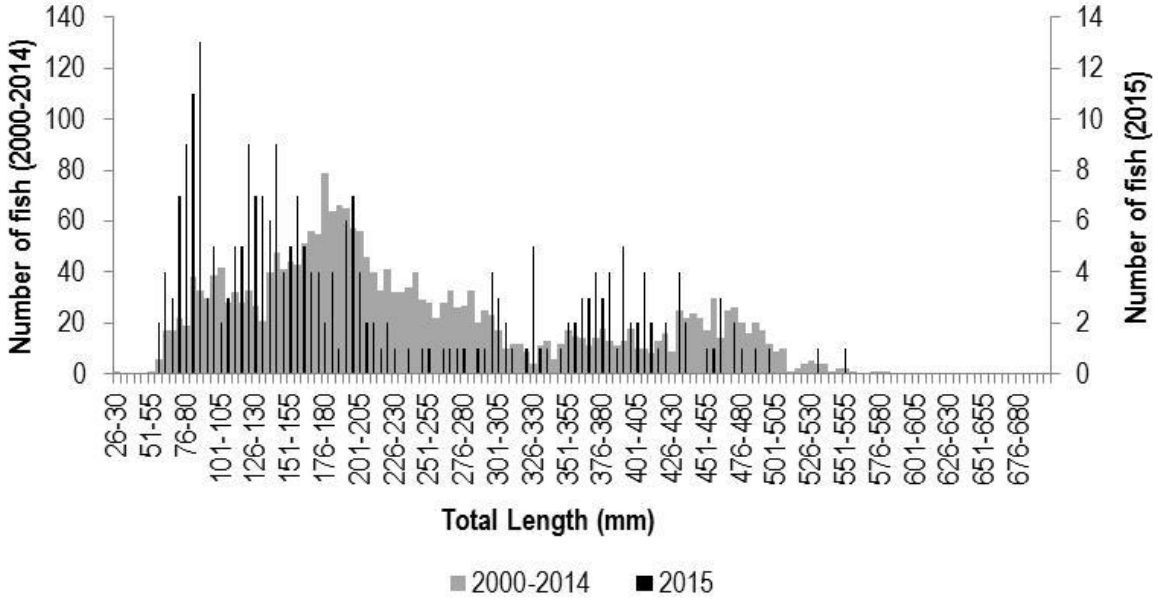


Figure 10. Length frequency distributions of flannelmouth suckers captured in the Little Colorado River (river km 0-13.57) during (A) spring 2001-2014 and 2015 and (B) fall 2000-2014 and 2015.

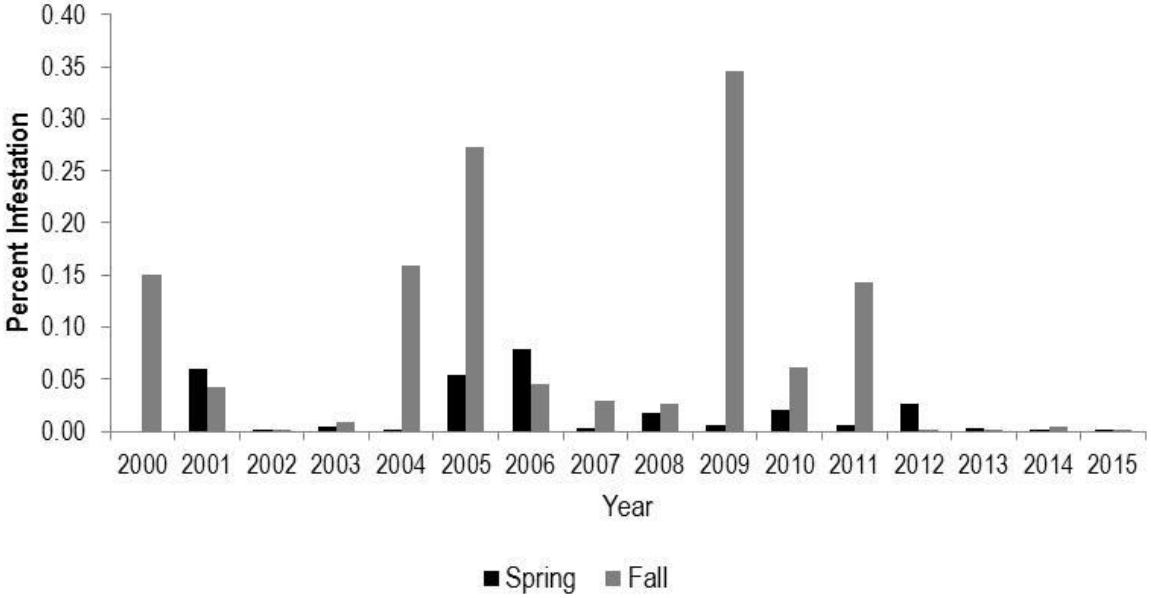
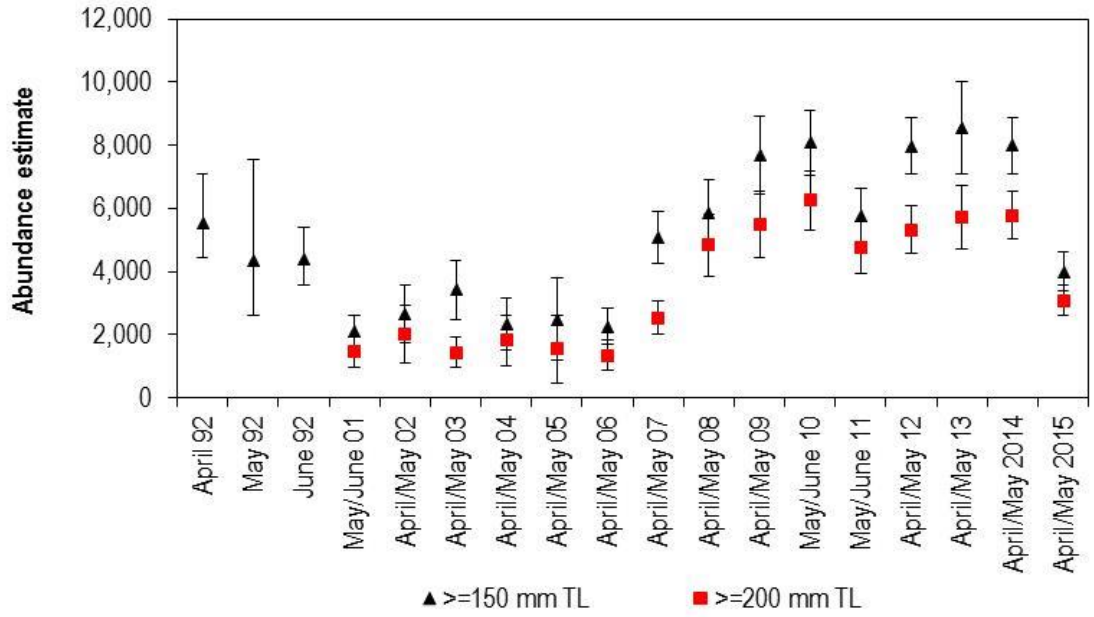


Figure 11. Percent occurrence of the external copepod parasite (*Lernaea cyprinacea*) on humpback chub in the Little Colorado River (river km 0-13.57), 2000-2015.

A.



B.

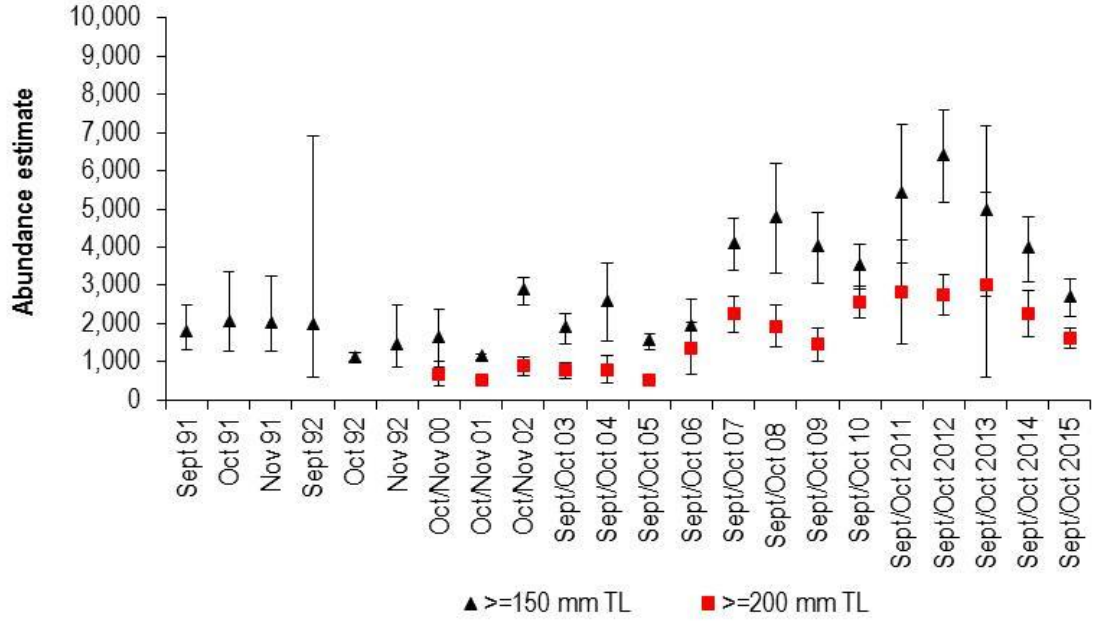


Figure 12. Chapman Petersen abundance estimates (±95% CI) of humpback chub ≥150 mm and ≥200 mm in the Little Colorado River during (A) spring (2001-2015) and (B) fall seasons (2000-2015). Closed spring and fall abundance estimates of humpback chub >150 mm in the Little Colorado River during 1991 and 1992 are from Douglas and Marsh (1996).

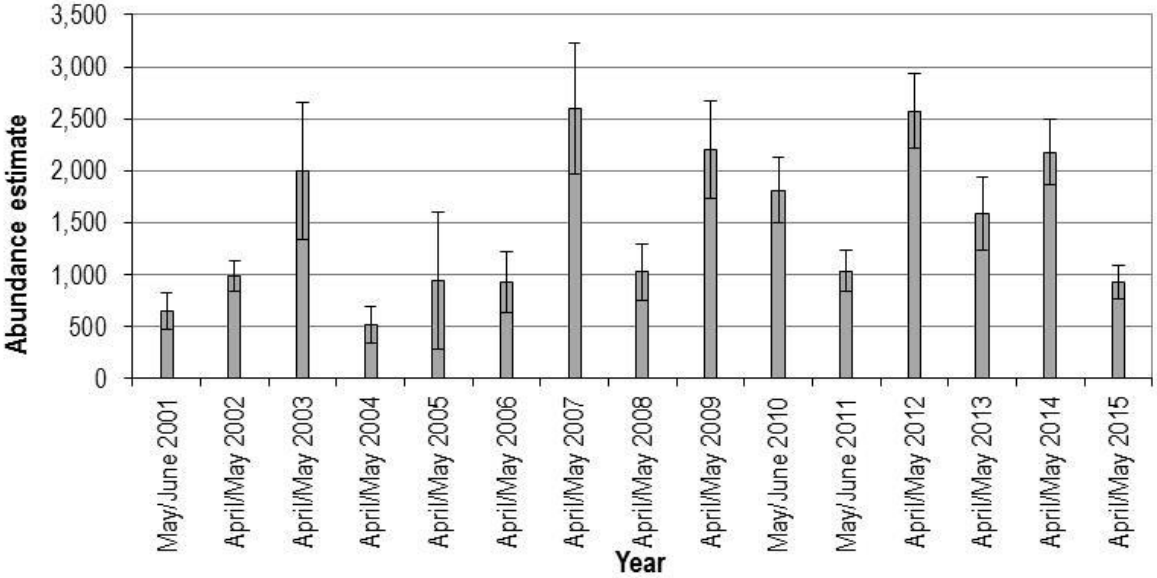
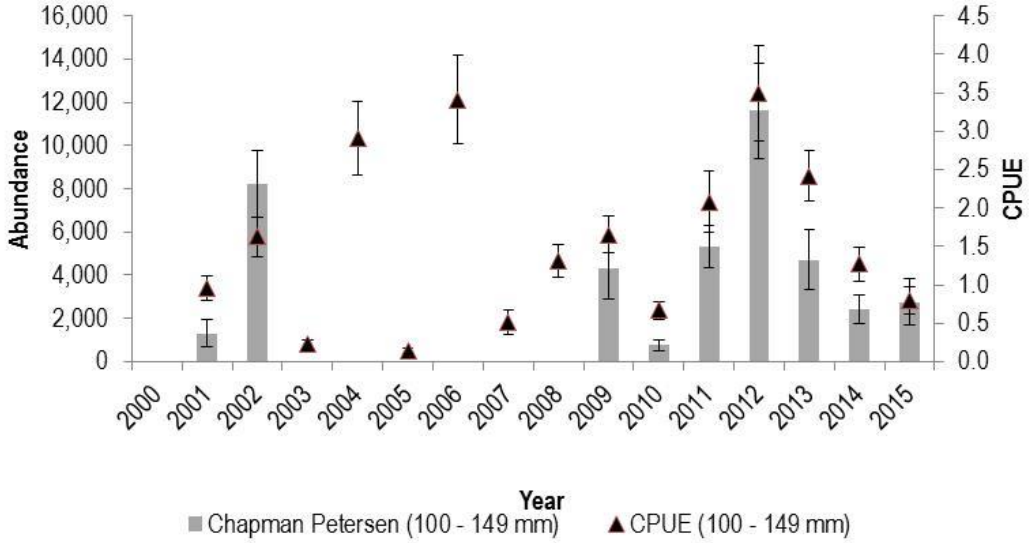


Figure 13. Spring abundance estimates (±95% CI) of humpback chub in the 150-199 mm size category; Little Colorado River, 2001-2015.

A.



B.

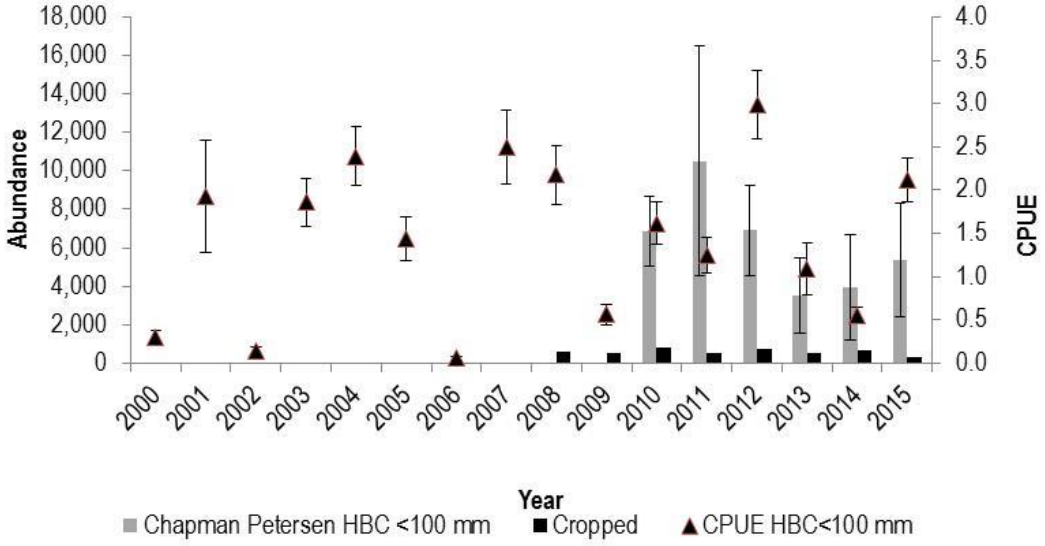


Figure 14. (A) Chapman Petersen abundance estimates (±95% CI) of humpback chub in the 100-149 mm size class during spring seasons (2001, 2002 and 2009-2015), and spring season catch per unit effort (CPUE, ±95% CI) of humpback chub in the 100-149 mm size class (2001-2015). (B) Chapman Petersen abundance estimates (±95% CI) of age 0 humpback chub (40-99 mm) during fall seasons (2010-2015) and fall season CPUEs ±95% CI of age 0 humpback chub (2000-2015). Also shown in (B) are the number age 0 humpback chub that have been cropped from the lower ~1.5 to 10 river km of the LCR since 2008 for Shinumo and Havasu creek translocation purposes or for establishment of a refuge at Southwestern Native Aquatic Research and Recovery Center. Note, in 2014 and 2015, larval age-0 chub (<30 mm) were collected for these activities.

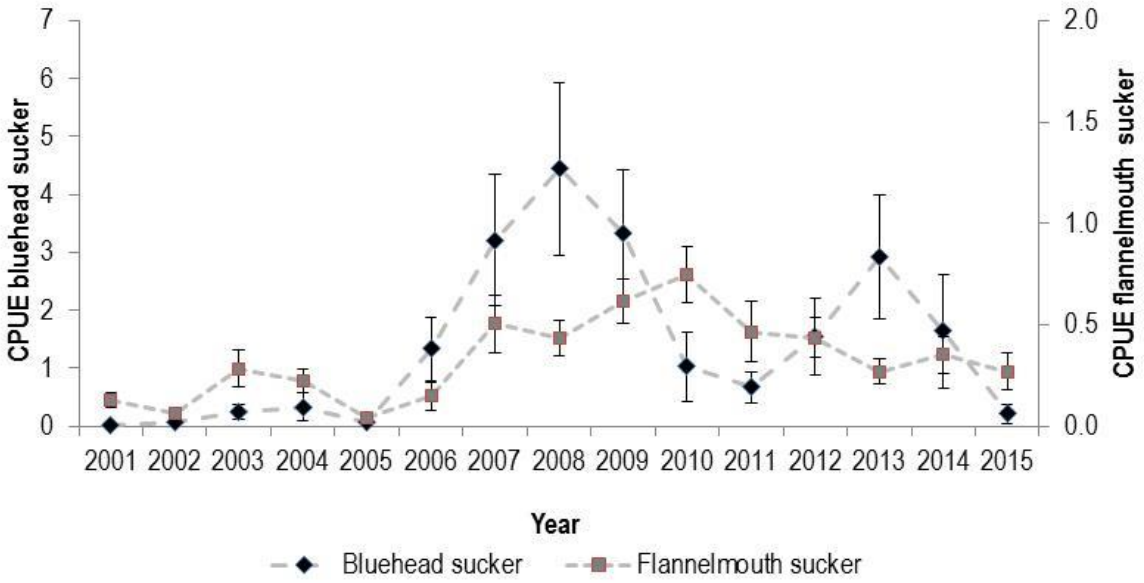
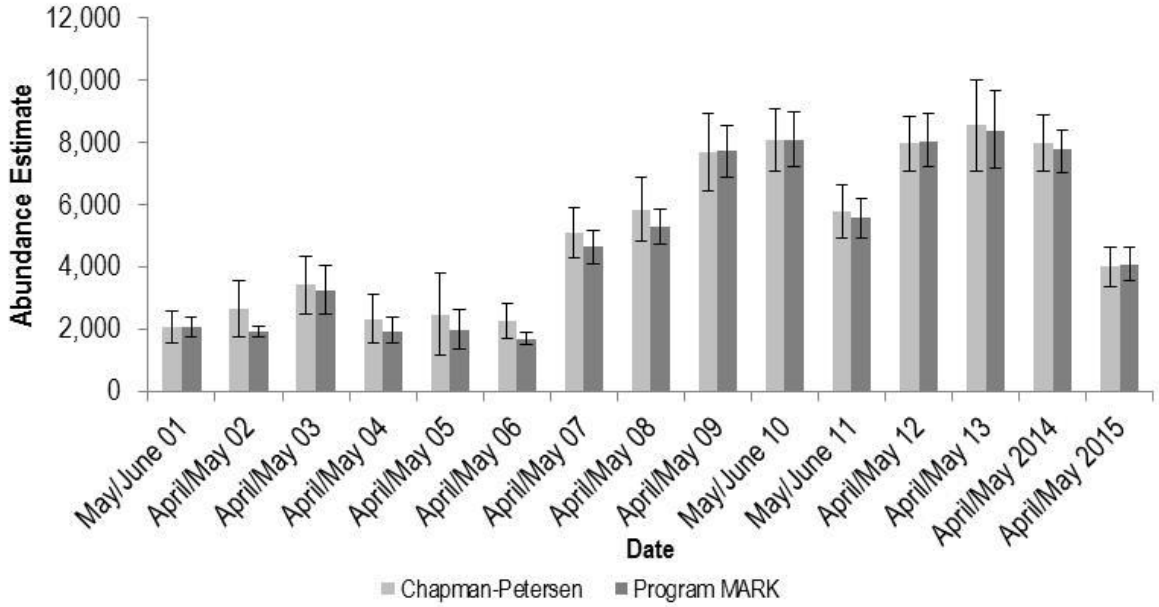


Figure 15. Relative abundance (catch per unit effort, CPUE ± 95% CI) of bluehead and flannelmouth sucker ≥150 mm during the spring season in the Little Colorado River (river km 0-13.57), 2001-2015.

A.



B.

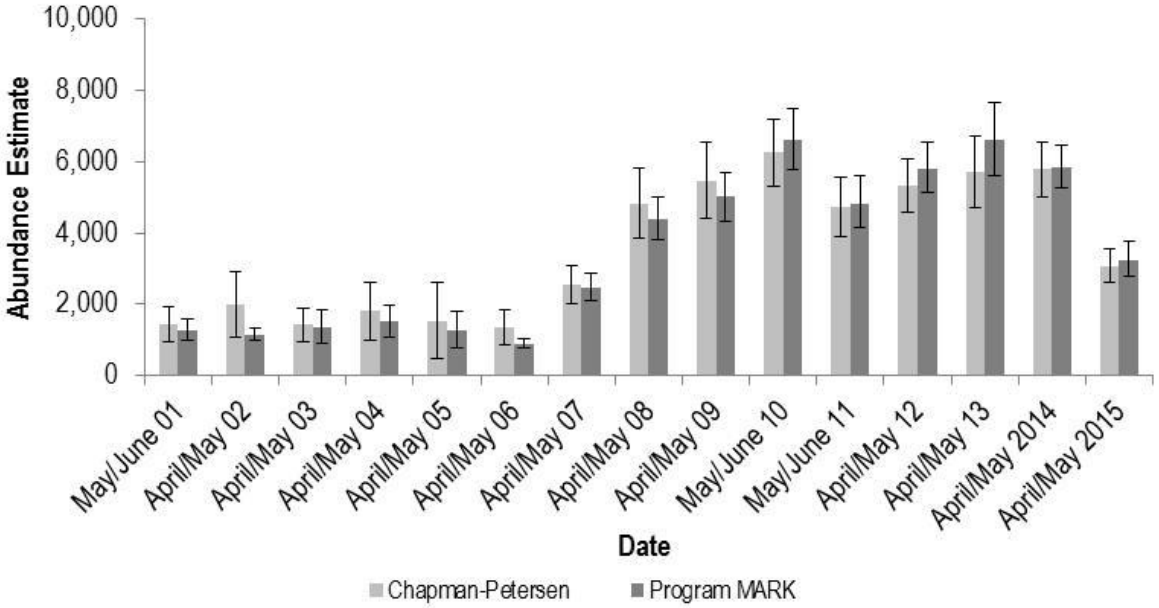
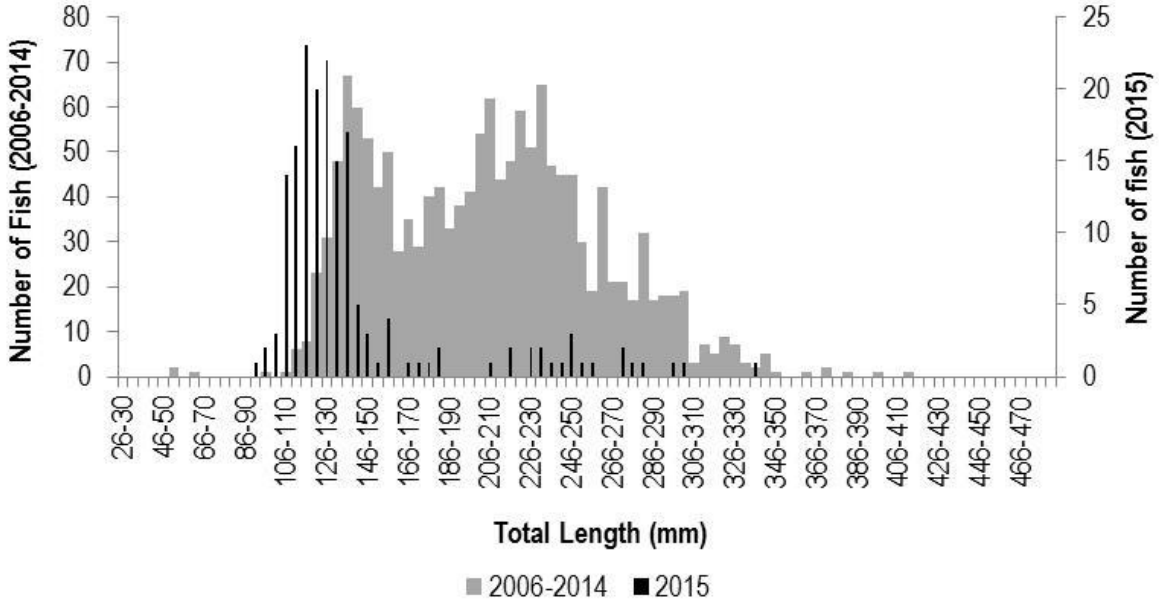


Figure 16. Abundance estimates (± 95% CI) of humpback chub ≥150 mm (panel A) and humpback chub ≥200 mm (panel B) generated with closed Chapman Petersen estimator and with robust design in Program MARK.

A.



B.

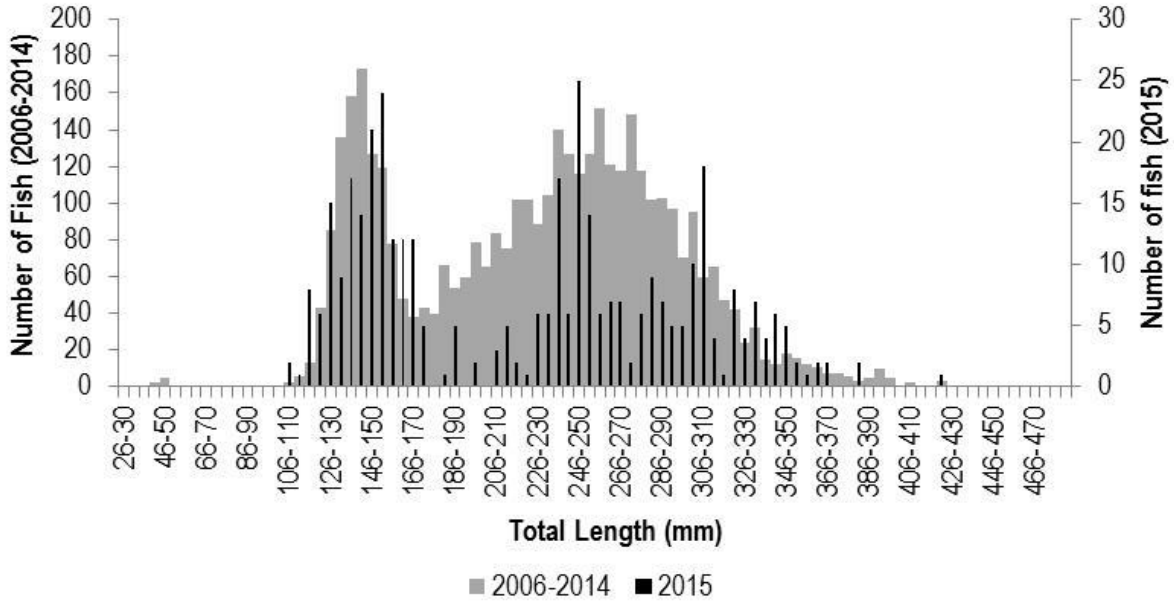
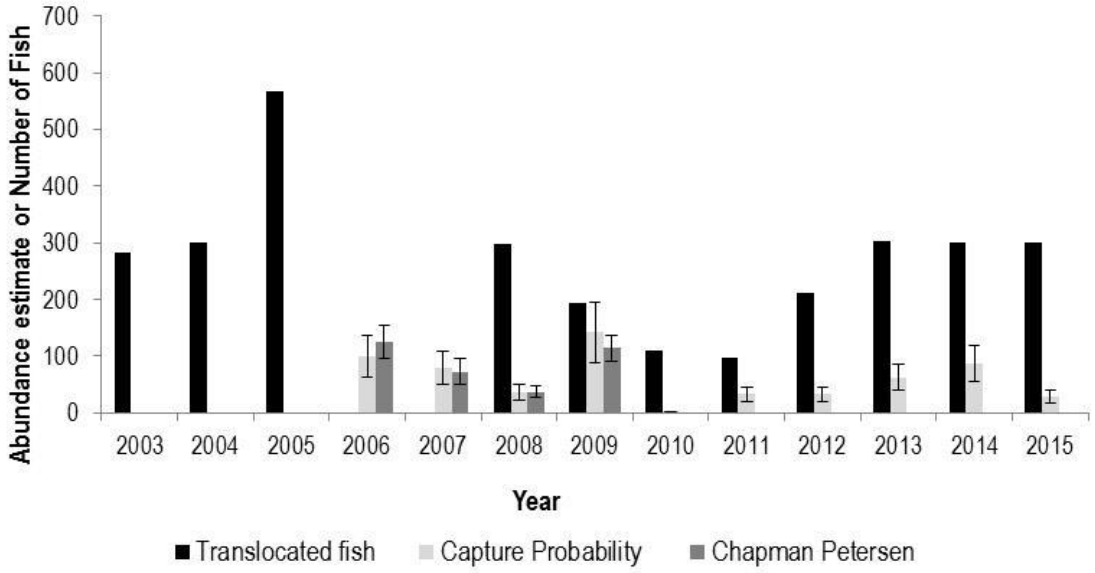


Figure 17. Length frequency distributions of unique humpback chub captured A) upstream of Chute Falls (river km [rkm] 14.1 to 17.7), and B) downstream of Chute Falls (rkm 13.57-14.1) during Chute Falls monitoring trips 2006-2014 and 2015; Little Colorado River.

A.



B.

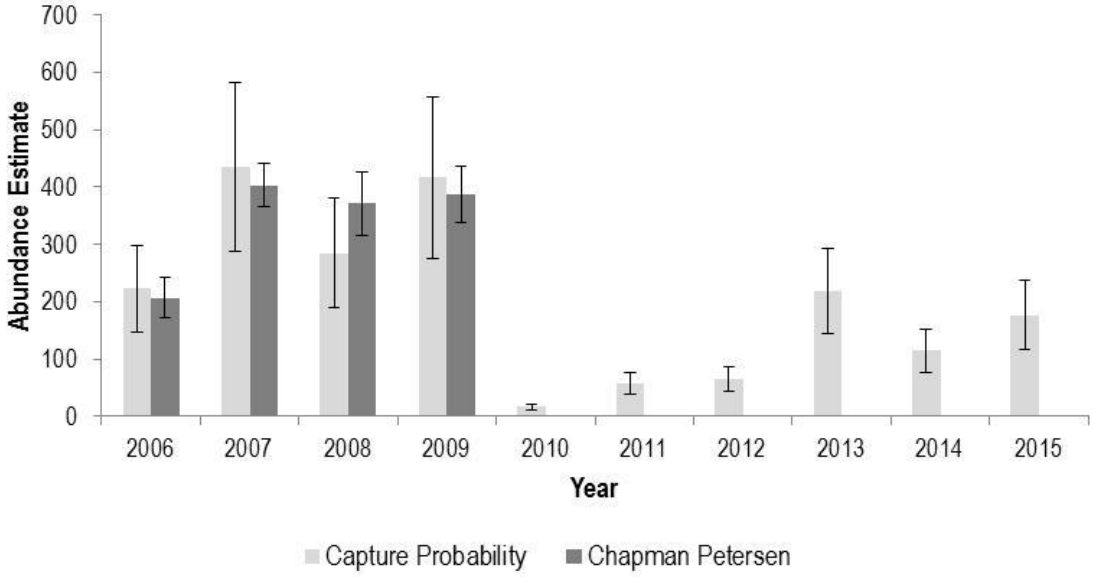


Figure 18. (A) Numbers of humpback chub that have been translocated upstream of Chute Falls since 2003 (black bars), and abundances (±95% CI) of adult humpback chub (≥ 200 mm) in upper reach upstream of Chute Falls (river km [rkm] 14.1 to 17.7) since summer 2006, and (B) abundances (±95% CI) of adult humpback chub in lower reach downstream of Chute Falls (rkm 13.57 – 14.1) since summer 2006. Note, abundances for both upper and lower reaches are shown as those estimated with Chapman Petersen mark-recapture (dark grey bars) and those estimated using capture probability data (light grey bars) derived from the 2006-2009 Chapman Petersen mark-recapture efforts.