POPULATION STATUS OF COLORADO PIKEMINNOW IN THE GREEN RIVER BASIN, UTAH AND COLORADO, 2006-2008

by

K. R. Bestgen, J. A. Hawkins, G. C. White,
C. D. Walford, P. Badame, and L. Monroe

Larval Fish Laboratory, Department of Fish, Wildlife, and Conservation Biology,
Colorado State University, Fort Collins, Colorado 80523 (KRB, JAH, CDW)

Department of Fish, Wildlife, and Conservation Biology, Colorado State University
Fort Collins Colorado 80523 (GCW)

Utah Division of Wildlife Resources, Moab, Utah (PB) 84532 and Vernal (LM,) Utah 84078

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EXECUTIVE SUMMARY

Multiple-pass, capture-recapture sampling was conducted in about 88% (819 river km) of warm water reaches of the Green River Basin, Utah and Colorado, to estimate demographic parameters for juvenile (< 400 mm TL), recruit (400 to 449 mm TL), and adult (≥ 450 mm TL) Colorado pikeminnow *Ptychocheilus lucius*. Three to six sampling passes were completed in each year for the Yampa River, middle Green River, White River, Desolation-Gray Canyon, and lower Green River reaches from 2006 to 2008. Parameter estimates derived from a Huggins robust-design multi-state model suggested about a 50% increase in abundance of adult Colorado pikeminnow throughout the Green River Basin over the study period, and about a 70% increase over 2003 estimates. Based on the trend in annual point estimates from 2006 to 2008, abundance increases were highest in Desolation-Gray Canyon, the middle Green River, and the White River, reaches which supported the most adult Colorado pikeminnow in the 2000 to 2003 period. Abundance of adult Colorado pikeminnow was stable and low in the Yampa River during the 2006 to 2008 period, but populations showed continued decline since 2003. Abundance of adult Colorado pikeminnow in the lower Green River declined over the study period, but abundance was higher than in the 2000 to 2003 period. Basinwide, estimates of adult Colorado pikeminnow abundance increased each year of the study, from 2,454 fish (95% CI = 2,190 to 3,185) in 2006, 2,718 (95% CI = 2,055 to 3,656) in 2007, and 3,672 (95% CI = 2,397 to 5,715) in 2008.

Low probabilities of capture during 2006 to 2008, particularly in 2008, produced estimates with wide and overlapping confidence intervals; lower numbers of captures and recaptures in the middle Green River, White River, and Desolation-Gray Canyon reaches in this study were likely caused by reduced sampling effort compared to the 2000 to 2003 period. However, multiple lines of evidence lend support to the notion of substantially increased

abundance of adult Colorado pikeminnow in the Green River Basin, particularly in the middle Green River and White River reaches. For example, abundance estimates for recruit-sized fish during 2006 to 2008 were relatively high in the Green River Basin, and averaged 22 % (17.4 to 30.4%) of estimated adult Colorado pikeminnow abundance; recruitment rates were more than sufficient to offset mortality rates of adults. High numbers of recruits were also evident in length frequency histograms of captured fish, particularly in the lower reaches of the Green River. Increased recruitment in 2006 to 2008, compared to the 2000 to 2003 period, was partly responsible for increased abundance of adult Colorado pikeminnow in the Green River Basin in 2006 to 2008. Most recruits likely originated from a large year class of age-0 Colorado pikeminnow produced in the lower Green River during 2000, a recruitment scenario which matches growth expectations over time.

Average annual survival rate estimated for all Colorado pikeminnow from 2006 to 2008 was 0.80 (95% CI 0.60 to 0.91), a substantial increase over the 0.65 rate for adults in the 2000 to 2003 period, and comparable to the 0.82 rate estimated for sub-adults and adults in the period 1991 to 1999 from Interagency Standardized Monitoring Program (ISMP) data. Increased survival rates from 2006 to 2008, along with increased recruitment, were important determinants of increased abundance of Colorado pikeminnow during this study. Increased survival of Colorado pikeminnow may be related to increased flows in the 2006 to 2008 period relative to the 2000 to 2003 period. Increased survival may also be due to ongoing non-native fish removal programs, although Colorado pikeminnow abundance did not increase in the Yampa River where intensive non-native fish removal was occurring.

We recommend continuing with the sampling protocol for Colorado pikeminnow in the Green River Basin as called for in the Recovery Goals. Increased sampling effort may be needed during the next abundance estimation sampling period in some areas to increase precision of estimates. Procedures to increase capture probabilities of Colorado pikeminnow in reaches where abundance estimates were relatively imprecise, such as increasing effort or adding alternative gears, should also be investigated. To assist managers tasked with conservation of Colorado pikeminnow, efforts should continue to obtain a better understanding of factors that influence adult survival rates and the link between abundance dynamics of early life stages of Colorado pikeminnow and recruitment to later life stages.

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INTRODUCTION

Demographic parameters that describe birth, movement, and mortality rates and population abundance are useful to understand dynamics and status of animal populations. Responses of those population parameters to biotic or abiotic drivers are of interest to ecologists attempting to understand the fundamental basis for population change. They are also useful to managers attempting to maintain or enhance abundance of free-ranging animal populations, particularly when the species of interest is rare and in need of conservation.

Endangered Colorado pikeminnow *Ptychocheilus lucius*, is a large, migratory, and predaceous cyprinid endemic to the Colorado River Basin. Once widespread and abundant throughout warm-water reaches of the basin, wild Colorado pikeminnow are presently restricted to the Upper Colorado River Basin in the Colorado and Green River sub-basins. Reasons for decline of Colorado pikeminnow center mainly on negative effects of habitat alteration from river regulation and non-native fishes (Minckley 1973; Carlson and Muth 1989; Tyus 1991). Over 140 main stem and tributary dams and reservoirs and several trans-basin water diversions provide agricultural and municipal water supplies to a rapidly expanding human population and have transformed water in the Colorado River Basin into one of the most tightly controlled supplies in the world (Iorns et al. 1965; Carlson and Muth 1989). Effects of main stem dams on biota have been damaging because they restrict movements of fishes such as Colorado pikeminnow, reduce seasonal variability of discharge, water temperature, and sediment load, and increase daily hydrograph variation (Vanicek and Kramer 1969; Holden 1979; Ward and Stanford 1979; Stanford et al. 1996; Poff et al. 1997). No fewer than 60 non-native fishes have been established in the Colorado River Basin, many of which prey upon or compete with various life stages of native species (Carlson and Muth 1989; Ruppert et al. 1993; Bestgen et al. 2006).

The outcome of these environmental and biotic changes for the highly endemic fish fauna of the Colorado River Basin has been dramatic: two of the 35 native species in the basin are extinct, an additional 18 are federally listed as threatened or endangered or are very rare, and most others are listed by one or more basin states as declining (Stanford and Ward 1986; Carlson and Muth 1989; Bezzerides and Bestgen 2002; Mueller and Marsh 2002). Colorado pikeminnow is federally listed as endangered under the Endangered Species Act of 1973, as amended (U. S. Fish and Wildlife Service 1974).

Colorado pikeminnow, endangered bonytail *Gila elegans*, humpback chub *Gila cypha*, and razorback sucker *Xyrauchen texanus* are the focal species of the Upper Colorado River Endangered Fish Recovery Program (Recovery Program) in the Upper Colorado River Basin (Wydoski and Hamill 1991). Recovery goals for Colorado pikeminnow provide criteria that must be achieved before downlisting or delisting can be considered (U.S. Fish and Wildlife Service 2002). The recovery criteria include demographic attributes that describe the required number of sub-basin populations and individuals (adults and juveniles) within each population, and recovery factor criteria that are directly linked to management actions and tasks needed to minimize or remove threats.

Maintenance of a metapopulation is central to Colorado pikeminnow recovery, and demographic criteria require “a genetically and demographically viable, self-sustaining population in the Green River sub-basin; and self-sustaining populations that meet or exceed estimated carrying capacity either in only the upper Colorado River sub-basin, or in both the upper Colorado River sub-basin and San Juan River sub-basin”. For consideration of downlisting or delisting, specific demographic criteria for the Green River sub-basin portion of the Colorado pikeminnow metapopulation require that, over the specified monitoring period, (1) trends in abundance estimates for adults (≥ 450-mm total length, TL) in both the middle and lower Green River do not decline significantly, (2) estimated mean recruitment of fish 400 to 449-mm TL (recruit-sized fish) equals or exceeds estimated mean annual adult mortality for the sub-basin, and (3) each abundance estimate for the sub-basin exceeds 2,600 adults (U.S. Fish and Wildlife Service 2002).

Sampling from 2006 to 2008 was undertaken as described in the Recovery Goals and consisted of three consecutive years of sampling for Colorado pikeminnow abundance estimation followed by two years with no specific Colorado pikeminnow sampling (U. S. Fish and Wildlife Service 2002). Our goal was to obtain accurate and precise abundance and survival estimates for Colorado pikeminnow in the Green River Basin. Study objectives listed for the Green River abundance estimates to achieve that goal were summarized as follows:

1. Complete three or more sampling passes through the study area to capture recruit-sized and adult Colorado pikeminnow;
2. Obtain highest possible rates of capture of Colorado pikeminnow within concentration habitats and maximize number of individuals marked on each sampling occasion; and
3. Calculate estimates of probability of capture and abundance for Colorado pikeminnow in each reach and for the entire study area.

This report describes the second major effort to quantify abundance, survival rates, recruitment, and population trends for Colorado pikeminnow in the Green River Basin based on sampling conducted from 2006 to 2008.

Status and natural history of Colorado pikeminnow.—Abundance of Colorado pikeminnow varies in the three occupied sub-basins of the Upper Colorado River Basin. The wild population in the San Juan River sub-basin, which is isolated from the remainder of the upper Colorado River Basin by Lake Powell Reservoir, is relatively small and may be extirpated (Platania et al. 1991, Holden 2000). In the Colorado River sub-basin, abundance estimates for Colorado pikeminnow were conducted from 1991 to 1994 and 1998 to 2000 using multiple-pass capture-recapture sampling. Abundance estimates for the 278-river km (RK) reach from 1991 to 1994 were variable among years but averaged about 600 sub-adult and adult fish (Osmundson and Burnham 1998). Estimates conducted from 1998 to 2000 suggested population abundance increased to about 750 sub-adult and adult fish (Osmundson 2002). Subsequent sampling and abundance estimation suggested that numbers of Colorado pikeminnow in the Colorado River continued to increase, as abundance of adults in the 1992 to 2005 period increased from about 200 to nearly 900 adult fish (Osmundson and White 2009).

Sampling in the beginning of the 2000 to 2003 period showed that populations of Colorado pikeminnow exceeded the recovery goal abundance criterion, with an estimated population of nearly 4,100 adults in 2000 (Bestgen et al. 2005; 2007). However, by 2003, population abundance declined to about 2,150 adults, a 48% decline. Main reasons for the decline were low recruitment of young fish after 1993, and reduced survival of adults. Reductions were most severe in the middle Green River (59%) and the White River (63%), sub-basin segments which supported the largest number of Colorado pikeminnow in 2000.

Historically, Colorado pikeminnow achieved 1.8 m in length and 40 kg in weight (Jordan and Evermann 1896; Minkley 1973; Tyus 1991; Quartarone 1995), although the largest individual known since intensive sampling began in the late 1970's was 1,240-mm TL (Bestgen et al. 2007). Large individuals may be 35 to 50 years old, and were very slow-growing, based on average growth rates of 10 mm/yr or less for recaptured individuals (Osmundson et al. 1997). Sexual maturity is not reached until five to seven years old at a length of 450 to 550-mm TL

(Vanicek and Kramer 1969; Osmundson et al. 1997; Osmundson and Burnham 1998; Osmundson 2006).

In the Green River Basin, adults migrate to two main spawning areas in late spring when snow-melt runoff subsides and water temperatures warm (Tyus 1990; Irving and Modde 2000). Migrations up to 745-RK round-trip to and from spawning areas have been documented by radio-tracking adults in spring and summer, and those fish often return to established home ranges (Tyus 1990; Irving and Modde 2000). Colorado pikeminnow in the Colorado River are much less mobile during the reproductive season and make only local movements to spawning areas (McAda and Kaeding 1991). Colorado pikeminnow typically began spawning around the summer solstice, when flows decline to near base level and water temperatures range from 16 to 22°C (Haynes et al. 1984; Nesler et al. 1988; Tyus 1991; Bestgen et al. 1998). Eggs are deposited over geomorphically complex riffle habitat and embryos hatch within four to seven days at water temperatures of 18 to 26°C (Hamman 1981; Marsh 1985; Tyus 1990; Harvey et al.1993; Bestgen and Williams 1994). About five to nine days later, emerging larvae are transported downstream 40 to 200-RK or more to alluvial river reaches, where they rear in low-velocity shoreline areas such as backwaters throughout the summer (Nesler et al. 1988; Tyus and Haines 1991; Bestgen 1996; Bestgen et al. 1998).

Variation in abundance of adult Colorado pikeminnow in the Colorado River was attributed to changes in abundance of young-of-year that reared mostly in the lower portion of the river (Osmundson et al. 1997; Osmundson and Burnham 1998). Recruits moved upriver as subadults and eventually established home ranges (Osmundson et al. 1998), apparently in response to a productivity gradient that increased upstream (Osmundson et al. 1998; Osmundson et al. 2002). In the Green River Basin, size-structure stratification of Colorado pikeminnow was similar to that the Colorado River, as most juveniles and recruits (400-449 mm TL) captured were found in downstream reaches (Osmundson et al. 1997; McAda 2002; Bestgen et al. 2007). Growth analysis of Colorado pikeminnow, based on capture-recapture data, has not been conducted in the Green River Basin, but movement and recruitment have been studied via transition rate estimation of marked animals (Bestgen et al. 2007). Those investigations revealed a pattern similar to that in the Colorado River because downstream areas such as the lower Green River served as nursery habitat for young Colorado pikeminnow. Those fish later moved upstream as large juveniles or recruits to the Desolation-Gray Canyon and middle Green reaches of the Green River, as well as the White and Yampa rivers.

Most Colorado pikeminnow inhabit rivers regulated by main stem dams. Thus, flow and water temperature management in the Green, Colorado, and San Juan River main stems have focused on restoring regimes that more closely resemble historical conditions (Poff et al. 1997; Muth et al. 2000). Release of propagated Colorado pikeminnow in the Colorado and Green River sub-basins has been limited because natural populations were thought sufficient to achieve recovery (Tyus 1991). Only in the San Juan River sub-basin has use of propagated fish been extensive. Another emphasis of the Recovery Program during this study was to reduce effects of non-native fishes, particularly large-bodied predaceous forms. Smallmouth bass *Micropterus dolomieu* and particularly northern pike *Esox lucius*, are formidable threats to multiple life-stages of Colorado pikeminnow including large adults, particularly in the Yampa River of the upper Green River Basin. Those threats have diminished somewhat due to reduced abundance of northern pike, particularly large individuals (Martin et al. draft report; Hawkins et al. 2009).

STUDY AREA

The Green River sub-basin (hereafter Green River Basin unless specified or comparisons among sub-basins are being made) drains high-elevation areas in southwestern Wyoming, northeastern Utah, and western Colorado (Figure 1). The study area focused mainly on warmwater river reaches designated as critical for recovery of Colorado pikeminnow (U. S. Fish and Wildlife Service 2002), which included the lowermost 193 RK of the Yampa River, the 555.6-RK reach of the Green River (including up to the lower 0.5 km of the Duchesne River) downstream of the confluence of the Yampa River to the Colorado River, and the lower 167.4 RK of the White River. River geomorphology in the study area consisted of relatively low gradient, depositional reaches in valleys interspersed with higher gradient, erosive, canyon-bound reaches. Alluvial river reaches were more braided, had mostly sand or gravel substrate, meandered to some extent within the floodplain, and were dominated by run and pool habitat. Canyon-bound river reaches were typically constrained, single-thread channels, with a mix of riffles, runs, and pools, and a mix of substrate that ranged from sand to boulder-sized particles. River flows were highest in spring and early summer during snow-melt runoff and declined to base level by mid-summer (Figure 2). Flows were relatively higher in the 2006 to 2008 period, particularly in 2008, compared to the drought period from 2000 to 2003.

The Green River Basin was divided into five main reaches: the Yampa and White rivers, and three reaches of the Green River. The Yampa River reach was 118-RK long and extended from RK 192 just downstream of Craig, CO, to RK 74 just upstream of Yampa Canyon; few Colorado pikeminnow have been documented upstream of that area (Holden and Stalnaker 1975, Finney 2006). The canyon-bound lower reach of the Yampa River (74 RK) was excluded mostly because few fish were thought to occur there outside of the spawning season, and also because logistical constraints prevented extensive sampling there (Holden and Stalnaker 1975). The sampled reach of the Yampa River flowed mostly through alluvial valleys but included Little Yampa Canyon in the upper portion of the study reach. The 5 RK-long Cross Mountain Canyon and the 3 RK-long Juniper Canyon were not sampled because they were inaccessible. The

Yampa River reach was sampled by personnel from the Larval Fish Laboratory, Colorado State University, and the Colorado Division of Wildlife.

The middle Green River study reach was 143-RK long and extended from RK 539.4 (16.2 RK downstream of the Yampa River confluence) downstream to just above Desolation Canyon at RK 396 (near the White River confluence). The reach was in an alluvial valley, with the exception of Split Mountain Canyon (RK 528.2 to 513.8), which was sampled infrequently. The 16.2 RK-long Whirlpool Canyon reach from the confluence of the Yampa River downstream to upper Island Park was also excluded from sampling. Most of the relatively short reaches within the study area that received only cursory sampling in this study historically held few Colorado pikeminnow (Holden and Stalnaker 1975). The middle Green River reach was sampled by the Utah Division of Wildlife Resources, Vernal, Utah.

The White River study reach was 167.4-RK long and extended from just below Taylor Draw Dam downstream to the confluence with the Green River. Although Colorado pikeminnow historically occurred above Taylor Draw Dam, few or none are thought to occupy that reach since the reservoir began filling in 1984 (Martinez 1986; Martinez et al. 1994). The White River winds through alluvial valleys interspersed with short bluffs. The U. S. Fish and Wildlife Service, Vernal, Utah, was responsible for sampling the White River and the Desolation-Gray Canyon reach of the Green River (below).

The Desolation-Gray Canyon Green River reach was 189.8-RK long and extended from the head of Desolation Canyon at RK 395.9 downstream to near the lower end of Gray Canyon at RK 206.1. That reach was mostly canyon-bound and geomorphically constrained. The reach between RK 206.1 (at Tusher Diversion) and 193.2 was usually not sampled because of logistical constraints.

The lower Green River reach was 193.2-RK long and extended from near the town of Green River downstream to the confluence with the Colorado River (RK 0), and passed through the low-gradient Labyrinth and Stillwater canyons. The Utah Division of Wildlife Resources, Moab, Utah, was responsible for sampling there.

During low flow periods in all reaches, low-velocity habitat was near shore, in small eddies and pools, and behind or adjacent to mid-channel sand or gravel bars. When flows were elevated by snow-melt runoff in spring, main channel velocities were swifter, and low-velocity areas were more limited, often consisting of near shore areas, flooded tributary mouths and canyon washes, and a few large backwaters.

Additional areas not sampled that may harbor Colorado pikeminnow included smaller tributaries such as the Price, San Rafael, upper Duchesne, and Little Snake rivers (McAda et al. 1980; Wick et al. 1991; Hawkins et al. 1996; Cavalli 1999; Muth et al. 2000). Adult Colorado pikeminnow in those areas were thought relatively rare compared to larger main stem reaches because habitat size was small, or because use occurred in seasons outside of our sampling period. The Green River in Lodore Canyon upstream of the Yampa River was also known to support adult Colorado pikeminnow (Bestgen and Crist 2000; Kitcheyan and Montagne 2005, Bestgen et al. 2006). Supplemental sampling conducted there and in other reaches in some years when abundance estimation sampling was being conducted will be discussed.

METHODS

Sampling and fish handling .—Sampling for abundance estimation was conducted in spring in each year from 2006 to 2008 in each of the five study reaches. We used Pollock's robust design to allocate sampling effort (Pollock 1982; Pollock et al. 1990). This was accomplished by conducting at least three short-term sampling occasions (usually 7 to 11 days each) through each reach at approximately the same time in spring of each year, and repeating that design over the remainder of the study years. Short-term sampling occasions were conducted in spring between the times when ice off occurred and prior to or during spring runoff before Colorado pikeminnow spawning migrations began. Using hard-bottomed boat (Yampa, middle Green, and lower Green reaches) or inflatable raft-based (White River and Desolation-Gray Canyon Green River reaches) electrofishing as the standard technique, sampling during each occasion began at the top of each reach and proceeded downstream. Electrofishing units were either pulsed-DC Coffelt or Smith-Root types, with one or two anode booms with spheres. Two boats were typically used on each sampling occasion, one on each shore, and one or two netters captured stunned Colorado pikeminnow. All near shore habitat was electrofished.

Approximately 7 to 10 d elapsed between short-term sampling occasions in each reach to allow for sufficient mixing of marked and unmarked fish. A block-and-shock technique was sometimes used in the Yampa River, where a large, nearshore, quiet-water area (e.g., backwater, flooded wash) was isolated from the main channel with a trammel net and electrofishing commenced inside the block net. Colorado pikeminnow were captured by netters or in trammel nets as they attempted to leave the backwater for the main channel. Use of these techniques was limited in most years and reaches.

In most reaches, sampling focused only on Colorado pikeminnow, although other endangered fishes, and some non-native species such as northern pike or smallmouth bass, were also captured. Colorado pikeminnow were measured (TL, nearest mm), weighed (nearest g), scanned for the presence of a PIT tag, and unmarked fish (>150 mm) received a PIT tag inserted into the body cavity just posterior to the pelvic girdle. The initial capture and release location (nearest 0.15 RK) was determined from river maps and a Global Positioning System unit and all Colorado pikeminnow were released within 0.15 km of their capture location.

Additional data utilized in this study was from an Interagency Standardized Monitoring Program (ISMP, McAda 2002). The ISMP sampled adult and sub-adult Colorado pikeminnow from ten reaches (8 to 25 RK-long) of the Green River Basin, five from the Green River (RK 539.4 to 526.5, 513.6 to 483, 418.6 to 394.5, 185.2 to 154.6, 90 to 64), three from the Yampa River (RK 167.4 to 153, 128.8 to 112.7, 86.9 to 78.9), and two from the White River (RK 169.1 to 153, 33.8 to 0). The reaches totaled about 23% of critical habitat of Colorado pikeminnow in the Green River Basin and were chosen because they were accessible by a flat-bottom boat and represented reaches known to support Colorado pikeminnow. Sampling was conducted during spring each year from 1986 to 2000 when water levels were rising due to snow-melt runoff but were usually below peak runoff levels. A single electrofishing sampling pass was made down each shoreline, stunned Colorado pikeminnow were captured with dipnets, and electrofishing time was recorded. Captured fish were tagged, measured, and released with a protocol similar to that described above for abundance estimation sampling. Sampling effort was stratified among four to eight sub-reaches of each river reach and catch per unit effort statistics were calculated for each sub-reach sample. Variances and standard errors for catch/effort indices were calculated based on those samples. Prior to 1991, Colorado pikeminnow were tagged with Carlin dangler tags, which were presumed subject to relatively high tag loss. Therefore, data from 1986 to 1990 was not included in analyses presented here. After 1990, tag loss was considered negligible because all Colorado pikeminnow were PIT-tagged.

To facilitate comparisons between abundance estimation sampling and historical ISMP sampling, during 2001 to 2003 and 2006 to 2008 we designated a sampling pass as one that conformed to when ISMP sampling was previously conducted. We calculated catch/effort statistics for Colorado pikeminnow to examine trends from 1991 to 2008, exclusive of 2004 and

2005. No ISMP sampling was conducted in the Desolation-Gray Canyon reach of the Green River, so no comparisons were available for that reach.

Robust design for capture-recapture studies.—Robust-design sampling and analysis capitalizes on the strengths of closed and open population models used to estimate demographic parameters (Pollock 1982; Pollock et al. 1990). Sampling occasions completed at closely-spaced intervals (e.g. weeks) were used to estimate population size using closed population models. That level of sampling completed in two or more consecutive years allowed for estimation of population size of adults, recruits, and juveniles and survival rates between years. In some reaches and years, data from two sample passes made close in time were combined to achieve three passes of sampling data and maintain symmetry of the capture histories and enhance model fitting. Combining data was done after analyses showed that only a couple of fish (<1%) moved between sampling reaches between passes within a year. Thus, potential confounding due to fish movement to spawning areas was minimized.

Statistical modeling.—The combined robust-design (Kendall 1999; Kendall et al. 1995; 1997) multi-state (Brownie et al. 1993; Hestbeck et al. 1991) model in Program MARK (White and Burnham 1999) was used to estimate survival in year t (S_t), probability of transition between reach i and j (ψ_{ij}), capture-recapture probabilities within reach i (reach is the state) for each year t and sampling pass k (p_{itk}), and Colorado pikeminnow adult, recruit, and juvenile abundance in each reach i for each year t (N_{it}). Abundance of adult, recruit, and juvenile Colorado pikeminnow in each reach was estimated with the Huggins estimator (Sananathan 1972; Huggins 1989; Alho 1990; Huggins1991). Abundance estimates from the Huggins model were derived by the equation:

$$\hat{N} = \sum_{i=1}^{M_{t+1}} (1/p_i^*),$$

where M_{t+1} was the number of unique animals captured over all short-term sampling passes, and

$$p_i^* = 1 - \prod_{j=1}^{t} (1 - p_{ji}),$$

and p_{ji} was the probability of initial capture within the sampling season. Animals in the population that were never captured have capture probability $(1 - p)$ but were removed from the likelihood. The new multinomial distribution still summed to one, and because only fish that were captured were included in the likelihood, individual covariates (here TL or polynomials for such) were incorporated to estimate p, ψ, and S, where appropriate. Information for the p^* estimates are from both the closed-capture portion of the likelihood used for abundance estimation and the Cormack-Jolly-Seber (CJS) component of the model used to estimate annual survival rates. With the information provided about p^* from the CJS portion of the likelihood, the individual p's per pass within the annual sampling period are identifiable based on the numbers of fish initially captured during each sampling pass within a year. Thus, we could calculate abundance estimates for river reaches and years where no fish were recaptured between passes within a single year if such was needed (e.g., Yampa River 2007, Bestgen et al. 2007). In addition to the CJS contribution to p^*, recaptures of fish in reaches between passes within a single year provided more efficient estimates of abundance. River-wide abundance estimates were obtained by summing the separate reach estimates in each year. Standard errors for river-wide estimates were obtained from the variance-covariance matrix of the likelihood from program MARK. We used confidence intervals and their overlap among pairs of estimates to assess significance; high precision estimates had CV's < 10%, moderate precision estimates had CV's of 10-25%, and low precision estimates had CV's > 25%.

Unlike our previous analysis where TL at first capture was held constant (Bestgen et al. 2007), we used a von Bertalanffy function to estimate fish growth between years after first capture. The function was based on Green River length data collected from 2006 to 2008. To use length as a covariate, lengths for each captured fish were needed for each year of the study. However, because individual fish were not captured in each sampling year, their lengths in years when not captured had to be estimated by interpolation or extrapolation. For fish that were captured more than once within a year, the mean of the measured lengths was used for that year. The von Bertalanffy model was used to estimate missing lengths following Osmundson and White (2009). To fit the von Bertalanffy model, a difference equation was assumed, following generally the procedures of White and Brisbin (1980). For the von Bertalanffy model:

$$L_{i+1} = (t_{i+1} - t_i)k(L_\infty - L_i) + L_i,$$

where L_i is the length at year i, t_i is the actual year of the observation, k is the von Bertalanffy growth coefficient, and L_∞ is the asymptotic length. To estimate the two parameters, the equation was implemented recursively, with $t_{i+1} - t_i = 1$. So, to predict a length for a fish not captured in 2008 from a length from the same fish in 2006, for example, the equation was first applied with the observed length from 2006 to predict a 2007 length. The predicted length in 2007 was then used to predict a length in 2008. The model was thus used to produce individual covariate values of length for each year. Using these lengths, an input file for Program MARK was created. Paired analyses, one using von Bertalanffy size adjustments and one with fish length held constant as in previous work (Bestgen et al. 2007), showed minimal variation in abundance estimates across years and similar trends over time. However, use of the more complicated von Bertalanffy growth estimation approach was justified because it was more realistic. It is important to test for the effect of the covariate TL in abundance or survival estimation modeling because of the potential effects of fish size on probabilities of capture. Abundance estimators such as those in program CAPTURE (White et al. 1982) do not have the capability to use individual covariates because the likelihood includes probabilities for animals that are never captured, so the covariates are unknown.

Selection between models was performed with information-theoretic procedures (Akaike's Information Criterion adjusted for small sample size [AIC_c], Burnham and Anderson 1998). Previous analyses demonstrated that capture probabilities were equal to recapture probabilities among the short-term and annual sampling occasions (i.e., $p_k = c_k$), so heterogeneity due to capture effects was assumed minimal (Bestgen et al. 2007). We initially tested for differences in rates of capture and recapture in various models to evaluate if behavior effects (e.g., fish avoidance of boats) were influencing recapture rates. We also fit mixture models of Pledger (2000) in a preliminary analysis (not reported), which were designed to incorporate heterogeneity caused by differing probabilities of capture for different segments of the population. Similar to our previous study, we did not consider these models further because higher numbers of recapture occasions (e.g., minimum of 5) were needed to detect differences in capture probabilities among groups of animals in the same population. We also attempted to explain much individual heterogeneity by including the covariate TL in other analyses, so heterogeneity effects were presumed minimized.

The robust-design multi-state models in program MARK (White and Burnham 1999) were used to estimate reach-specific apparent survival for Colorado pikeminnow captured in the Green River Basin. Apparent survival rates (S) were the joint probability of a fish surviving from one year to the next and remaining in the population available for capture. In other words, estimates from these models do not distinguish a fish that died in the study area from one that survived and moved from the study reach to an unsampled reach. Because of that, survival rates obtained from ISMP data were likely conservative (low) because capture data were gathered from reaches that represent only about 23% of the basin. Thus, Colorado pikeminnow that moved out of reaches sampled by ISMP and were never recaptured would be treated as mortalities. These models also could not distinguish if fish that were previously captured avoided subsequent recapture by some behavioral change mechanism. Such a behavioral change would result in reduced capture probability and lower apparent survival rates. Assuming that no behavioral change occurred, survival rates obtained from 2000 to 2003 and 2006 to 2008 during abundance estimation sampling likely approached true survival, because nearly all the Green River Basin habitat where Colorado pikeminnow likely occurred was sampled. The goal of survival analyses was to determine if a composite, and perhaps conservative, survival rate from 1991 to 1999 was different than survival in the 2000 to 2003 period, and the 2006 to 2008 period. Differences in survival rates over time may be useful to interpret trends in population abundance. The AIC_c (AIC for small samples) was used as a guide in model selection. We were careful to guard against overfitting models with the sometimes sparse data available for some reaches or rivers and focused on those that gave reasonable estimates of parameters that were critical to understanding the status of Colorado pikeminnow in the Green River Basin.

To call attention to the trends in reach-specific and specific population abundances of different life stages of Colorado pikeminnow, we fit regression relationships of abundance as a function of time, and included intercept-only models, as well as those with linear (T) and quadratic (T^2) terms to describe changes in abundance over time. We used all estimates available from reaches in the study periods 2000 to 2003 and 2006 to 2008 to analyze trends. Support for the intercept-only model would indicate no substantial change (minimal slope, stable population) in abundance over time, a linear model would describe a population relationship as increasing or decreasing in a substantial but straight line manner, and a quadratic model would describe changes in population abundance (positive, negative, or both) that vary among the time periods. For example, a negative linear term in a quadratic model might describe a declining population in the 2000 to 2003 period, and a positive quadratic term may indicate a substantial population increase in the 2006 to 2008 period. However, because these estimates have sampling covariances among them induced by common parameters across reaches and size classes, we performed weighted regression (Proc IML, SAS Institute, Cary, NC) to obtain best inferences regarding trends in population abundance over time. We accomplished this by using estimates from the variance-covariance matrices produced by program MARK as weights for abundance estimates from 2000 to 2003 data, as well as those from 2006 to 2008 data, and regressed abundance as a function of the intercept, time, and time squared. This analysis is more conservative (fewer significant relationships) than simply regressing the abundance values over time as if no uncertainty existed. We also fit weighted regression models for recruits and juveniles and simply reported weights in the text. Relationships were plotted for abundance as a function of time and may show a positive or negative trend, even if model weights indicated an intercept-only (stable population) model was most appropriate. This was done to show the general trajectory in estimates for which few and often, highly variable data were often available.

We used AIC_c model selection and model weights to assess the level of support for intercept only, linear, or quadratic models used to describe Colorado pikeminnow abundance trends over time. Model weights were proportions between 0 and 1, with weights of the competing intercept-only, linear, or quadratic models summing to 1, and represented the likelihood (probability) of a certain model among the three types, given the data. This is a departure from the typical approach where model selection is based on decisions regarding inclusion or exclusion of model explanatory variables using subjective alpha-levels to specify Type I error rates (e.g., alpha $\leq$ 0.05). It is also a departure from typical approaches because more than one model is considered as a candidate to explain the data. Fitting of several models better reflected the uncertainty in abundance estimates and their trend over time compared to a single model, and allowed comparison of the robustness of conclusions regarding trends in an objective manner.

RESULTS

River reach abundance estimates.—We captured a total of 2,221 Colorado pikeminnow in the 45 sampling occasions (3 passes per year, 5 reaches, 3 years) during 2006 to 2008 (Appendices I-XIII). In comparison, a total of 3,800 were captured in the period 2000 to 2003. Of the 2,221, 93% were captured in only one year and not seen in any other year, 6% were captured in each of two years, and $< 0.5\%$ ($n = 6$) were captured in all three years (Table 1). We estimated abundance of Colorado pikeminnow adults, recruits, and juveniles in each of the five river reaches of the Green River Basin for each sampling year to determine spatial abundance patterns and temporal dynamics. A set of 21 models was fit to the data to examine the importance of year-specific apparent survival (S), reach transition probabilities (ψ, probability of a fish moving from one reach to another), and capture probabilities (p's, Table 2). The top model in the set of 21 contained 23% of the AIC_c weight and had 66 estimable parameters, the simplest among the top six models. The five other competing models (numbered 2–6) each contained 9 to 12% of the total weight and were slightly more complex (67 to 71 estimable parameters) than the top model.

The top model did not include a TL effect with any parameter, while the next five models had TL as a linear or quadratic term with survival or probability of capture. No length effects were well estimated, and confidence intervals sometimes overlapped zero. For example, model 3 had linear (positive) and quadratic (negative) terms for TL in the probabilities of capture that resulted in a bell-shaped curve with an asymptote near the average length fish, similar to that observed for the 2000 to 2003 data set, but each had a small statistical effect. Reporting of specific parameter estimates (*S*, ψ, *p*), from the top model were used to illustrate general trends. That model had a single survival estimate (*S*) over all reaches and years, 20 estimates of ψ (one each for fish in a given reach moving to any of the other four reaches for each of five reaches, no year effect), and 45 estimates of *p* (one for each year, reach and pass combination, 3 x 5 x 3, respectively, = 45; 66 total parameters). The estimating model used for the 2000 to 2003 data set was more complicated with 81 parameters, including linear, quadratic, and cubic effects of TL to model a single *S* over the 2000 to 2003 period (three length effects, one *S*, four total parameters), a linear effect of TL to model ψ (a single length effect plus 20 ψ's, one each for fish in a given reach moving to any of the other four reaches for each of five reaches; 21 total parameters), and quadratic effects of TL to model *p*'s (two length effects, plus those for five reaches, three sampling passes per year, three or four sampling years depending on the reach, 56 parameters, the top model weight was 0.35, or 35%). Absence of important length effects for the 2006 to 2008 analysis was perhaps not surprising given that the data were sparse relative to the period 2000 to 2003 and that the sampling period was one year shorter.

Based on trends in point estimates over the period 2006 to 2008, abundance of adult Colorado pikeminnow showed an apparent increase in three river reaches (middle Green, White River, and Desolation-Gray Canyon reaches), was stable but low in another (Yampa River), and declined in one reach (lower Green River) of the Green River Basin over the period 2006 to 2008 (Tables 3–7, Figures 3–7).

Abundance of adult Colorado pikeminnow in the Yampa River reach was the lowest observed among the five study reaches (Table 3, Figure 3). Abundance estimates were similar across all years and ranged from 140 (SE = 52) fish in 2008 to 153 (SE = 66) fish in 2007. Overlapping confidence intervals among pairs of point estimates suggested none were statistically significant. Yampa River estimates had relatively low precision (wide confidence intervals, CV's of 37 to 51%; recall that high precision = CV < 10%, moderate precision = CV

10-25%, low precision = CV > 25%) owing to the low number of fish captured and recaptured. Probabilities of capture were also very low in most years, especially 2008 (Table 8). No estimate of Colorado pikeminnow recruit or juvenile abundance was available in any year for the Yampa River, because few or no fish < 450 mm TL in those years.

Population trend analysis via weighted regression of abundance estimates as a function of time showed a continued decline in the Yampa River population of adult Colorado pikeminnow over the two sampling periods (2000–2003, 2006–2008), in spite of apparent stabilization of estimates in the recent period (Table 9). Model weights suggested a linear model with a negative slope coefficient (declining population) had the most support (0.99, e.g., 99%); intercept only or quadratic models had little support. No trend analyses were conducted for recruit or juvenile fish because no abundance estimates were available.

Abundance of adult Colorado pikeminnow in the White River was higher than that observed in the Yampa River from 2006 to 2008 and estimates increased over time (Table 4, Figure 4). Estimated numbers of adult fish increased from 321 (SE = 83) in 2006, to 451 (SE = 95) in 2007, to 660 (SE = 224) in 2008, an increase of about 106% over the duration of the sampling period. Confidence intervals for abundance estimates in all years overlapped, due mostly to the low precision 2008 estimate. Numbers of unique animals captured varied widely from 55 in 2008 to 100 in 2006 (106 to 265 in 2000 to 2003). Adult pikeminnow abundance estimates in the White River abundance estimates had moderate to low precision, with CV's ranging from 21 to 34%.

Population trend analysis via weighted regression of White River adult pikeminnow abundance estimates over the two sampling periods (2000 to 2003, 2006 to 2008) showed most support for the quadratic model (0.52, Table 9). Model coefficients suggested a significant decline (large and negative linear coefficient relative to the standard error) in the White River population of adult Colorado pikeminnow in the 2000 to 2003 period followed by a significant increase (large and positive quadratic coefficient relative to the standard error) in the 2006 to 2008 period. There was also support for the intercept only model (0.40), but only low support (0.08) for the linear model which indicated a population decline (negative slope coefficient).

Number of Colorado pikeminnow recruits in the White River were variable during the study period and estimates ranged from 0 in 2006 to 88 (SE = 24) in 2007. Confidence intervals for abundance estimates of recruits present in the White River in 2007 and 2008 overlapped and CV's were relatively large, especially in 2008. Estimates over the two sampling periods (2000 to 2003, 2006 to 2008) showed a stable or slightly increased abundance of Colorado pikeminnow recruits in the White River (Figure 4). We did not perform weighted regression analysis of recruit abundance as a function of time because no recruits were captured in 2003 and 2006.

Number of juvenile Colorado pikeminnow in the White River increased over the study period from 0 in 2006 to 83 (SE = 40) in 2008. Confidence intervals for abundance estimates of juveniles present in the White River in 2007 and 2008 just overlapped and had CV's of 55% in 2007 and 48% in 2008. Juvenile Colorado pikeminnow in the White River showed a weak but increasing trend over the period 2006 to 2008 (Figure 4); juvenile abundance estimates were not available for any reach in the 2000 to 2003 period so were not compared here.

Abundance of adult Colorado pikeminnow in the middle Green River was consistently the highest of any of the reaches in the Green River Basin and also increased over the duration of the study period (Table 5, Figure 5). Adult Colorado pikeminnow abundance was lowest in 2006 at an estimated 674 fish (SE = 255), increased in 2007 to 1,026 (SE = 324) in 2007, and was highest in 2008 at 1,109 (SE = 460), a 65% increase over the study period. Confidence intervals for abundance estimates overlapped in all years. Number of unique animals captured declined from 104 in 2006 to 53 in 2008. Abundance estimates for the middle Green River reach had relatively low precision, with CV's ranging from 32 to 41%. The relatively high CV's were due to the relatively low numbers of captured and recaptured fish.

Weighted regression of abundance estimates over the two sampling periods (2000 to 2003, 2006 to 2008) showed most support for the quadratic model (weight = 0.99, e.g., 99%), and based on signs of coefficients, suggested a significant decline (large and negative linear coefficient relative to the standard error) in the middle Green River population of adult Colorado pikeminnow in the first period followed by a significant increase in the 2006 to 2008 period (Table 9). There was little support for the intercept-only or linear models (weight <0.01).

Colorado pikeminnow recruits in the middle Green River reach increased over time from 25 (SE = 15) in 2006 to 207 (SE = 104) in 2008; confidence intervals for estimates in 2006 and 2008 did not overlap. Estimates of Colorado pikeminnow recruit abundance in the middle Green River had low precision, with CV's that ranged from 40 to 59. Weighted regression analysis of recruit abundance as a function of time for the middle Green River (not shown) showed most support for the intercept only model (0.94) or a linear model with a positive slope coefficient (0.06).

Abundance of juvenile Colorado pikeminnow also increased in the middle Green River over the study period, from 6 (SE = 6) in 2006 to 124 (SE = 70) in 2008; confidence intervals for estimates in 2006 and 2008 did not overlap. Estimates of Colorado pikeminnow juvenile abundance in the middle Green River had low precision, with CV's that ranged from 44 to 99%. The trend for juvenile Colorado pikeminnow abundance as a function of time over the 2006 to 2008 period was positive (Figure 5) but model weight (0.97) suggested an intercept-only model was appropriate.

Abundance estimates for adult Colorado pikeminnow in the Desolation-Gray Canyon reach of the Green River were relatively low in 2006 and 2007 but increased dramatically in 2008, and represented the largest estimate for adult Colorado pikeminnow recorded in this study for any reach (Table 6, Figure 6). Abundance of adult Colorado pikeminnow was 519 (SE = 115) in 2006, 484 (SE = 120) in 2007, and 1,296 (SE = 463) in 2008, a 150% increase from 2006 to 2008. Overlapping confidence intervals among pairs of point estimates indicated that none of the differences were statistically significant, due mostly to the imprecision of the 2008 estimate. Numbers of unique animals captured declined from 117 in 2006 to 69 and 73 in 2007 and 2008, respectively. Estimates of adult abundance in the Desolation-Gray Canyon reach of the Green River had moderate to low precision in the 2006 to 2008 period (CV range = 22–36%).

Weighted regression of Desolation-Gray Canyon abundance estimates for adult Colorado pikeminnow over the two sampling periods (2001 to 2003, 2006 to 2008) showed most support for the intercept only model (0.97), with little support for the linear or quadratic models (<0.03, Table 9).

Similar to the 2001 to 2003 period, the Desolation-Gray Canyon reach of the Green River consistently supported a relatively large number of Colorado pikeminnow recruits during the 2006 to 2008 study period. Recruit abundance was lowest in 2006 at 79 (SE = 23), increased to 391 (SE = 100) in 2007, and remained high at 265 (SE = 112) in 2008; confidence intervals for estimates did not overlap for 2006 and 2007 but those for all other year-pairs overlapped. Estimates of Colorado pikeminnow recruit abundance in the Desolation-Gray Canyon reach of the Green River were less precise than abundance estimates for adults, with CV's that ranged from 26 to 42%. Similar to trends for adults, weighted regression analysis of trends in abundance estimates over the two periods of sampling (2001 to 2003, 2006 to 2008) showed most support (0.99) for the intercept only model (stable trend); support was low for a linear model with a positive slope coefficient even though abundance estimates increased in 2007 and 2008 (Figure 6).

Estimates of juvenile Colorado pikeminnow abundance were also relatively high during this study in the Desolation-Gray Canyon reach of the Green River at 182 (SE = 45) in 2006, 87 (SE = 30) in 2007, and 105 (SE = 56) in 2008; confidence intervals for all pairs of estimates overlapped. Estimates of Colorado pikeminnow juvenile abundance in the Desolation-Gray Canyon reach of the Green River had moderate to low precision, with CV's that ranged from 24 to 53%. The trend was for a weak and negative relationship of juvenile Colorado pikeminnow abundance as a function of time over the 2006 to 2008 period (Figure 6); the intercept only model was well-supported in weighted regression analysis (0.93).

Estimates of adult Colorado pikeminnow abundance in the lower Green River reach in this study showed a substantial decline from 2006 to 2008, but estimates remained high relative to the 2001 to 2003 period (Table 7, Figure 7). Adult Colorado pikeminnow abundance declined from 791 (SE = 103) fish in 2006, to 604 (SE = 77) in 2007, and 467 (SE = 112) in 2008, a 41% reduction. Overlapping confidence intervals among pairs of point estimates suggested that estimates were not significantly different. Numbers of unique animals captured was 126 in 2006, increased to 169 in 2007, and declined to 68 in 2008. Lower Green River reach abundance estimates had moderate precision (CV's = 13 to 24%), reflecting the relatively large number of fish captured and relatively high recapture rates.

Weighted regression of lower Green River abundance estimates for adult Colorado pikeminnow over the two sampling periods (2001 to 2003, 2006 to 2008) showed most support for the intercept only model (0.96, Table 9). There was little support for the linear model with an increasing slope (0.04) even though abundance estimates were higher in the 2006 to 2008 period compared to 2001 to 2003 (Figure 7).

Estimates of Colorado pikeminnow recruit abundance in the lower Green River reach were relatively high but declined over the duration of the study period from 321 (SE = 47) in

2006, to 207 (SE = 32) in 2007, and 157 (SE = 45) in 2008. Estimates of Colorado pikeminnow recruit abundance in the lower Green River were relatively precise with CV's that ranged from 15 to 29%, but confidence intervals for all pairs of abundance estimates overlapped. Weighted regression analysis of abundance estimates of Colorado pikeminnow recruits over the two periods of sampling (2001 to 2003, 2006 to 2008) showed most support for the intercept only model (0.92), with the remaining support (0.08) for an increasing abundance trend in the lower Green River (Figure 7).

Similar to trends for adults and recruits, juvenile Colorado pikeminnow abundance also decreased over time from 987 (SE = 124) in 2006, to 212 (SE = 33) in 2007, and 163 (SE = 46) in 2008. Confidence intervals for the large and relatively precise 2006 estimate (CV = 13%) did not overlap with that for 2007 or 2008 (CV = 15 and 28%, respectively); confidence intervals for estimates in those latter two years overlapped. The trend was for a weak and negative relationship of juvenile Colorado pikeminnow abundance as a function of time over the 2006 to 2008 period (Figure 7); model weights supported an intercept-only model (0.99).

Basin-wide abundance estimates.—River-wide annual abundance estimates for Colorado pikeminnow adults, recruits, and juveniles reported for the period 2006 to 2008 were the sums of annual abundance estimates from the various reaches in the multi-state model. Abundance of adult Colorado pikeminnow apparently increased over the period of sampling in the Green River Basin (Table 10, Figure 8). In 2006, abundance of adult Colorado pikeminnow was estimated at 2,454 (SE = 319) individuals, and increased in 2007 and 2008 to 2,718 (SE = 404) and 3,672 (SE =828), respectively, an increase of 50% from 2006 to 2008. Estimates of Colorado pikeminnow adult abundance had moderate precision, with CV's that ranged from 13 to 23%. Confidence intervals for all pairs of estimates overlapped. The trend for abundance estimates over the two sampling periods (2000 to 2003, 2006 to 2008) showed a decline in the Green River Basin population of adult Colorado pikeminnow in the first period followed by a substantial increase in the 2006 to 2008 period (Table 9, Figure 8). We did not perform weighted regression for the basinwide estimates, and instead relied on reach estimates to inform changes regarding trends.

River-wide estimates of Colorado pikeminnow recruit abundance from 2006 to 2008 were relatively high, and varied from 426 (SE = 55) in 2006, to 828 (SE = 128) in 2007, and 652 (SE = 174) in 2008. On average, abundance of recruits represented 22% (17 to 30 %) of the number of adults present from 2006 to 2008. Estimates were variable over time and perhaps suggested a stable or increasing trend for abundance of Colorado pikeminnow recruits over the sampling period. The number of Colorado pikeminnow recruits expressed as a percentage of the number of adults (22%) was slightly higher than the adult mortality rate (20%), which is consistent with an increasing population of adults over the study period. Estimates of Colorado pikeminnow recruit abundance were nearly as precise as those for adults, with CV's that ranged from 13 to 27%. The trend for Colorado pikeminnow recruit abundance over the two periods of sampling (2000 to 2003, 2006 to 2008) showed a positive linear increase in the Green River Basin (Figure 8). Also, the lower confidence intervals for abundance estimates of Colorado pikeminnow recruits in 2007 and 2008 did not overlap with the upper interval for 2003, and indicated a significantly larger recruit population.

Abundance of juvenile Colorado pikeminnow in the Green River Basin was very high in 2006 at 1,176 (SE = 133), and declined to relatively lower but similar levels in 2007 (N = 410, SE = 65) and 2008 (N = 475, SE = 119). In spite of a declining abundance trend for 2006 to 2008 (Figure 8), abundance of juveniles was relatively high in each of the three study years.

Survival estimates.—The single best estimate for S for Colorado pikeminnow of all sizes over the study period 2006 to 2008 in the Green River Basin was 0.80 (SE = 0.078; Table 11). Because there was no TL effect included in the model for survival rates, the survival estimate was for all fish captured during this study and was most indicative of the average size fish. The confidence interval for this estimate was relatively broad because there were only 3 primary occasions over which to estimate survival.

Probabilities of capture.—Model selection supported estimation of capture probabilities for Colorado pikeminnow that were specific to each sampling pass, reach, and year, but unlike prior analyses of 2000 to 2003 data, did not support consistent inclusion of TL effects in the top six estimating models (Table 2). Lack of support for inclusion of a length covariate was likely due to insufficient data to estimate an effect and poor precision of estimates, rather than absence of such an effect. We think this because prior analyses for the 2000 to 2003 period, for which more data were available, showed that length importantly affected capture probabilities.

A simple means of illustrating how capture probabilities were used to generate abundance estimates was to simply divide the number of animals in the capture sample by the probability of capture, and assume all animals at risk of capture in the population have identical capture probabilities. For example, if 100 animals were captured in a sample and the animals had a known and constant probability of capture of 0.10, there must have been 1,000 animals in the population (100/0.10 = 1,000). In this example, each fish in the capture sample contributes equally to the abundance estimate. This assumption of non-heterogeneity among individual capture probabilities was inherent in most estimating models in program CAPTURE. Because capture probabilities of individuals often varied spatially or over time (this study), model selection supported inclusion of reach-specific and sampling-pass- specific capture probabilities.

As was apparent from estimation and model selection, probabilities of capture were relatively low, imprecise, and varied widely among sampling occasions, reaches, and years (Table 8). Capture probabilities per sampling pass ranged from 0.007 to 0.154. Average probabilities of capture were highest in the lower Green River, followed by the Yampa and White rivers, the

Desolation-Gray Canyon reach, and the middle Green River. Average annual probabilities of capture were lowest in all reaches in 2008, with the exception of the Yampa River, which was lowest in 2007 when no fish marked or released that year were recaptured. Year 2008 was characterized by relatively high and cool flows late in the year, which may have reduced capture rates. Trajectories of probabilities of capture by reach and year were mixed, with some increasing with later season passes (e.g., Yampa River), while others remained stable (e.g., White River, 2007), or declined as the season progressed (lower Green River).

Probabilities of transition.—Transition probabilities (ψ_{ij}) characterized the likelihood that tagged fish would move between any two of the five different Green River Basin reaches between the annual sampling periods. Estimates of transition probabilities adjusted probabilities of capture because the likelihood of a fish being captured in a given reach was partially a function of its continued presence there ($1 - \psi_{ij}$). Estimates of reach transition probabilities also gave insights into rates and direction of movement of Colorado pikeminnow to and from various reaches, which may vary with fish TL. However, unlike analyses for the 2000 to 2003 data, a length effect on transition probability was not supported explicitly in model estimation for data collected from 2006 to 2008. Thus, no length-specific or life-stage-specific estimates of transition probabilities were available. However, like probabilities of capture, transition probabilities were estimated for a specific reach and are representative of the fish that reside there. Thus, if mostly larger fish reside in certain reach (e.g., White River) that has a low transition probability, those fish must move little. In contrast, if transition probabilities for a particular reach are higher and mostly smaller fish reside there (e.g., lower Green River), those fish must move more.

In general, most ψ's for Colorado pikeminnow were low, especially those for non-adjacent reaches (e.g., lower Green River to the White or Yampa River, Table 12, 13). Average transition probabilities (only non-zero values used) for Colorado pikeminnow moving from the Yampa

River (0.0) and the White River (0.03) were low, reflecting a relatively high propensity of fish to remain in those reaches. The average ψ from the middle Green River (0.06), the Desolation-Gray Canyon reach (0.063), and the lower Green River reach (0.108) were higher. Mean ψ to a particular reach from all other reaches were lower for tributaries at the extremities of the Green River Basin (Yampa River = 0.012, White River = 0.027) and the lower Green River reach (0.015) than to main stem Green River reaches in the middle of the study area (Desolation-Gray Canyon reach = 0.066, middle Green River = 0.054). The negative values for net ψ from the lower Green River suggested a net movement of fish from that area. The relatively high and positive values for net ψ to the middle Green River and Desolation-Gray Canyon river reaches suggested a net movement of fish to those areas during this study; the near-zero net ψ value for the middle Green River suggested equal numbers of fish entering or leaving that area.

The relatively high and negative net ψ's for the relatively small fish in the lower Green River (see length frequency histograms below) reflected a mostly upstream transition rate. Thus, even though no size effect was supported in the estimating model, the bulk of the fish that were moving, particularly from the lower Green River, were small. Annual estimates of ψ for fish moving from the lower Green River to the Desolation-Gray Canyon reach (0.32), and for fish moving from Desolation-Gray Canyon to the middle Green River reach (0.18) were the largest detected in this study. Upstream ψ to the White and Yampa rivers from those areas was lower, but substantial in some cases. For example, ψ for fish moving from the lower Green River to the White River was 0.068. However, the average ψ for fish moving to the Yampa River was small at 0.013. The highest downstream ψ's detected were for fish moving from the White River to Desolation-Gray Canyon (0.047) or the middle Green River (0.053).

ISMP catch/effort trends, 1991 to 2008.—Catch/effort indices at standard ISMP sites for Colorado pikeminnow in the four reaches of the Green River Basin for which data were available were variable over years but generally increased in the period 2006 to 2008 compared to 2003, supporting trends in abundance estimates (Figure 9). This was especially true in the White River, where abundance indices rose in the 2006 to 2008 period, after a severe decline from 2000 to 2003. Catch/effort indices also suggested that abundance of Colorado pikeminnow in the Yampa River remained low in the period 2006 to 2008, supporting results of abundance estimates.

Length-weight and length-frequency analyses.—River-wide mean TL of adult (those >450 mm TL) Colorado pikeminnow remained essentially the same over time, 548 mm in the 1991 to1999 period (SD = 71.2), 544 mm (SD = 67.9) in the 2000 to 2003 period, and 544 mm (SD = 68.0) from 2006 to 2008. Analysis-of-covariance (ANCOVA) showed that length-weight relationships for the three groups of fish were significantly different (df = 3, 1416, F = 3,549.6, $p < 0.0001$, $R^2 = 0.883$). The $\log_e$ length - $\log_e$ weight relationships estimated for Colorado pikeminnow 450 mm TL or greater for the three groups follow:

1991 to 1999; $\log_e WT = -13.823 + 3.336*\log_e TL$

(SE intercept = 0.269, SE slope = 0.0427),

2000 to 2003; $\log_e WT = -13.237 + 3.233*\log_e TL$

(SE intercept = 0.367, SE slope = 0.058), and

2006 to 2008; $\log_e WT = -12.244 + 3.083*\log_e TL$

(SE intercept = 0.506, SE slope = 0.080).

Differences in predicted weight for a hypothetical 600-mm TL Colorado pikeminnow showed that a fish from 1991 to 1999 weighed 1839 g, a fish captured in the period 2000 to 2003 was 1710 g, and a fish captured in the 2006 to 2008 period weighed 1768 g. This suggested that a fish from 2006 to 2008 was about 3.4% heavier on average than a fish from 2000 to 2003, the period with the lightest fish.

Total length of Colorado pikeminnow captured from 2006 to 2008 ranged from 151 to 890 mm. Average TL of all captured and recaptured Colorado pikeminnow included in capture-recapture analyses was 471 mm. The largest Colorado pikeminnow captured was from the Desolation-Gray Canyon reach of the Green River, and only 12 captures of fish > 800 mm TL were made.

Length-frequency distributions for the upstream Yampa River, White River, and middle Green River reaches (Figures 10 to 12) suggested presence of a larger proportion of relatively large Colorado pikeminnow, and relatively fewer fish less than 450 mm TL. However, all reaches had a relatively high proportion of small fish compared to 2000-2003, especially in the Desolation-Gray Canyon and lower Green River reaches, where most fish captured in most years were < 450 mm TL (Figures 13 and 14).

Population-structure of recruit and adult Colorado pikeminnow in ISMP-reach samples changed dramatically between the three periods, 1991 to 1999, 2000 to 2003, and 2006 to 2008 (Figure 15). Number of Colorado pikeminnow recruits (*n* = 186) in the period 1991 to 1999 averaged 24.7% (7.9 to 58.5%) of the number of adults in samples (*n* = 826). During the period 1991 to 1999, there were four years (three from 1992 to 1994) when proportion of recruits was high (>20%), three years when proportion of recruits was moderate (>10 to 20%), and two years when it was low (0 to 10%). In the period 2000 to 2003, number of Colorado pikeminnow recruits (*n* = 14) was low, at only 3.4% (0 to 6.6%) of the number of adults present (*n* = 418), and was zero in three of those (2001 to 2003). In the period 2006 to 2008, and consistent with abundance estimates, the percentage of Colorado pikeminnow recruits in ISMP samples increased to an average of 22.1% (9.2 to 33.3%) of the number of adults present (*n* = 166), with % recruits increasing each year through the period.

DISCUSSION

Comparison of point estimates derived from capture-recapture sampling and data analysis suggested that abundance of adult Colorado pikeminnow in the Green River Basin increased from over 2,454 fish in 2006 to about 3,672 individuals in 2008, an apparent increase of 50%. Although confidence intervals for individual estimates overlapped, trends suggested a substantial and positive increase in abundance of adult and recruit-sized Colorado pikeminnow. The increasing abundance trend for Colorado pikeminnow in the Green River Basin was supported by other data and analyses, which showed increased numbers of juveniles and recruits from both abundance estimates and ISMP sampling data, and higher survival rates, compared to the 2000 to 2003 period. Higher abundance of Colorado pikeminnow juveniles and recruits apparently derived from a relatively strong year class of age-0 Colorado pikeminnow produced in the lower Green River in 2000. Below we discuss the multiple and consistent lines of evidence that support the thesis of increased Colorado pikeminnow abundance in the Green River Basin, but acknowledge that some estimates were imprecise. We also discuss the abundance estimation model, model assumptions, and implications of parameter estimates, and potential reasons for the apparent increase of Colorado pikeminnow abundance in the Green River Basin during the study period.

Model selection and assumptions.—We used an estimating model for 2006 to 2008 data similar to that which was used for data collected from 2000 to 2003. We explored a series of increasingly complex models that led us to choose the Huggins robust-design multi-state model as the most realistic one for estimation. The sampling design (three primary annual sampling periods with three closely-spaced secondary sampling occasions in each year) led logically to a robust-design estimator which allowed estimation of Colorado pikeminnow abundance for every sampling year and potentially, estimation of survival between years of sampling. The Huggins model allowed use of the individual covariate TL, which was potentially important because size was known to affect capture probabilities and survival rates of fishes, including Colorado pikeminnow (Bestgen et al. 2007). Incorporation of size effects into survival and capture probabilities may allow for more efficient and realistic population modeling. However, model selection results showed that TL effects were not supported in analyses of data collected in 2006 to 2008 data, compared to 2000 to 2003. This is due, in part, to the fewer fish captures and recaptures made in 2006 to 2008, which made significant TL effects more difficult to detect.

The multi-state (states are reaches, called "strata" in Bestgen et al. 2007) aspect of the estimating model was important because of the five-reach sampling design, and because differences in size-structure of Colorado pikeminnow among reaches affected capture probabilities and ultimately abundance estimates. Differences in capture probabilities across reaches might also be expected because of differences in geomorphic conditions (canyon vs. valley), sampling crews, and the type of sampling craft (raft vs. boat) used in each reach. Finally, this model offered the further flexibility of estimating effects of fish moving from one reach to another (ψ) between years. Thus, the manner in which the data were collected, and the biology of the subject animal, logically led to use of this estimating model.

Fulfilling the assumptions of the underlying model was a critical first step in obtaining reliable abundance estimates. Aspects of the experimental design employed in this study ensured that most assumptions of closed-model abundance estimators were met. The assumption of demographic closure was met, in part, because within-year sampling was limited to a relatively short time period in spring prior to Colorado pikeminnow migration to spawning areas. This reduced the possibility of movement to the small areas that were not efficiently sampled. Static population size was also ensured in the period encompassed by within-year sampling occasions, because of the large size of the study area. The only location of emigration/immigration for fish was from the distant and downstream Colorado River. The likelihood of substantial movement from there was much reduced at that time of year because fish tend to occupy small and stable home ranges (Tyus 1990; Irving and Modde 2000). This notion was further supported by the low number of Colorado pikeminnow moving between river reaches within a sampling season (Bestgen et al. 2007; unpublished data). The short period encompassed by the sampling occasions also ensured that mortality and recruitment were minimized.

The assumption of homogeneity of capture probabilities of individuals was unlikely to be fulfilled completely except in all but the most restricted conditions. We attempted to minimize heterogeneity effects by incorporating the covariate TL into analyses, but model selection again did not identify length as a significant effect. In a prior analysis using a larger data set (Bestgen et al. 2007), we investigated the likelihood of a population composed of groups of individuals with inherently different capture probabilities. We found no support for such based on preliminary analyses using mixture models (Pledger 2000) for data collected in the period 2000 to 2003, so we did not attempt further analyses. Further, with only three secondary occasions per primary occasion, the data were inadequate to detect two mixtures with the Pledger model. Prior analyses also demonstrated that initial capture probabilities were equal to recapture probabilities among the short-term sampling occasions (i.e., $p_k = c_k$) by including an additive parameter to the top model (additive model is #4 in the set, in Bestgen et al. 2007). The additive model suggested that recapture probabilities were slightly (usually about 0.001) but not importantly higher that initial capture probabilities. Thus, to the extent possible, we have tested for and found no effects of heterogeneity.

Another relevant assumption in this study was that animals mixed freely between concentration habitat (backwaters, shorelines, eddies, main channel) and adjoining areas between sampling occasions such that all animals in the population were available for capture. A corollary assumption was that sampling effort was distributed over most occupied habitat. Evidence from the Colorado River indicates Colorado pikeminnow mix between concentration areas and other habitat types among sampling occasions; Osmundson and Burnham (1998) found high probabilities of capture within concentration backwater habitat in a single sampling occasion, but relatively low probabilities of recapture in those same locations between occasions. The logical explanation for this capture pattern is that many fish moved into and out of concentration habitat between sampling occasions. In the Green River Basin during this and past studies (Bestgen et al. 2007), we demonstrated similar mixing because initial capture probabilities were equal to recapture probabilities among the short-term sampling occasions (i.e., $p_k = c_k$). If fish were not mixing, we would expect that recapture probabilities would be much higher than initial capture probabilities, because the same shoreline habitat was sampled during each pass. We probably had low sampling efficiency in very deep pools (> 2-m deep), but the amount of that habitat type relative to shallower, easier-to-sample areas where Colorado pikeminnow typically resided was small (Tyus and McAda 1984). Thus, short-term fish movement patterns, analysis of capture and recapture rates, and our relatively complete sampling coverage of occupied habitat likely minimized bias due to incomplete mixing of marked and unmarked animals.

We also assumed that recognition of marked Colorado pikeminnow was high (all were scanned) and that tag loss was low. Although differences in capture rates may exist because of differences in crew experience or effort, effects of such on abundance estimates should be minimized because capture probabilities were estimated for all sampling occasions, reaches, and years.

Abundance estimates.—Confidence intervals of annual abundance estimates for individual reaches generally overlapped during the 2006 to 2008 period. This was due in large part to imprecise estimates, particularly in 2008, when relatively few captures and recaptures were made.

However, consistent increases in abundance estimates over time and in most river reaches suggested a river-wide increase in abundance of adult Colorado pikeminnow in the Green River Basin from 2006 to 2008. Increases were especially substantial in middle Green River and White River reaches. That conclusion was based on weighted regression analysis and the finding that most model selection weight was for quadratic models which demonstrated substantial recent abundance increases. Desolation-Gray Canyon and lower Green River reaches showed indications of higher abundance estimates in the 2006 to 2008 period compared to the 2001 to 2003 period, but the conservative weighted regression analysis for the entire period instead suggested stable population abundance of adult Colorado pikeminnow in those reaches. Only the small Yampa River population demonstrated a convincing decline in abundance of adult Colorado pikeminnow based on weighted regression results. Given the absence of obvious violations of assumptions for abundance estimation models, and that trends in estimates for reaches with the largest populations were either increasing or stable, we consider the conclusion of increased abundance of adult Colorado pikeminnow in the Green River Basin to be valid. Details associated with other life stages or reach-specific estimates are discussed below.

Abundance of Colorado pikeminnow recruits was much higher in period 2006 to 2008 than from 2000 to 2003, which was certainly responsible for the increased abundance of adults as recruits grew to ≥450 mm TL. This was especially evident in 2008, when adult abundance increased sharply over 2007. This was likely a result of a large group of recruits in 2007 growing into the adult size class, a scenario which was reasonable based on expected growth rates and changes in length frequency histograms, especially in the Desolation-Gray Canyon and lower Green River reaches. Recruitment dynamics for Colorado pikeminnow were episodic, occurring at intervals of several years in the Colorado and Green River systems (Osmundson and Burnham

1998, Bestgen et al. 2007, but see Osmundson and White 2009), and such may have occurred again in the period 2006 to 2008.

Estimates for the Yampa River in the period 2006 to 2008 suggested a stable number of adult Colorado pikeminnow, but also supported a general declining trend that began in the 2000 to 2003 period. Based on declines in capture rate from 2000 and 2001 (82 and 120 individuals captured, respectively) to 33 and 31 in each of 2002 and 2003, respectively, and continued low numbers of fish captured in the 2006 to 2008 period, reduced abundance patterns were perhaps not surprising. It may also be that Yampa River estimates from 2002 and 2003 were biased high. This was because in each of those years, not a single within-year recapture was made. The low probabilities of capture resulted in abundance estimates for 2002 and 2003 that were only slightly lower than those for 2000 and 2001, in spite of small capture samples. Although definitive statements about the status of Colorado pikeminnow in the Yampa River were difficult to make because abundance estimates were relatively imprecise (high CV's, wide CI's), it seems clear that their abundance remained low.

Continued presence of predaceous northern pike in some reaches of the Yampa River, in spite of intensive removal efforts, may also be suppressing abundance of Colorado pikeminnow, although abundance of large northern pike has been reduced (Martin et al. 2009). Continued and more widespread northern pike removal in upstream source reaches that recently began may enhance Colorado pikeminnow abundance in the Yampa River in the future. It may also be that the large number of Colorado pikeminnow that were recruiting to adult life stage in the Green River Basin in 2006 to 2008 have simply not yet colonized the Yampa River, because transition rates to the Yampa River were very low. Resumption of Colorado pikeminnow abundance estimation sampling in 2011 may resolve that question.

Increased abundance of adult Colorado pikeminnow in the White River and the middle Green River reaches was encouraging because those segments previously supported the largest numbers of Colorado pikeminnow in the 2000 to 2003 period (Bestgen et al. 2007). Increased abundance of adult Colorado pikeminnow in those reaches through 2008 almost certainly derived from upstream movement (high transition rates) of large numbers of juvenile and recruit-sized Colorado pikeminnow that originated in downstream reaches of the Green River in 2006 and 2007. Abundance increases in the 2006 to 2008 period were also supported by weighted regression analysis. While the thesis of increased Colorado pikeminnow abundance in those reaches appears sound, higher numbers of captures and recaptures are needed in the next set of abundance estimates (2011-2013) to better understand the magnitude of population change.

The 2008 estimate of adult Colorado pikeminnow abundance ($\hat{N}$ = 1,769) in the White and middle Green River reaches (combined), was the highest of the 2006 to 2008 period, but remained nearly 1,000 fish less than that recorded in 2000 ($\hat{N}$ = 2,713). This may suggest that those areas, and perhaps the entire system, may be capable of supporting a substantially larger population of Colorado pikeminnow in the future. This may be occurring as juvenile and recruit-sized Colorado pikeminnow remained abundant in the Desolation-Gray Canyon and lower Green River reaches in 2008 and would be expected to move upstream in the future.

Populations of adult Colorado pikeminnow in the Desolation-Gray Canyon reach of the Green River remained at relatively low levels in 2006 and 2007 and increased dramatically in 2008. Although the 2008 abundance estimate had a very wide confidence interval and was less reliable than others, a large population in that reach was expected based on the large number of recruits present there and in downstream reaches in 2007. Specifically, the Desolation-Gray Canyon reach supported a large number of recruits in the reach in 2007 (about 400) that would grow into the adult life stage by 2008 (Bestgen et al. 2007), and, based on expected transition rates, the reach also received a large number of recruits and perhaps small adult fish moving in from the lower Green River. This pattern of abundance dynamics for Desolation-Gray Canyon adult Colorado pikeminnow would also explain the declining abundance of recruits and adults in the lower Green River reach over the 2006 to 2008 study period. There might also be an expectation for continued population increases in Green River reaches upstream of the lower Green River because of high abundances of juveniles and recruits available to transition upstream.

As stated previously, abundance of adult, recruit, and juvenile (most juveniles in the size range 350–399 mm TL, from the length frequency histogram) Colorado pikeminnow in the lower Green River was very high in 2006 (nearly 2,100 fish of all size classes), and was substantially higher than any time during 2000 to 2003, but abundances declined steadily in 2007 and 2008. Most of the declines in abundance were perhaps attributable to fewer juvenile fish being produced in the lower Green River reach nursery area and high rates of upstream movement (e.g., $\hat{\psi} = 0.32$) of recruits and small adults from the lower Green River to Desolation-Gray Canyon.

Trends in the ISMP catch/effort indices were generally consistent with abundance estimates. For example, White River catch rates increased as abundance estimates increased in 2006 to 2008, similar to declining trends for both metrics in the 2000 to 2003 period. Also, Yampa River catch/effort indices suggested continued low abundance of Colorado pikeminnow, which was consistent with abundance estimates. Catch rates in 2008 were lower overall perhaps due to decreased sampling efficiency. Middle Green River catch rates were somewhat inconsistent and lower Green River catch rates for 2008 reflected the apparent decline in abundance of adult, recruit, and juvenile Colorado pikeminnow, some of which was due to movement out of the reach.

Survival rates.—Increased abundance of adult Colorado pikeminnow over the 2006 to 2008 period in the Green River Basin was attributable, in part, to a 15% higher adult survival rate compared to the 2000 to 2003 period. For example, given a hypothetical population size of 2,000 fish with constant recruitment, a survival rate increase from 65% to 80% would result in an additional 300 fish being present in the system per year compared to the lower survival rate, or about an additional 900 fish over a 3-year period. Apparent survival rates in the period 2006 to 2008 have returned to rates that were similar to those from the period 1991 to 1999, when Colorado pikeminnow populations were expanding in the Green River Basin, and were substantially higher than that for the 2000 to 2003 period, when Colorado pikeminnow populations were declining (Bestgen et al. 2007). The recent higher survival rate was also more similar to that estimated for adult Colorado pikeminnow in the Colorado River, a population that has generally been increasing in abundance over time (Osmundson et al. 1997; Osmundson and Burnham 1998, Osmundson and White 2009). These observations collectively point to the importance of maintaining high survival rates of adult fish, especially when recruitment was episodic (Bestgen et al. 2007).

The survival rates and TL relationships for Colorado pikeminnow were different for each of the periods 2006 to 2008, 2000 to 2003, and 1991 to 1999. For 2006 to 2008, a single fixed rate survival estimate was the one best-supported, even though previous studies have shown that survival relationship for fish in general, and Colorado pikeminnow in particular, may have a bell-shaped survival curve related to fish length (Bestgen et al. 2007, Osmundson and White 2009). However, the second, fifth, and sixth models in the set examined for 2006 to 2008 data included TL as a covariate in some form, albeit those relationships were weak. In those models, the quadratic relationship showed low survival for smaller fish, higher survival for intermediate-sized fish, and low survival for the largest fish, similar to that in Bestgen et al. (2007) and Osmundson and White (2009). It was likely that the relatively sparse data would not support those TL covariate effects for 2006 to 2008 data. Another factor that may play a role was that survival rates were higher overall, and the length range of fish included in the analysis was not as great (fewer small as well as large fish). For example, the 2000 to 2003 data set contained many fish that were >800 mm TL, and many of those were never seen again, compared to the more recent data set which had fewer such individuals, which may have caused more weight to be put on those fish in estimating quadratic relationships which predicted declining survival rates for larger pikeminnow.

Higher survival rates of Colorado pikeminnow in the Green River Basin captured in the period 2006 to 2008 may be due to several factors including higher stream flows, lower stress-induced mortality due to lower water temperatures, continued efforts to reduce populations of introduced predaceous fishes such as northern pike, or a combination of these and other yet undiscovered factors. Higher flows likely produced a higher quantity and quality of habitat in the 2006 to 2008 period (96.5 m^3/sec mean daily average) compared to 2000 to 2003 (73.0 m^3/sec). For example, mean annual average daily flows for 2000, 2001, 2002, and 2003 were the 21st, 8th , 2nd, and 11th lowest, respectively, that have been recorded in the 62 years of gage operation (1947–2008), whereas 2006, 2007, and 2008 ranked 25th, 9th, and 29th lowest. Flows were even higher in the period 1991 to 1999 (126.0 m^3/sec), when Colorado pikeminnow populations were also expanding (Bestgen et al 2007). Low flows are known to be stressful to fish, and Anderson (2005) documented reduced populations of nearly every Yampa River fish species during low flow events in the same period, with the exception of smallmouth bass, which increased in abundance.

Continued removal of large and piscivorous northern pike may also have benefitted Colorado pikeminnow in some portions of the basin such as the middle Green River, where northern pike abundance remained low through the study period. However, in the Yampa River where the largest northern pike populations in the Green River Basin occurred and removal of pike is ongoing (e.g., Martin et al. 2009), the small but stable Yampa River population of Colorado pikeminnow apparently did not respond. This may be due to insufficient removal or, as stated previously, because newly recruited Colorado pikeminnow have not yet invaded the Yampa River from downstream.

Bestgen et al. (2007) discussed at length the potential negative effects of electrofishing on Colorado pikeminnow survival in the Green River Basin, and based on field observations and specific experimental results of other studies, found no support for that hypothesis. Findings during this 2006 to 2008 study period further supports the thesis of minimal electrofishing sampling effects on survival of Colorado pikeminnow, because we were sampling a relatively small portion of the population and because substantial population increases would not be expected if sampling mortality was high. We also did not detect substantial size-dependent effects on survival in the period 2006 to 2008, which further substantiated the idea that electrofishing sampling did not negatively affect large Colorado pikeminnow.

Apparent survival estimates reflect that estimates of S were the joint probability of an individual surviving, and remaining, in the reach so that it was available for sampling. Thus, if a fish moved from a sampled reach to an unsampled one and remained there, by definition, that fish was deemed a mortality. We did not sample about 12% of critical habitat occupied by Colorado pikeminnow in the Green River Basin. Those areas and others such as Lodore Canyon of the Green River just upstream of the Yampa River have supported Colorado pikeminnow in the past (Bestgen and Crist 2000; Kitcheyan and Montagne 2005; Bestgen et al. 2006). Although large numbers of Colorado pikeminnow have been occasionally captured in such reaches, particularly Lodore Canyon, occupancy of those canyon areas occurred mostly in seasons other than when spring-time abundance estimation sampling was conducted. For example, based on telemetry and tag recapture data, most Colorado pikeminnow that moved to Lodore Canyon in portions of 2001, and all of 2002 and 2003, did so in summer, with most fish coming from the Green River in Island Park, other downstream portions of the middle Green River reach, or even the Yampa River (Kitcheyan and Montagne 2005; Bestgen et al. 2006; Recovery Program study 115).

These movement and tag-recapture data for Colorado pikeminnow in canyons have two main implications. First, apparent survival estimates may be relatively close to true survival because fidelity to the original capture reaches was high. This was true because even though some Colorado pikeminnow move seasonally (mostly in summer), fidelity of fish to reaches sampled for abundance estimation was high because fish move back to those reaches by spring. Thus, the apparently low level of permanent emigration to unsampled reaches does not dramatically affect survival rates, which made apparent S more closely approximate true S. A second implication of these data was for abundance estimates themselves. The mostly seasonal use of canyon reaches such as Lodore and Whirlpool Canyon, and likely lower Yampa Canyon, suggested that most Colorado pikeminnow moved to alluvial reaches by spring when abundance estimation sampling was conducted. This meant that abundance estimates for Colorado pikeminnow for the reaches sampled in this study were likely representative for the entire Green River Basin because they are not biased by presence of large numbers of Colorado pikeminnow in unsampled canyon reaches.

The ANCOVA of condition factors for Colorado pikeminnow was similar to that for survival rates in that fish condition was high in the 2006 to 2008 and 1991 to 1999 periods when flows were higher, but was reduced in 2000 to 2003 during drought years. Increased habitat size may increase prey abundance and habitat suitability, which would likely increase fish condition during non-drought years.

Recruitment rates.—Past studies and data collected during this investigation supported the idea that differences in recruitment among years plays a large role in abundance dynamics of Colorado pikeminnow in the Green River Basin (Bestgen et al. 2007). The definition of a recruit was a Colorado pikeminnow 400–449-mm TL (U. S. Fish and Wildlife Service 2002). Based on expected growth of about 43 mm/yr for Colorado pikeminnow in the 400–449-mm TL size-class (Osmundson et al. 1997), the average recruit-sized Colorado pikeminnow would become part of the adult population the following year. The expectation of recovery goals was that recruitment will, over time, equal or exceed mortality of adults to produce a stable or increasing Colorado pikeminnow population. In other words, the adult population was maintained when the number of adults that die in year i is balanced by the number of recruits present in year $i - 1$ that survive to the following year. Adult Colorado pikeminnow abundance declined in the period 2000 to 2003 when the number of recruits in samples used for abundance estimation was only 4.9–13.3% of all fish sampled, numbers which were insufficient to offset the 35% apparent annual mortality rate ($1 - S*100$); the mortality rate in that period was for the average size fish in samples (in adult size class, 560 mm TL). However, abundance of adult Colorado pikeminnow increased in the periods1991 to 1999 and 2006 to 2008, when the average proportion of recruits in the population (25% [Bestgen et al. 2007] and 22% [this study], respectively) exceeded the mortality rate of adults in each period (about 20%). Higher recruitment, coupled with higher survival, were the main reasons for expanding populations of adult Colorado pikeminnow in the Green River Basin in those periods.

The frequency of high recruitment episodes needed to sustain Colorado pikeminnow populations in the Green River Basin is yet uncertain. However, the notion that this species can sustain itself with rare recruitment events (e.g. 1 or 2 years in 10) may not be valid. For example, in the 1991–1999 period, recruitment events appeared to occur with reasonable frequency, (e.g.,

Figure 15), with moderately strong (percent of recruits = 10–20% of adults in population, *n* = 3 years) or strong (recruits > 20% of adults in population, *n*= 4) recruitment year classes occurring in seven of nine years. Similarly, when Colorado pikeminnow populations expanded during 2006–2008, recruitment year classes were moderately strong (2006) or strong (2007, 2008) in all years. Similar to abundance estimates, percent recruits from ISMP sampling reaches also showed a consistent increase in the number of recruits present from 2006 to 2008. In contrast, only a single high recruitment year occurred in the later 1990's (1998), and recruitment was low (proportion of recruits < 10% of the adult population) in all years from 2000 to 2003, when the adult Colorado pikeminnow population declined by about 40%. Thus, size-structure metrics supported the thesis that variation in recruitment was an important factor affecting abundance dynamics of Colorado pikeminnow, and that relatively frequent recruitment events were needed to maintain populations.

The mechanism driving the frequency and strength of recruitment events was likely the strength of age-0 Colorado Colorado pikeminnow year-class production in backwater nursery habitats, particularly in the lower Green River in recent years. For example, high production of recruits from 1992 to 1994 was apparently derived from strong year-classes of age-0 fish from 1986 to 1989 (Figure 16). Similarly, a strong recruit year class in 1999 was apparently produced by a large group of age-0 fish hatched in 1993. That year class would have first contributed adult Colorado pikeminnow to the Green River population in year 2000, the year when estimated abundance of adults was high at over 4,000 fish (Bestgen et al. 2007). Those events were largely responsible for expanding populations of Colorado pikeminnow adults in the Green River Basin from 1991 to 2000. The pattern of increasing numbers of adults, but attendant declining abundance of age-0 fish in nursery areas through 1998 was noted in Muth et al. (2000). The period of increased adult abundance through year 2000 was followed by a population decline from 2001 to 2003 (Bestgen et al. 2007). A main contributing factor to that decline was low abundance of recruit-sized Colorado pikeminnow in 2000 to 2003 which was a function of relatively low abundance of young-of-year produced in nursery areas from 1994 to1999 (Figure 16, Muth et al. 2000; McAda 2002; Utah Division of Wildlife Resources, unpublished data).

These recruitment scenarios are based on growth rates of Colorado pikeminnow presented by Osmundson et al. (1997), where an average age-0 fish in a given year-class (e.g., 1993, 2000) was expected to grow to a recruit-sized fish averaging 425 mm TL six years later (Osmundson et al. 1997). That same group of fish would then recruit to adult size (≥450 mm TL) on average one year later at age 7 (e.g. year 2000, and 2007 respectively). Because of variation in growth rates, a strong age-0 year class of Colorado pikeminnow (e.g., 2000) may contribute to strong recruitment year-classes possibly five, but certainly six or seven years subsequent (e.g., 2006 and 2007), which was a likely reason for large increases in adult abundance in the Green River Basin in 2007 and 2008. High abundance of recruits in 2008 may also contribute to a substantial increase in the adult population of Colorado pikeminnow in 2009, but data to assess that hypothesis was not available.

In the Colorado River, strong recruitment year-classes of Colorado pikeminnow may also be linked to strong year-classes of early life stages, but recent sampling suggested those relationships were more equivocal (Osmundson and Burnham 1998, Osmundson and White 2009). The link between early life stage year-class strength and abundance of recruit-sized Colorado pikeminnow in the Green River Basin is under further investigation and will include information on production of larvae (Bestgen et al. 1998), abundance of juveniles in backwaters (Haines and Tyus 1990; Tyus and Haines 1991; Haines et al. 1998; McAda 2002), and biotic and abiotic factors that may influence year-class strength and recruitment to the adult size class (Bestgen 1996; Bestgen et al. 1997; Bestgen and Bundy 1998; Osmundson and Burnham 1998).

Probabilities of capture.—Previous analyses demonstrated that small and very large Colorado pikeminnow had very low probabilities of capture, and intermediate sizes had the highest ones (Bestgen et al. 2007), which produced a bell-shaped curve for capture probabilities. There was some support for that same relationship in models other than the top model (e.g., model 3, Table 2), but generally there was insufficient data to support inclusion of TL covariates. Thus, probabilities of capture were fixed for fish of different lengths, but varied by sampling pass, reach, and year.

Overall, probabilities of capture may have been lower from 2006 to 2008 than from 2000 to 2003, but were somewhat difficult to compare because maximum *p*'s from quadratic relationships were reported for 2000 to 2003 data, whereas only mean *p*'s were reported from 2006 to 2008. However, reductions in the number of passes completed, reduced sampling effort per pass, and reduced overall electrofishing effort in several study reaches (independent of probability of capture for individual fish) were likely the main factors responsible for reductions in the number of fish captured and recaptured in most cases (Table 14). White River, middle Green River, and Desolation-Gray Canyon reaches had fewer sampling passes, fewer sampling days, and apparently reduced electrofishing hours per day and total, during the 2006 to 2008 period, compared to the 2000 to 2003 period. In the Yampa River, sampling effort based on all metrics was greatly increased in the 2006 to 2008 period, in part because of supplemental effort for non-native fish removal; numbers of Colorado pikeminnow captured remained low. Lower Green River reach sampling effort was consistent among the two periods. The Yampa River and the lower Green River reaches had the highest mean capture probabilities during the study. Reduced overall sampling effort, lower number of fish captured and recaptured, and smaller capture probabilities contributed to consistent lack of size effects in estimating models (both for *p*'s and *S*), and more importantly, lower precision of estimates.

Probabilities of capture for Colorado pikeminnow were especially low in 2008. Especially low capture probabilities that year may have been caused by relatively high, cold, and sustained flows throughout the period of abundance estimation sampling (Figure 2), which may have reduced netting efficiency in turbid or higher velocity water, and may have spread fish out more and made them more difficult to capture. Those low capture probabilities were the main reason that abundance estimates were especially imprecise in 2008. Increasing the number of captures and recaptures is the main key to increasing precision of abundance estimates and reducing potential bias, and future sampling for Colorado pikeminnow abundance estimation should endeavor to return to at least the level of sampling intensity achieved in the 2000 to 2003 period.

Transition rates.—Transition probabilities (ψ_i) reflected a general movement pattern of Colorado pikeminnow from the lower Green River and the Desolation-Gray Canyon reach to upstream reaches. This was not surprising given the abundance of relatively small Colorado pikeminnow in those reaches, including recruits, compared to other reaches, patterns which were consistent with previous studies in the Green River and elsewhere (Osmundson et al. 1998; Bestgen et al. 2007; Osmundson and White 2009).

Summary .—Comparison of pairs of estimates across years showed that confidence intervals overlapped in many cases, which may call into question the validity of our assertion of increasing abundance trends for Colorado pikeminnow in the Green River Basin. However, we feel confident in our conclusions based on the many divergent lines of support. For example, estimates of juvenile and recruit abundance, which drive recruitment patterns in subsequent years and ultimately adult abundance estimates, were consistently supported by patterns from ISMP reaches and in length-frequency histograms for the various reaches. This was especially true in the lower Green River reaches, where high estimates of juvenile and recruit abundance in some years mirrored length frequency histograms showing similar high abundance of those same age groups of fish. Transition rates and presence of large numbers of recruits in the downstream reaches of the Green River matched consistently with increased numbers of adults in upstream reaches the following year. Examples of this were high abundances of recruits in the lower Green River and Desolation-Gray Canyon reaches in 2006 and 2007, and subsequent increased abundance of adults in 2007 and 2008 in upstream Desolation-Gray Canyon, the middle Green River, and the White River. Also, higher survival rate estimates coupled with recruitment rates that exceeded mortality can only lead to the logical conclusion of population increases. Finally, trends in adult abundance estimates either increased or were stable in those reaches containing the highest numbers of adult Colorado pikeminnow over sampling periods 2000 to 2003 and 2006 to 2008, with a decline indicated only for the small group of pikeminnow inhabiting the Yampa River. These consistent and logical patterns with divergent estimators and data give us confidence that the conclusion of a substantial increase in abundance of Colorado pikeminnow in the Green River Basin was valid.

CONCLUSIONS

1. The sampling design fulfilled assumptions of the estimating model sufficiently well. The level of sampling effort and number of fish captured supported a relatively realistic model that was used to obtain reliable abundance estimates and other demographic parameters for Colorado pikeminnow in the Green River Basin. Higher capture probabilities are needed to obtain more precise abundance estimates for Colorado pikeminnow, especially for small populations.
2. Capture-recapture sampling suggested a 50% increase in abundance of adult Colorado pikeminnow in the Green River Basin, Colorado and Utah, over the 2006 to 2008 study period, and about a 70% increase over abundance levels estimated in 2003. Based on trends in annual point estimates, increases in adult abundance were most apparent in the Desolation-

Gray Canyon, middle Green River, and White River reaches. Abundance of adult Colorado pikeminnow was stable and low in the Yampa River during the 2006 to 2008 study period, but overall, populations showed continued decline since 2003. Abundance of adult Colorado pikeminnow in the lower Green River declined over the study period, but abundance levels were higher than in 2003.

3. Survival rates for adult Colorado pikeminnow increased in the 2006 to 2008 period compared to the 2000 to 2003 period and were comparable to survival rates estimated from ISMP data collected from 1991 to 1999, a period when Colorado pikeminnow abundance was also expanding in the Green River Basin. Along with increased recruitment, increased survival rates were a main factor responsible for the increase in Colorado pikeminnow abundance in the Green River Basin during the study period. Increased survival rates may be due to relatively higher flows in the study area from 2006 to 2008, compared to the 2000 to 2003 period, and continued removal of non-native fish predators.
4. Similar to the 2000-2003 period, there was no support for the hypothesis that sampling activities increased mortality of adult Colorado pikeminnow in the period 2006-2008.
5. Abundance of recruit and juvenile Colorado pikeminnow during the 2006 to 2008 period was high and much increased compared to the 2000 to 2003 period. Recruitment rates higher than mortality rates, and increased survival rates, were responsible for increased abundance of Colorado pikeminnow in the Green River Basin in the 2006 to 2008 period.
6. Increased abundance of juvenile and recruit-sized fish likely derived from a relatively strong cohort of age-0 fish produced in the lower Green River in 2000. This strong cohort resulted from the large number of adult fish present in 2000, the year with the highest estimated abundance of adult Colorado pikeminnow in the Green River Basin in recent years (the 2000 to 2003 and 2006 to 2008 periods).

7. The ISMP catch/effort indices showed some concordance with increased abundance estimates in the 2006 to 2008 period, compared to 2003. Lower catch/effort estimates occurred during the higher water year 2008.
8. Apparent increased abundance of all life stages of Colorado pikeminnow in the Green River Basin may be related to increased flows observed during the study period and continued removal of non-native predator fishes, but mechanisms remain unknown.

RECOMMENDATIONS

● Continue with the sampling protocol for Colorado pikeminnow in the Green River Basin as called for in the Recovery Goals.

● Investigate means to obtain higher probabilities of capture of Colorado pikeminnow, especially in reaches where abundance estimates were relatively imprecise. This may include addition of other gears such as fyke nets, increasing crew training to increase sampling efficiency, longer duration of sampling passes, or more sampling passes. Minimally, sampling effort similar to that in the 2000 to 2003 period is needed.

● Conduct an empirical analysis of growth of Colorado pikeminnow, based on tag recaptures in the Green River Basin. This would verify patterns borrowed from the Colorado River that are important to assess recruitment schedules for age-0 fish.

● Complete investigations to determine the link between abundance dynamics of early life stages of Colorado pikeminnow and recruitment to later life stages. An understanding of effects of habitat, stream flow, and non-native fishes on recruitment would be especially useful.

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Table 1. Capture histories for Colorado pikeminnow captured in the period 2006 to 2008 in the Green River Basin, Colorado and Utah. The capture history digits represent whether an individual fish was captured in sampling years from 2006 to 2008, from left to right respectively, where a 1 denotes that an individual was captured that year and a 0 indicates that an individual was not captured. For example, a capture history of 011 (n = 45) indicates that an individual was not captured in 2006, and was captured in 2007 and 2008. A 1 indicates a capture in that year regardless of how many times it was recaptured among sampling passes within that year (e.g., no attempt was made to enumerate capture frequencies within years).

Capture history	Frequency	Proportion
100	822	0.37
010	659	0.30
001	581	0.26
110	75	0.03
101	33	0.01
011	45	0.02
111	6	< 0.01
	2,221	

Table 2. Huggins models to estimate abundance (derived from model parameters), survival (*S*), probability of capture (*p*), and transition rate (*psi*, or *P*) among reaches for Colorado pikeminnow in the Green River Basin, 2006 to 2008. Covariates include river reach (reach), sampling year or pass (year or pass), and fish total length (Tlpred = total length predicted by year from a von Bertalanffy function, the polynomial terms indicated by the carat sign and a numeral where 2 = quadratic term). *S*(.) indicates a constant survival rate over all years with no covariates. AIC was Akaike's Information Criterion, *W* is model weight, *L* is the likelihood of the model based on the weights, and *N* is the number of model parameters; DM (design matrix) and PIM (parameter index matrix) were code designation reminders to ourselves.

	Models	AIC_c	ΔAIC_c	*W*	*L*	*N*	Deviance
1	{S(.) psi(reach) p(reach*year*pass) DM}	7481.185	0.00	0.226	1.000	66	7345.04
2	{S(TLpred) psi(reach) p(reach*year*pass) DM}	7482.413	1.23	0.122	0.541	67	7344.15
3	{S(.) psi(reach) p(reach*year*pass+TLpred^2) DM}	7482.667	1.48	0.108	0.477	68	7342.27
4	{S(.) psi(reach) p(reach*year*pass+TLpred) DM}	7482.682	1.50	0.107	0.473	67	7344.41
5	{S(reach+TLpred) psi(reach) p(reach*year*pass) DM}	7483.050	1.87	0.089	0.394	71	7336.25
6	{S(TLpred^2) psi(reach) p(reach*year*pass) DM}	7483.138	1.95	0.085	0.377	68	7342.74
7	{S(TLpred) psi(reach) p(reach*year*pass+TLpred) DM}	7484.258	3.07	0.049	0.215	68	7343.86
8	{S(reach+TLpred) psi(reach) p(reach*year*pass+TLpred) DM}	7484.672	3.49	0.039	0.175	72	7335.74
9	{S(reach+TLpred) psi(reach+TLpred) p(reach*year*pass) DM}	7484.705	3.52	0.039	0.172	72	7335.77
10	{S(reach+TLpred^2) psi(reach+TLpred) p(reach*year*pass) DM}	7485.035	3.85	0.033	0.146	73	7333.96
11	{S(TLpred^2) psi(reach) p(reach*year*pass) DM}	7485.082	3.90	0.032	0.143	69	7342.55
12	{S(TLpred^2) psi(reach) p(reach*year*pass+TLpred^2) DM}	7485.167	3.98	0.031	0.137	70	7340.50
13	{S(reach+TLpred) psi(reach+TLpred) p(reach*year*pass+TLpred) DM}	7486.339	5.15	0.017	0.076	73	7335.26
14	{S(reach+TLpred^2) psi(reach) p(reach*year*pass+TLpred) DM}	7486.537	5.35	0.016	0.069	73	7335.46
15	{S(reach) psi(reach) p(reach*year*pass) DM}	7489.083	7.90	0.004	0.019	70	7344.42
16	{S(reach+year) psi(reach) p(reach*year*pass) DM}	7490.181	9.00	0.003	0.011	71	7343.38
17	{S(reach) psi(reach+TLpred) p(reach*year*pass+TLpred) DM}	7492.623	11.44	0.001	0.003	72	7343.69
18	{S(reach+TLpred^2) psi(reach+TLpred^2) p(reach*year*pass+TLpred^2) DM}	7492.807	11.62	0.001	0.003	76	7335.30
19	{S(reach*year) psi(reach) p(reach*year*pass) PIM}	7496.616	15.43	0.000	0.000	75	7341.26
20	{S(.) psi(reach) p(reach*year)}	7603.777	122.59	0.000	0.000	36	7530.55
21	{S(reach) psi(reach) p(reach*year)}	7611.639	130.45	0.000	0.000	40	7530.12

Table 3. Abundance estimates, 95% confidence intervals, coefficients of variation (CV's, as %), and numbers of unique individuals captured (M_{t+1}) for adult ($\geq$ 450-mm TL) Colorado pikeminnow in the Yampa River, Colorado, 2006 to 2008.

Life stage	Year	Abundance	SE	95% CI	CV	M_{t+1}
Adults						
	2006	149	75	71 - 409	51	37
	2007	153	66	74 - 354	43	23
	2008	140	52	75 - 297	37	30

Table 4. Abundance estimates, 95% confidence intervals, coefficients of variation (CV's, as %), and numbers of unique individuals captured (M_{t+1}) for adult ($\geq$ 450-mm TL), recruit-sized (400 to 449-mm TL), and juvenile (<400 mm TL) Colorado pikeminnow in the White River, Utah and Colorado, 2006 to 2008.

Life stage	Year	Abundance	SE	95% CI	CV	M_{t+1}
Adults						
	2006	321	83	207 - 548	26	94
	2007	451	95	309 - 691	21	100
	2008	660	224	355 - 1278	34	55
Recruits						
	2006	0				
	2007	88	24	54 - 154	28	21
	2008	24	18	7 - 91	75	2
Juveniles						
	2006	0				
	2007	13	7	6 - 38	55	3
	2008	83	40	36 - 207	48	7

Table 5. Abundance estimates, 95% confidence intervals, coefficients of variation (CV's, as %), and numbers of unique individuals captured (M_{t+1}) for adult ($\geq$ 450-mm TL), recruit-sized (400 to 449-mm TL), and juvenile (<400 mm TL) Colorado pikeminnow in the middle Green River, Utah, 2006 to 2008.

Life stage	Year	Abundance	SE	95% CI	CV	M_{t+1}
Adults						
	2006	674	255	350 - 1422	38	104
	2007	1026	324	575 - 1901	32	93
	2008	1109	460	520 - 2444	41	53
Recruits						
	2006	25	15	11 - 78	59	5
	2007	142	57	69 - 308	40	13
	2008	207	104	84 - 532	50	10
Juveniles						
	2006	6	6	2 - 34	99	1
	2007	97	43	45 - 227	44	9
	2008	124	70	46 - 352	57	6

Table 6. Abundance estimates, 95% confidence intervals, coefficients of variation (CV's, as %), and numbers of unique individuals captured (M_{t+1}) for adult ($\geq$ 450-mm TL), recruit-sized (400 to 449-mm TL), and juvenile (<400 mm TL) Colorado pikeminnow in the Desolation-Gray Canyon reach of the Green River, Utah, 2006 to 2008.

Life stage	Year	Abundance	SE	95% CI	CV	M_{t+1}
Adults						
	2006	519	115	350 - 813	22	117
	2007	484	120	307 - 793	25	69
	2008	1296	463	669 - 2580	36	73
Recruits						
	2006	79	23	48 - 141	29	17
	2007	391	100	246 - 651	26	60
	2008	265	112	123 - 594	42	15
Juveniles						
	2006	182	45	120 - 302	24	52
	2007	87	30	48 - 172	34	13
	2008	105	56	42 - 282	53	6

Table 7. Abundance estimates, 95% confidence intervals, coefficients of variation (CV's, as %), and numbers of unique individuals captured (M_{t+1}) for adult ($\geq$ 450-mm TL), recruit-sized (400 to 449-mm TL), and juvenile (<400 mm TL) Colorado pikeminnow in the lower Green River, Utah, 2006 to 2008.

Life stage	Year	Abundance	SE	95% CI	CV	M_{t+1}
Adults						
	2006	791	103	617 - 1025	13	126
	2007	604	77	476 - 783	13	169
	2008	467	112	301 - 752	24	68
Recruits						
	2006	321	47	245 - 434	15	85
	2007	207	32	157 - 284	15	65
	2008	157	45	94 - 277	29	23
Juveniles						
	2006	987	124	785 - 1279	13	330
	2007	212	33	161 - 292	15	67
	2008	163	46	98 - 286	28	24

Table 8. Probabilities of capture for Colorado pikeminnow from the Green River Basin 2006 to 2008, for each sampling occasion, reach, and year. Estimates of p^* were from the Cormack-Jolly-Seber component of the model used to estimate annual survival rates (recaptures between years) and from the *p*'s for passes within years.

River/reach	Sampling occasion	2006	2007	2008	mean
Yampa River	1	0.074	0.021	0.038	0.044
	2	0.040	0.042	0.053	0.045
	3	0.154	0.099	0.151	0.135
	means	0.090	0.054	0.081	0.075
White River	1	0.115	0.080	0.052	0.082
	2	0.119	0.086	0.019	0.074
	3	0.094	0.084	0.018	0.065
	means	0.109	0.083	0.029	0.074
Middle Green River reach	1	0.074	0.018	0.007	0.033
	2	0.055	0.029	0.019	0.034
	3	0.035	0.050	0.027	0.037
	means	0.055	0.032	0.017	0.035
Desolation-Gray Canyon reach	1	0.092	0.075	0.021	0.063
	2	0.095	0.054	0.019	0.056
	3	0.073	0.037	0.024	0.045
	means	0.087	0.055	0.021	0.054
Lower Green River reach	1	0.111	0.153	0.054	0.106
	2	0.093	0.123	0.056	0.091
	3	0.080	0.055	0.047	0.061
	means	0.095	0.110	0.052	0.086
	Overall mean	0.087	0.067	0.040	0.065

Table 9. Weighted regression models to estimates trends in adult Colorado pikeminnow abundance. Intercept-only (*I*), linear (*I, T*), or quadratic (*I, T, T^2*) regression relationship estimates of abundance estimates for adult Colorado pikeminnow in reaches (Yampa = Yampa River, White = White River, M. Green = middle Green River, Deso-Gray = Desolation-Gray Canyon, Green River, L. Green = lower Green River, Basin = all five reaches combined) of the Green River Basin, Colorado and Utah, 2006 to 2008, as a function of coefficients for *Time* (*T*, year, year 2000 = 1, year 2001 = 2, and so on) and *$Time^2$* (T^2, year squared); *I* = *Intercept*. For quadratic relationships, the *T* coefficient mostly estimates the rate of decline of Colorado pikeminnow populations from 2000-2003, and the T^2 coefficient mostly estimates the rate of increase for populations from 2006 to 2008. For relationships with intercept only or linear (*T*) terms, that coefficient estimates the trend of the population for the entire period. Estimates are for adult fish (≥450 mm total length (TL) only); SE = standard error. Weights are the relative degree of support (larger proportion = greater support) each model has among other competing models and sum to 1 for each set of models.

River	Model	df	Intercept (SE)	Time (SE)	$Time^2$ (SE)	Weight
Yampa	*I*	1,6	223.9 (36.0)			< 0.01
	I, T	2,6	356.3 (18.5)	-25.6 (3.1)		0.99
	I, T, T^2	3,6	404.9 (30.8)	-53.3 (15.6)	2.6 (1.5)	0.01
White	*I*	1,6	479.6 (89.5)			0.40
	I, T	2,6	769.5 (183.6)	-57.1 (32.9)		0.08
	I, T, T^2	3,6	1423.9 (127.0)	-382.2 (56.6)	32.4 (5.5)	0.52
M. Green	*I*	1,6	1033.2 (176.4)			< 0.01
	I, T	2,6	1466.0 (252.4)	-136.6 (66.7)		< 0.01
	I, T, T^2	3,6	2134.4 (73.9)	-584.3 (41.3)	54.0 (4.8)	0.99
Deso-Gray	*I*	1,5	573.2 (83.5)			0.97
	I, T	2,5	802.6 (170.9)	-44.4 (29.8)		0.03
	I, T, T^2	3,5	891.3 (525.3)	-91.6 (259.9)	4.8 (26.0)	< 0.01
L. Green	*I*	1,5	358.2 (85.2)			0.96
	I, T	2,5	144.3 (158.8)	52.1 (34.2)		0.04
	I, T, T^2	3,5	364.0 (483.5)	-55.2 (222.0)	10.3 (21.0)	< 0.01

Table 10. Abundance estimates, 95% confidence intervals, coefficients of variation (CV's, as %), and numbers of unique individuals captured (M_{t+1}) for adult ($\geq$ 450-mm TL), recruit-sized (400 to 449-mm TL), and juvenile (<400 mm TL) Colorado pikeminnow in the Green River Basin, Colorado and Utah, 2006 to 2008.

Life stage	Year	Abundance	SE	95% CI	CV	M_{t+1}	% recruits
Adults							
	2006	2454	319	1920 - 3185	13	478	
	2007	2718	404	2055 - 3656	15	454	
	2008	3672	828	2397 - 5715	23	279	
Recruits							
	2006	426	55	335 - 552	13	107	17
	2007	828	128	620 - 1130	16	159	30
	2008	652	174	396 - 1098	27	50	18
Juveniles							
	2006	1176	133	955 - 1481	11	383	
	2007	410	65	306 - 564	16	92	
	2008	475	119	297 - 777	25	43	

Table 11.–Apparent survival probability estimates (*S*, 95% CI) from capture-recapture data for Colorado pikeminnow captured in the Green River Basin in three periods, 1991 to1999, 2000 to 2003, and 2006 to 2008; estimates for the earlier two periods were from Bestgen et al. (2007). Because no TL effects are included for 2006 to 2008, those estimates are for all fish captured. Data for the intervals 1991 to 1999 were collected during a standardized monitoring program to estimate catch/effort indices for Colorado pikeminnow and were from about 23% of occupied habitat in the Green River Basin. Annual interval data from 2000 to 2003 were collected during a study to estimate abundance of adult and sub-adult Colorado pikeminnow throughout the Green River Basin; 2000 data were from only the middle Green, Yampa, and White rivers. Estimates of probabilities of capture (*p*) for Colorado pikeminnow for the three time periods are also presented.

Parameter	Period	*S* or *p*	95% CI
Survival	1991-1999	0.82	0.71 to 0.89
	2000-2003	0.65	0.59 to 0.71
	2006-2008	0.80	0.60 to 0.91
Probability of capture	1991-1999	0.053	0.038 to 0.074
	2000-2003	0.090	0.054 to 0.119
	2006-2008	0.065	0.036 to 0.118

Table 12. Annual transition probabilities (ψ_{ij}, movement to a different reach between years) for Colorado pikeminnow captured in the Green River Basin, Utah and Colorado, 2006 to 2008. River reaches are: Yampa R. = Yampa River (RK 192 to 74), White R. = White River (RK 167.4 to 0), middle Green R. = middle Green River reach (RK = 539.4 to 396.1), Deso-Gray = Desolation-Gray Canyon reach, Green River (RK 395.9 to 206.1), and lower Green R. = lower Green River reach (RK 193.2 to 0).

River reach	ψ	95% CI
White R. to Yampa R.	0.018	0.002 to 0.132
White R. to middle Green R.	0.053	0.006 to 0.356
White R. to Deso-Gray	0.047	0.006 to 0.286
White R. to Lower Green R	0	
Yampa R. to White R.	0	
Yampa R. to middle Green R.	0	
Yampa R. to Deso-Gray	0	
Yampa R. to lower Green R.	0	
middle Green R. to White R.	0.057	0.013 to 0.218
middle Green R. to Yampa R.	0	
middle Green R. to Deso-Gray	0.041	0.005 to 0.255
middle Green R. to lower Green R.	0.024	0.003 to 0.156
Deso-Gray to White R.	0.036	0.007 to 0.154
Deso-Gray to Yampa R.	0.024	0.006 to 0.098
Deso-Gray to middle Green R.	0.185	0.065 to 0.424
Deso-Gray to lower Green R.	0.008	0.000 to 0.156
lower Green R. to White R.	0.068	0.034 to 0.131
lower Green R. to Yampa R.	0.010	0.002 to 0.048
lower Green R. to middle Green R.	0.031	0.008 to 0.120
lower Green R. to Deso-Gray	0.323	0.214 to 0.455

Table 13. Average annual transition probabilities (ψ, annual probability of movement to or from each reach, using only non-zero values) for Colorado pikeminnow captured in the Green River Basin, Utah and Colorado, 2006 to 20008. A positive net ψ suggested more fish moved into the reach than out, a negative value of ψ suggested more fish moved out of the reach than into it. River reaches are: Yampa R. = Yampa River (RK 192 to 74), White R. = White River (RK 167.4 to 0), middle Green R. = middle Green River reach (RK = 539.4 to 396.1), Deso-Gray = Desolation-Gray Canyon reach, Green River (RK 395.9 to 206.1), and lower Green R. = lower Green River reach (RK 193.2 to 0).

River reach	Average ψ to:	Average ψ from:	Net ψ
Yampa River	0.013	0.000	0.013
White River	0.040	0.030	0.011
middle Green River	0.067	0.060	0.007
Desolation-Gray Canyon, Green R.	0.103	0.063	0.039
lower Green River	0.008	0.108	-0.100

Table 14. Annual sampling effort comparisons for each Green River Basin reach in two periods, 2000 to 2003 (2001-2003 for Desolation-Gray Canyon and lower Green River reaches) and 2006 to 2008. Effort metrics are in terms of sampling passes through each reach (passes), days spent sampling, and electrofishing hours. For passes when total electrofishing hours were incomplete or not available, effort was estimated based on the mean hours of sampling for other passes conducted in that year. Fyke net sampling was not included in effort calculations. CPM = total fish captured.

	Sampling	1st period					2nd period			
Reach	Metric	2000	2001	2002	2003	mean	2006	2007	2008	mean
Yampa R.										
	passes[1]	4	4	4	4	4	3	3	3	3
	days	34	33	30	35	33	58	60	72	63.3
	hours	92	185	166	231	169	360	417	498	425
	CPM	89	140	33	31	73.3	40	23	32	31.7
White R.										
	passes	3	3	3	3	3	3	3	3	3
	days	22	24	26	24	24	24	25	23	24
	hours	189*	204	180	175	186	146	133	140	140
	CPM	313	236	184	117	213	105	135	65	102
M. Green R.										
	passes	4	4	3	3	3.5	3	3	3	3
	days	29	31	25	31	29	23	23	18	21.3
	hours	205	251	183	194	208	148	127	126	134
	CPM	732	393	109	190	356	117	122	72	104
Deso-Gray										
	passes		3	3	4	3.33	3	3	3	3
	days		29	27	34	30	24	24	24	24
	hours		252*	230	268*	230	194	163	165	174
	CPM		281	137	178	199	201	146	92	146
L. Green R.										
	passes		4	3	3	3.33	3	3	3	3
	days		35	27	27	29.7	25	26	26	25.7
	hours		329	247	253	276	236	232	231	233
	CPM		249	160	208	206	597	332	127	352

[1] Yampa River effort, 2006-2008 consisted of 6-9 passes in some reaches, 3 in the remainder
*the majority or all of the effort (189 and 252) is estimated for pass 2 in each reach, or (268), only pass 1 effort is not estimated, at least 50% of effort estimated on other 3 passes.

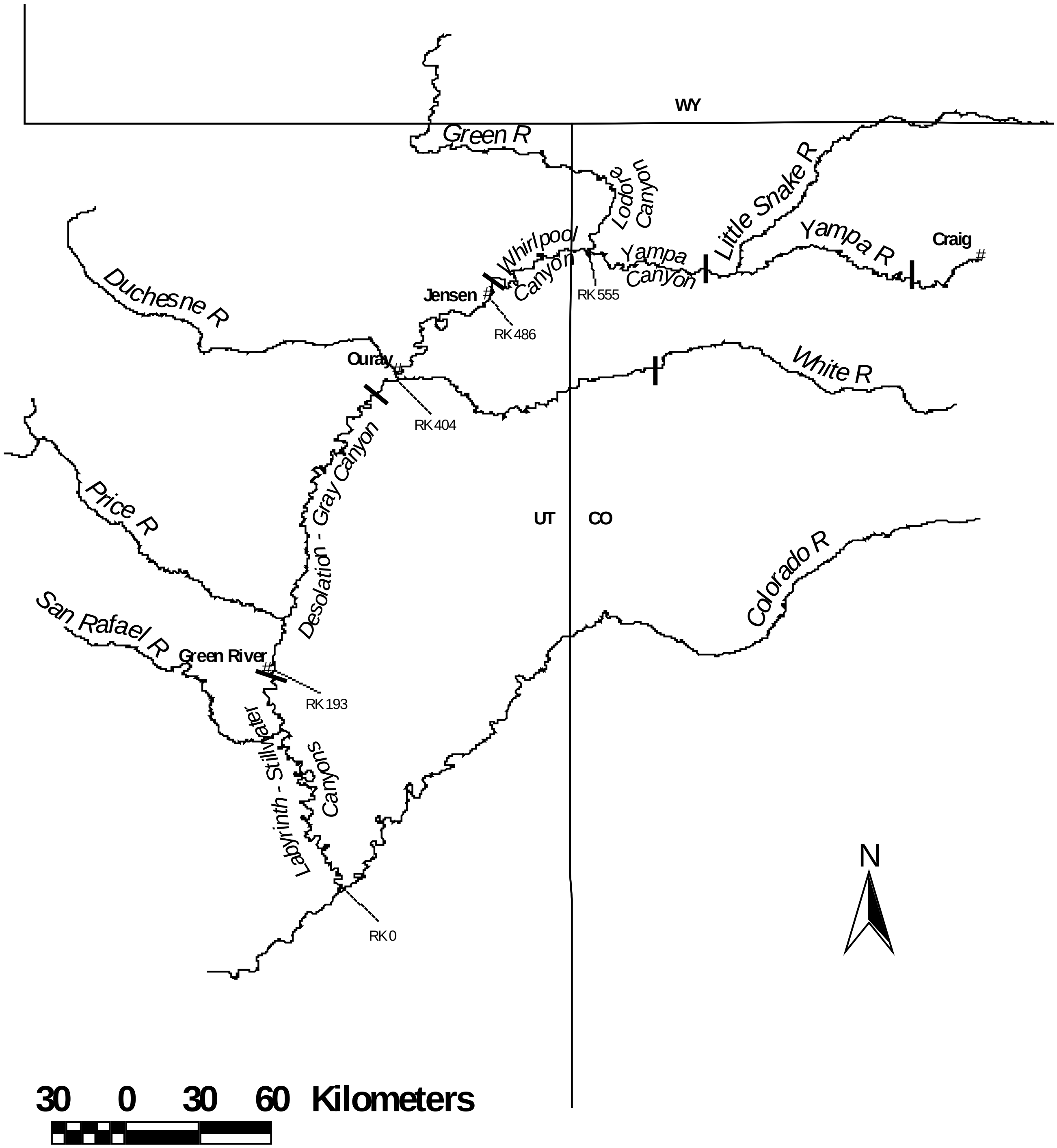

Figure 1. Map of Green River Basin study area. Heavy bars transverse to river denote study area segments in the Yampa River, the White River, and three segments of the Green River, the middle Green River, Desolation-Gray Canyon, and the lower Green River. No sampling occurred in Yampa Canyon or Whirlpool Canyon. Sampling also occurred in Island-Rainbow Park just downstream of Whirlpool Canyon, but not in Split Mountain Canyon.

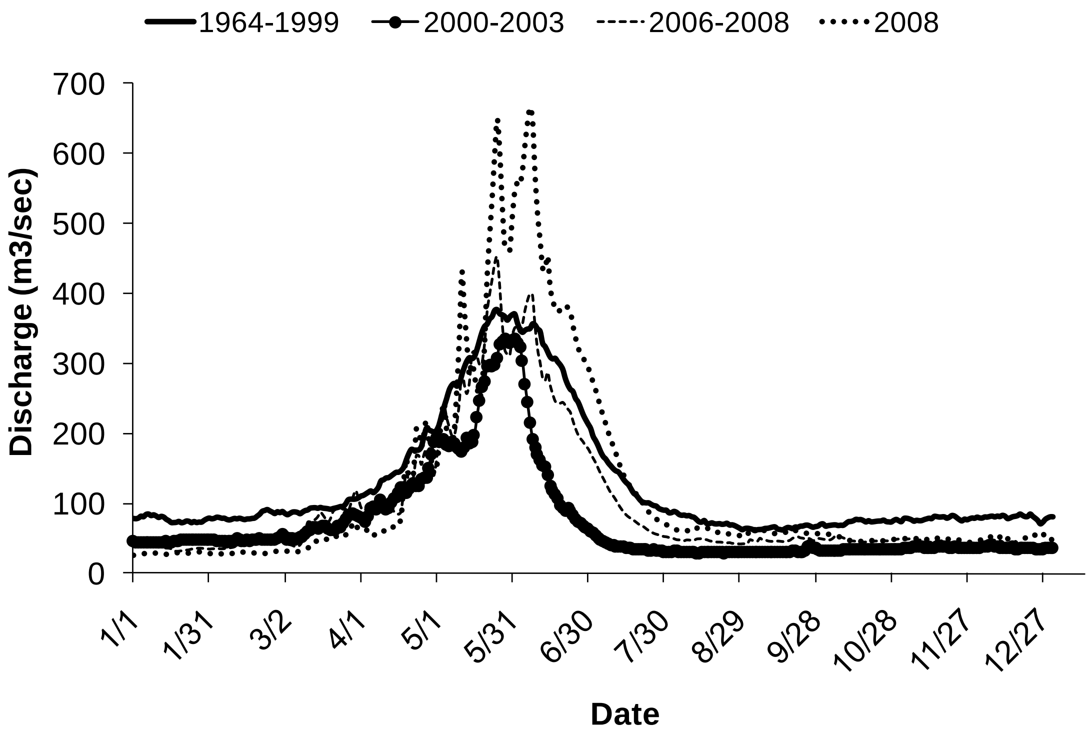

Figure 2. Average daily discharge of the Green River, near Jensen, Utah (gauge # 09261000), for the period 1964 to 1999, mean daily discharge in two abundance estimation periods, 2000 to 2003 and 2006 to 2008, and in year 2008.

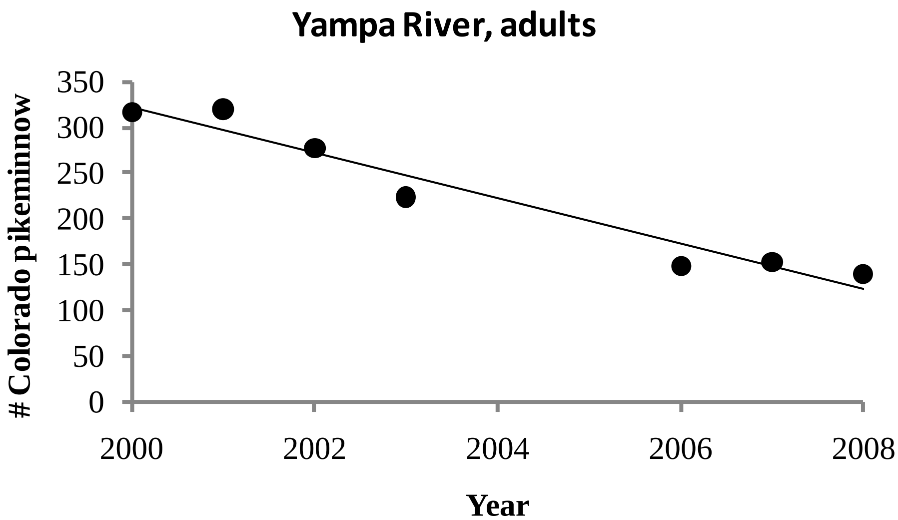

Figure 3. Abundance trend of Colorado pikeminnow adults (≥ 450-mm TL) in the Yampa River, Colorado, 2000 to 2003 and 2006 to 2008. Regression relationship is shown in Table 9.

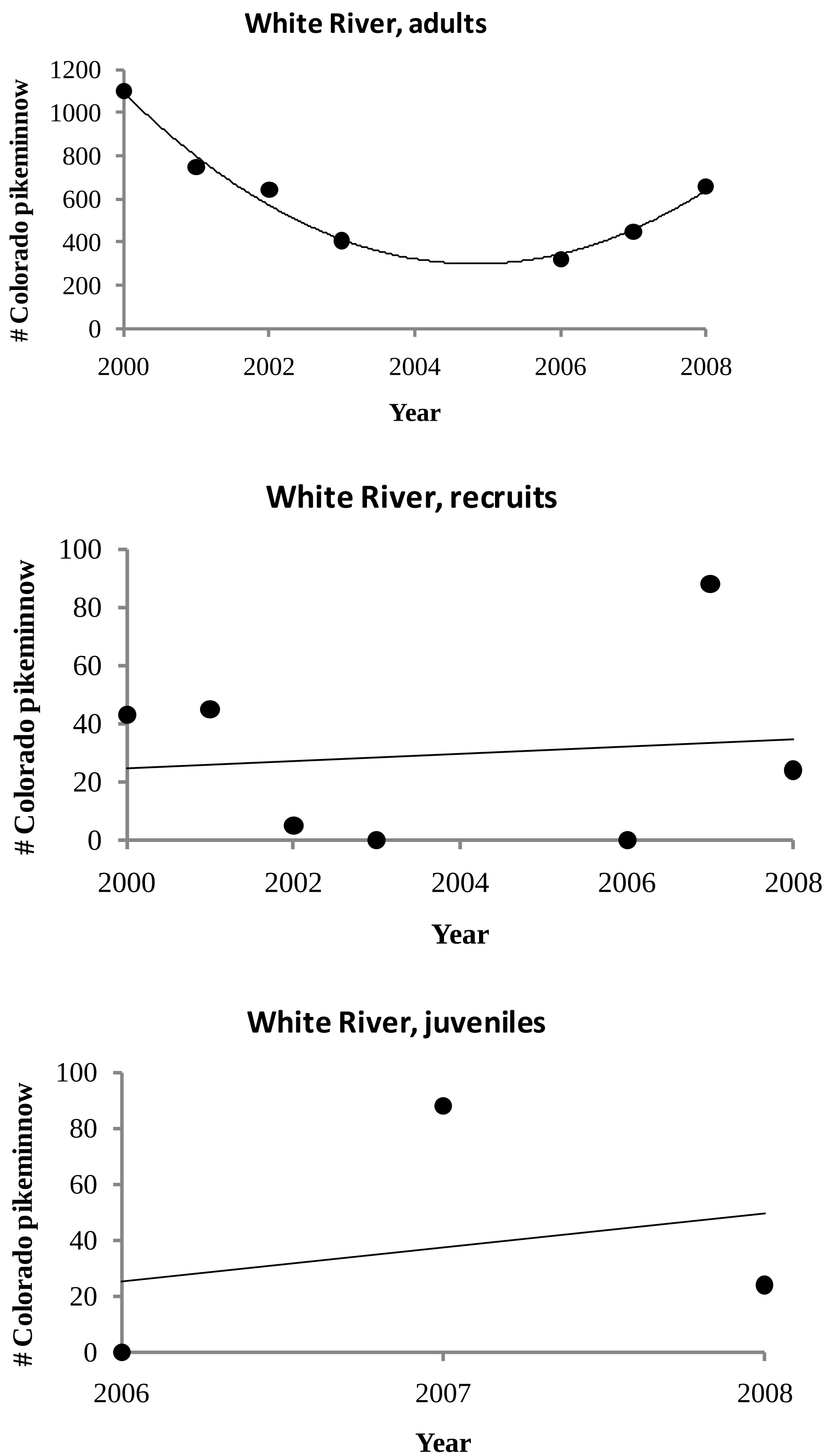

Figure 4. Abundance trends of Colorado pikeminnow adults (≥ 450-mm total length [TL]), recruits (400 to 449 mm TL), and juveniles (< 400 mm TL) in the White River, Utah and Colorado, 2000 to 2003 and 2006 to 2008. Regression relationship for adults is shown in Table 9.

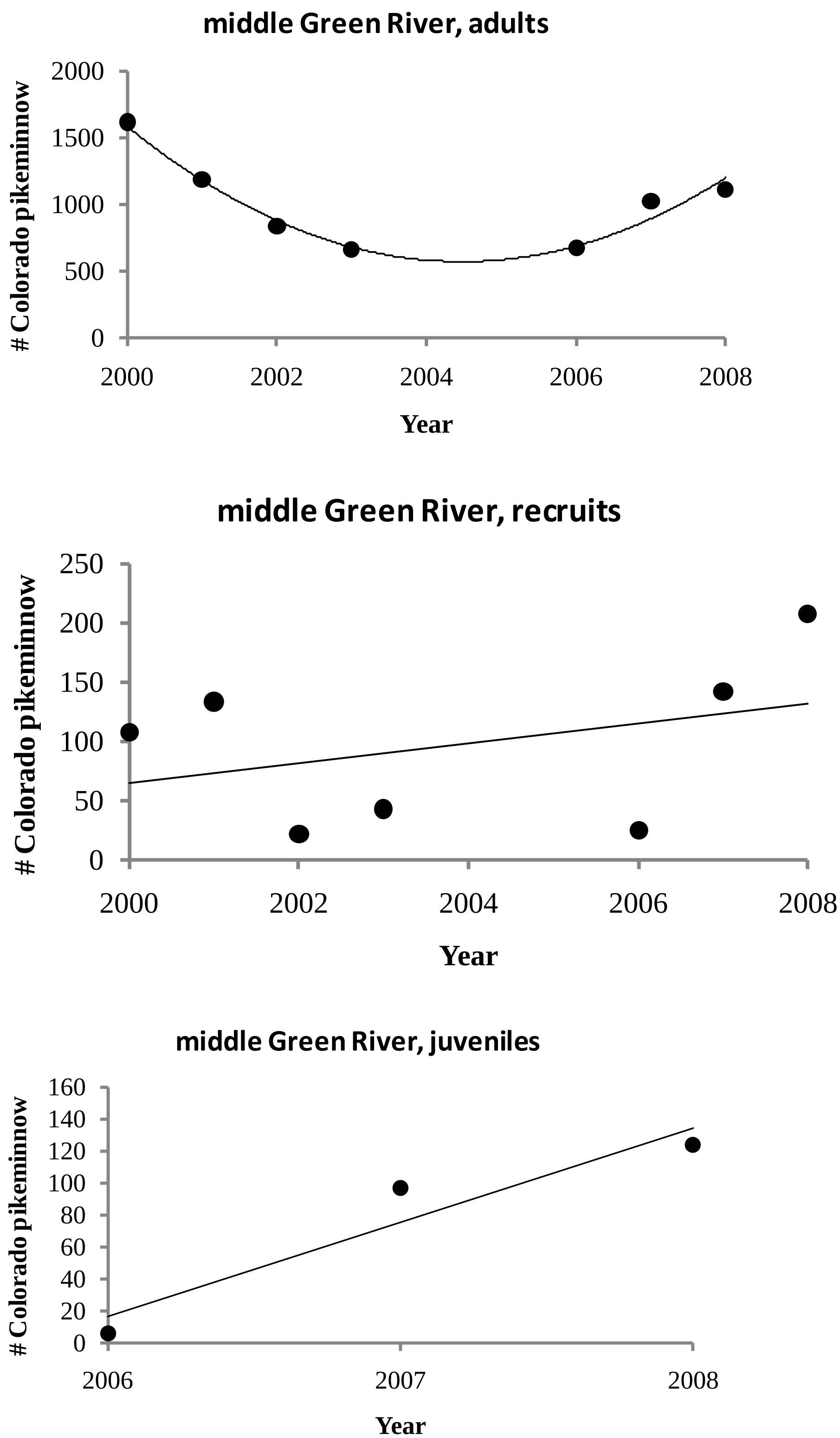

Figure 5. Abundance trends of Colorado pikeminnow adults (≥ 450-mm total length [TL]), recruits (400 to 449 mm TL), and juveniles (< 400 mm TL) in the middle Green River, Utah, 2000 to 2003 and 2006 to 2008. Regression relationship for adults is shown in Table 9.

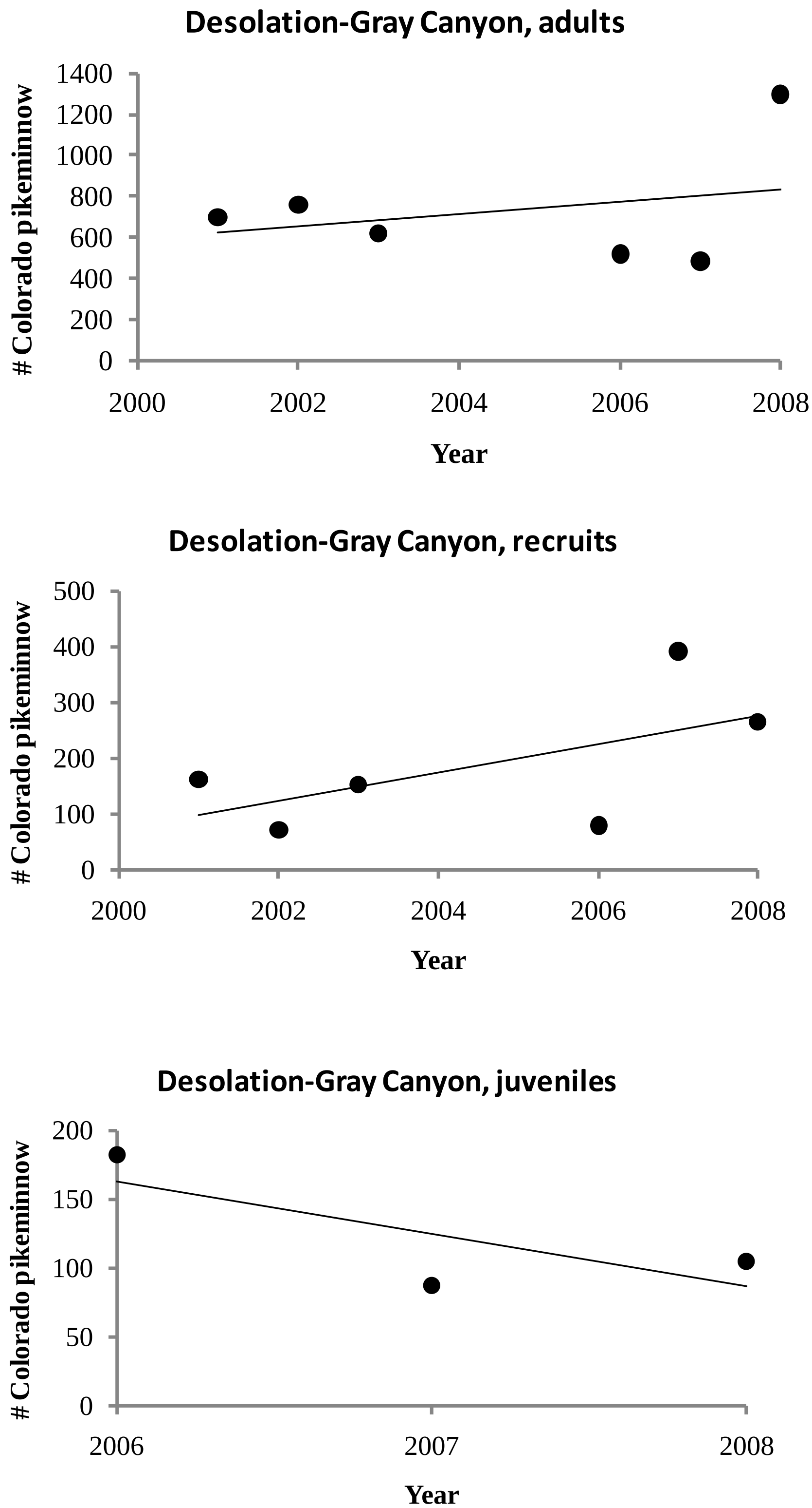

Figure 6. Abundance trends of Colorado pikeminnow adults ($\geq$ 450-mm total length [TL]), recruits (400 to 449 mm TL), and juveniles (< 400 mm TL) in the Desolation-Gray Canyon reach of the Green River, Utah, 2000 to 2003 and 2006 to 2008. Regression relationship for adults is shown in Table 9.

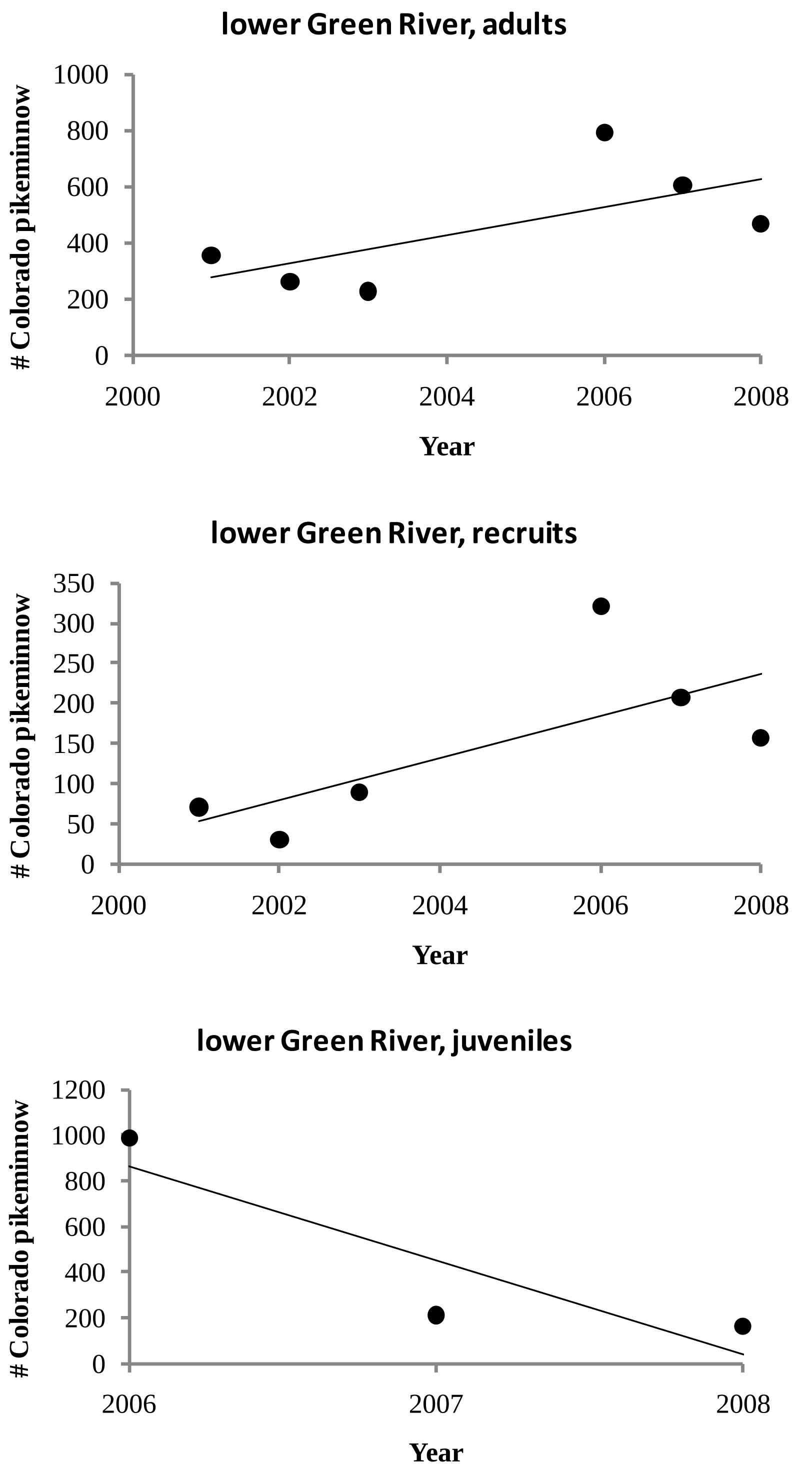

Figure 7. Abundance trends of Colorado pikeminnow adults ($\geq$ 450-mm total length [TL]), recruits (400 to 449 mm TL), and juveniles (< 400 mm TL) in the lower Green River, Utah, 2000 to 2003 and 2006 to 2008. Regression relationship for adults is shown in Table 9.

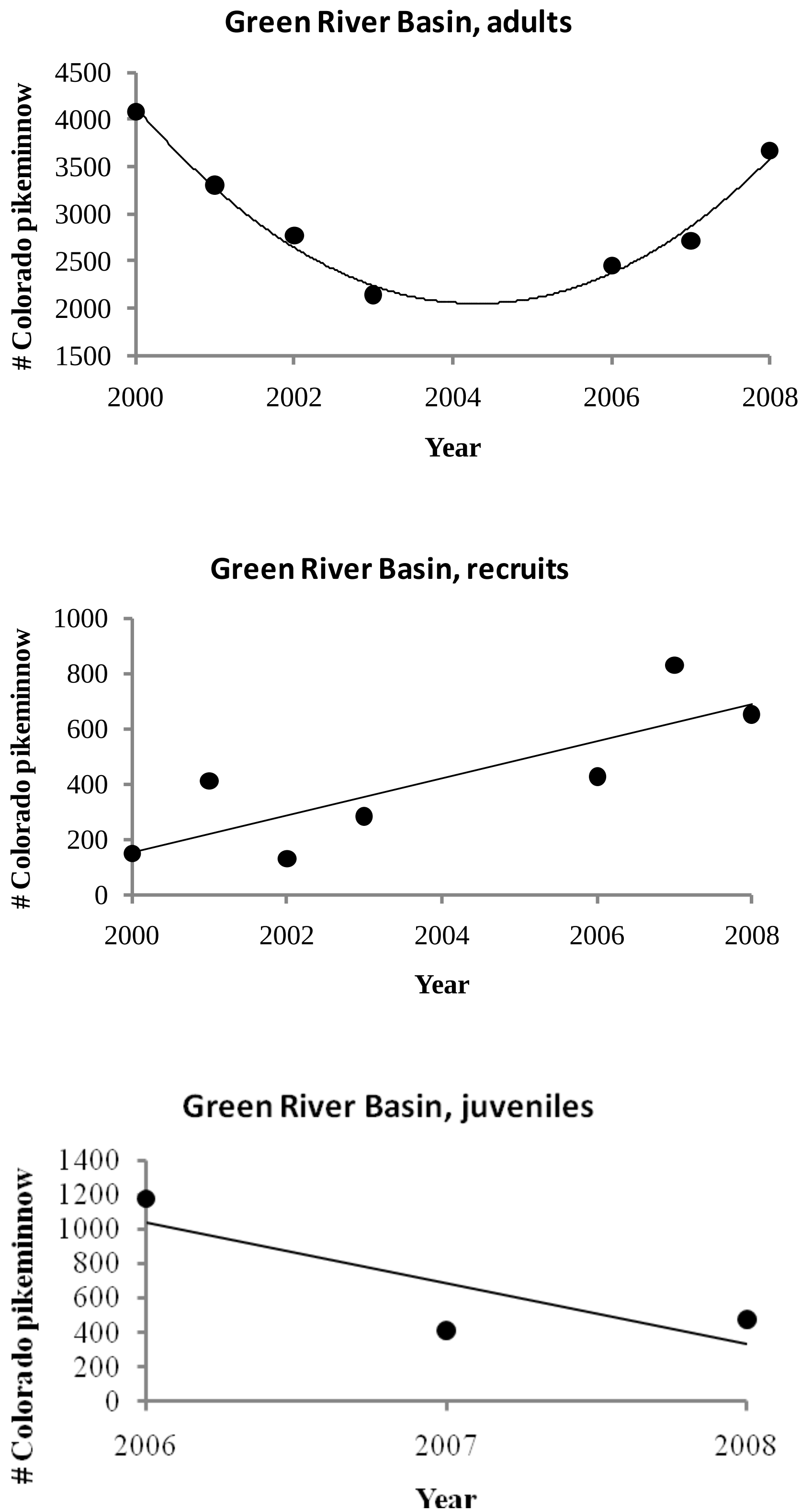

Figure 8. Abundance trends of Colorado pikeminnow adults (≥ 450-mm total length [TL]), recruits (400 to 449 mm TL), and juveniles (< 400 mm TL) in the Green River Basin, Utah and Colorado, 2000 to 2003 and 2006 to 2008. Regression relationship for adults is shown in Table 9.

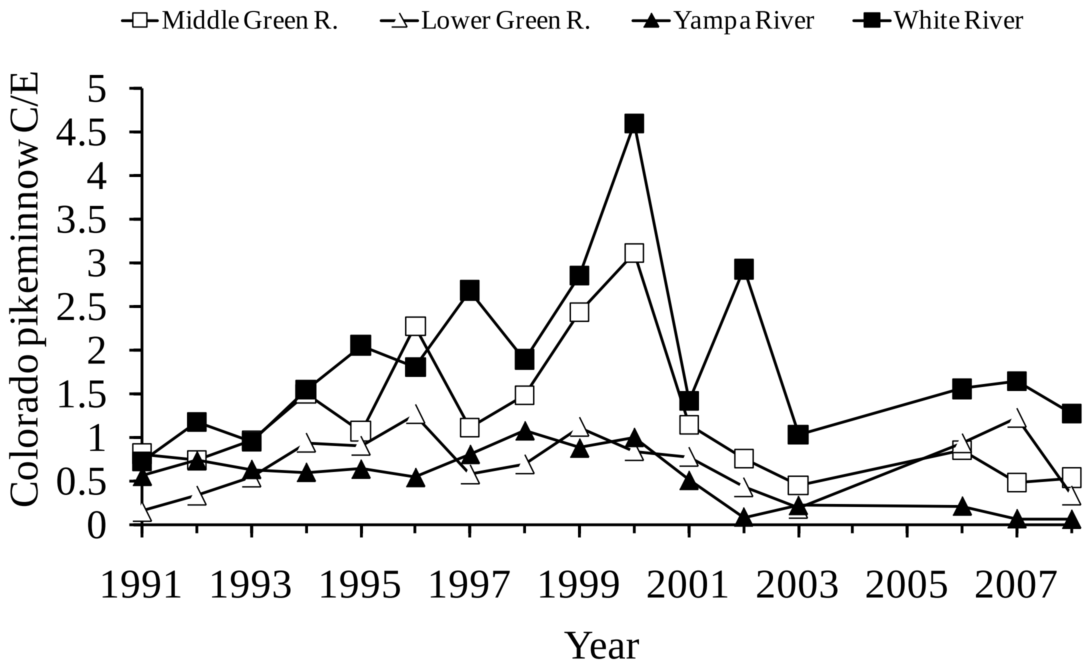

Figure 9. Interagency standardized monitoring program (ISMP) captures of sub-adult and adult Colorado pikeminnow per hour of electrofishing effort (C/E) in the Green River Basin, 1991 to 2003, and 2006 to 2008.

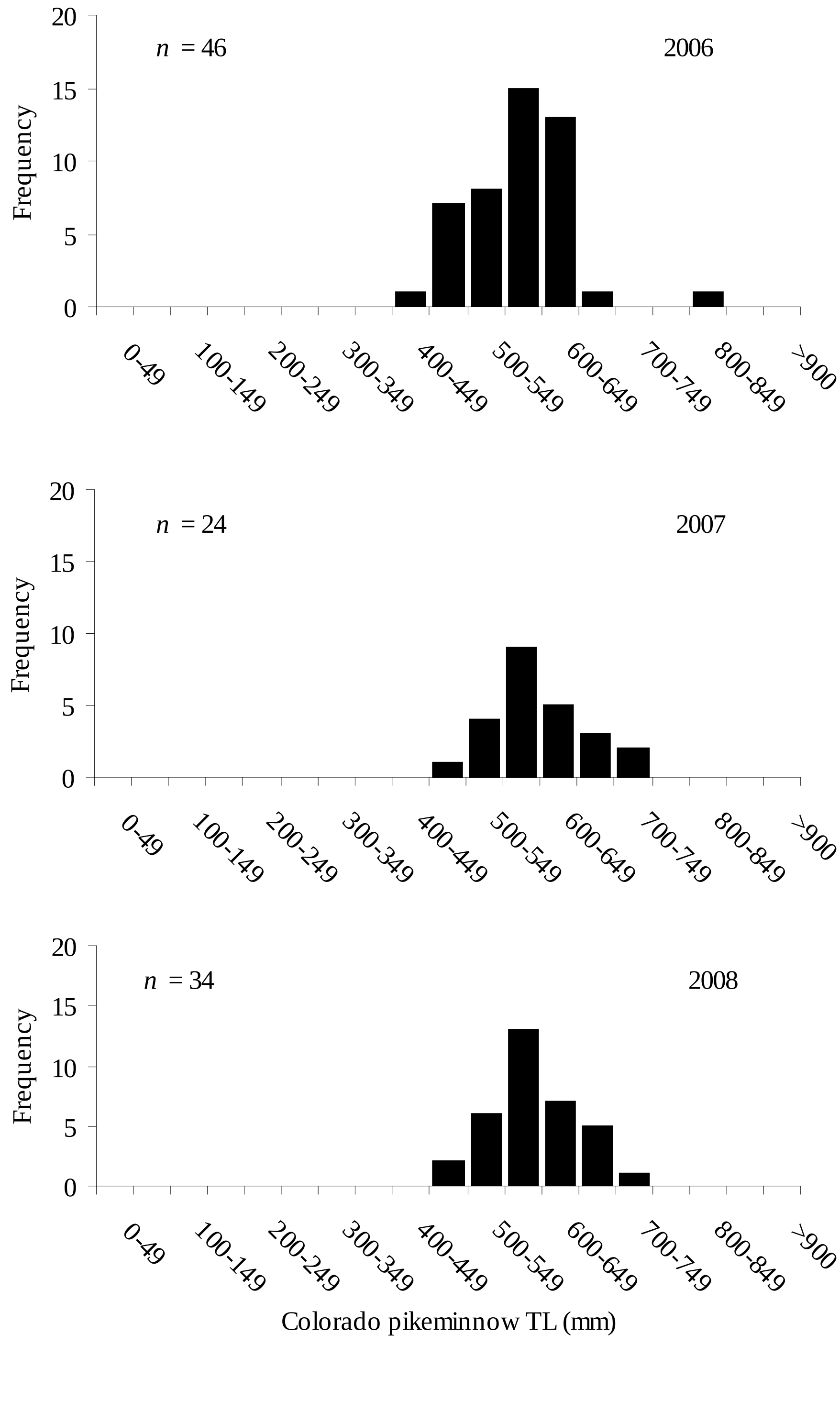

Figure 10. Length-frequency histograms for Colorado pikeminnow captured in the Yampa River, Colorado, 2006 to 2008, during Green River Basin abundance estimation sampling.

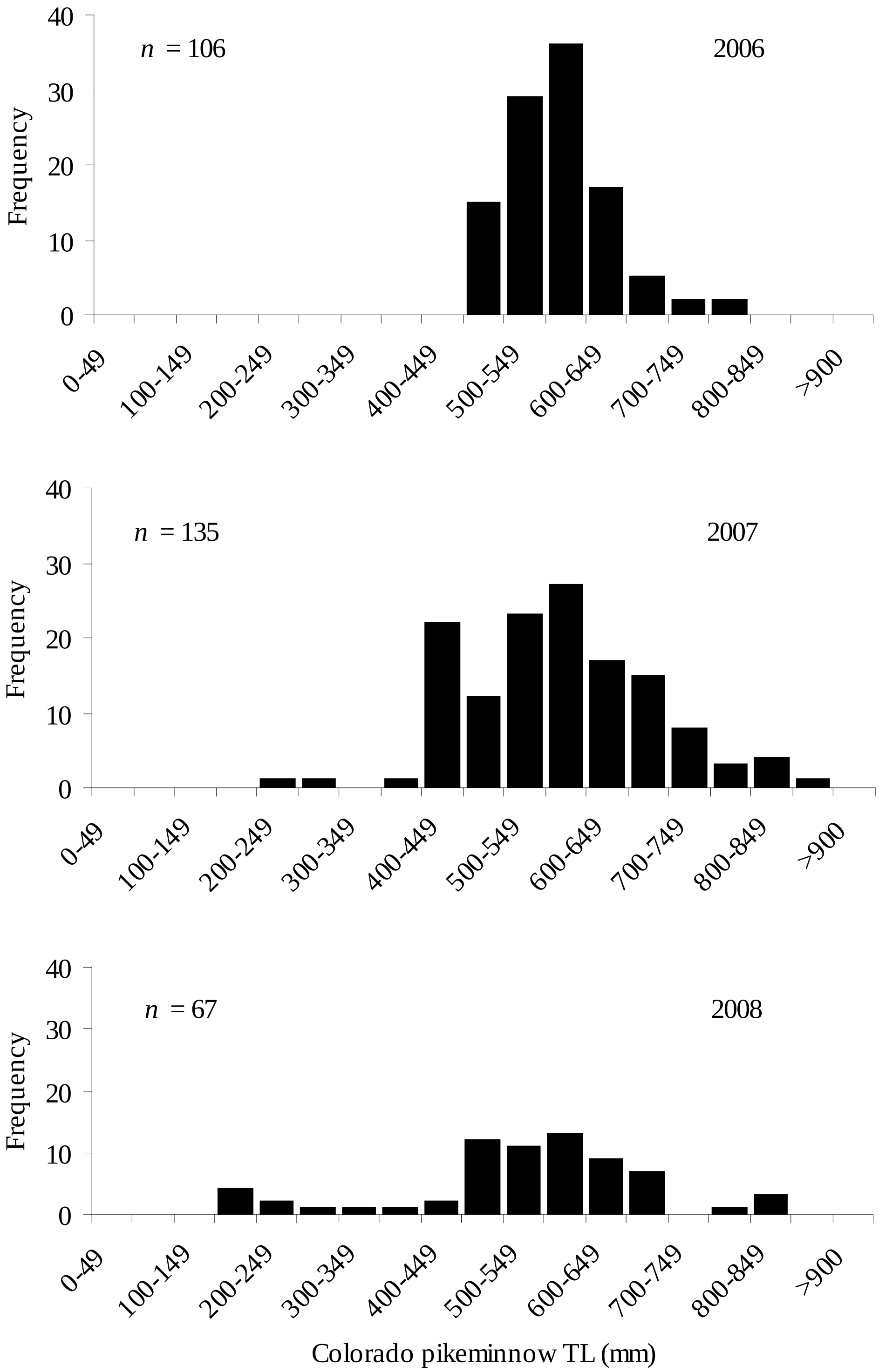

Figure 11. Length-frequency histograms for Colorado pikeminnow captured in the White River, Colorado and Utah, 2006 to 2008, during Green River abundance estimation sampling.

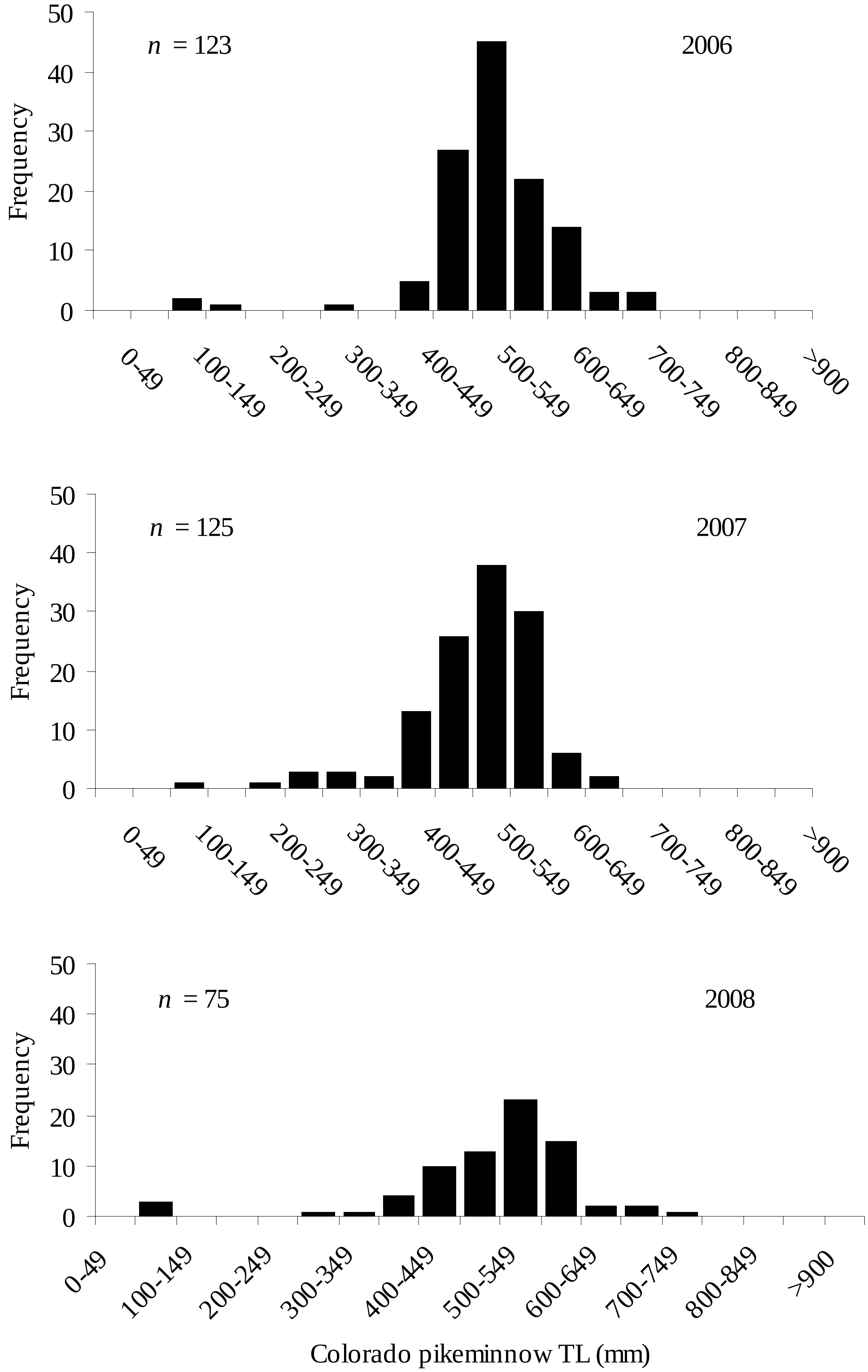

Figure 12. Length-frequency histograms for Colorado pikeminnow captured in the middle Green River, Utah, 2006 to 2008, during Green River abundance estimation sampling.

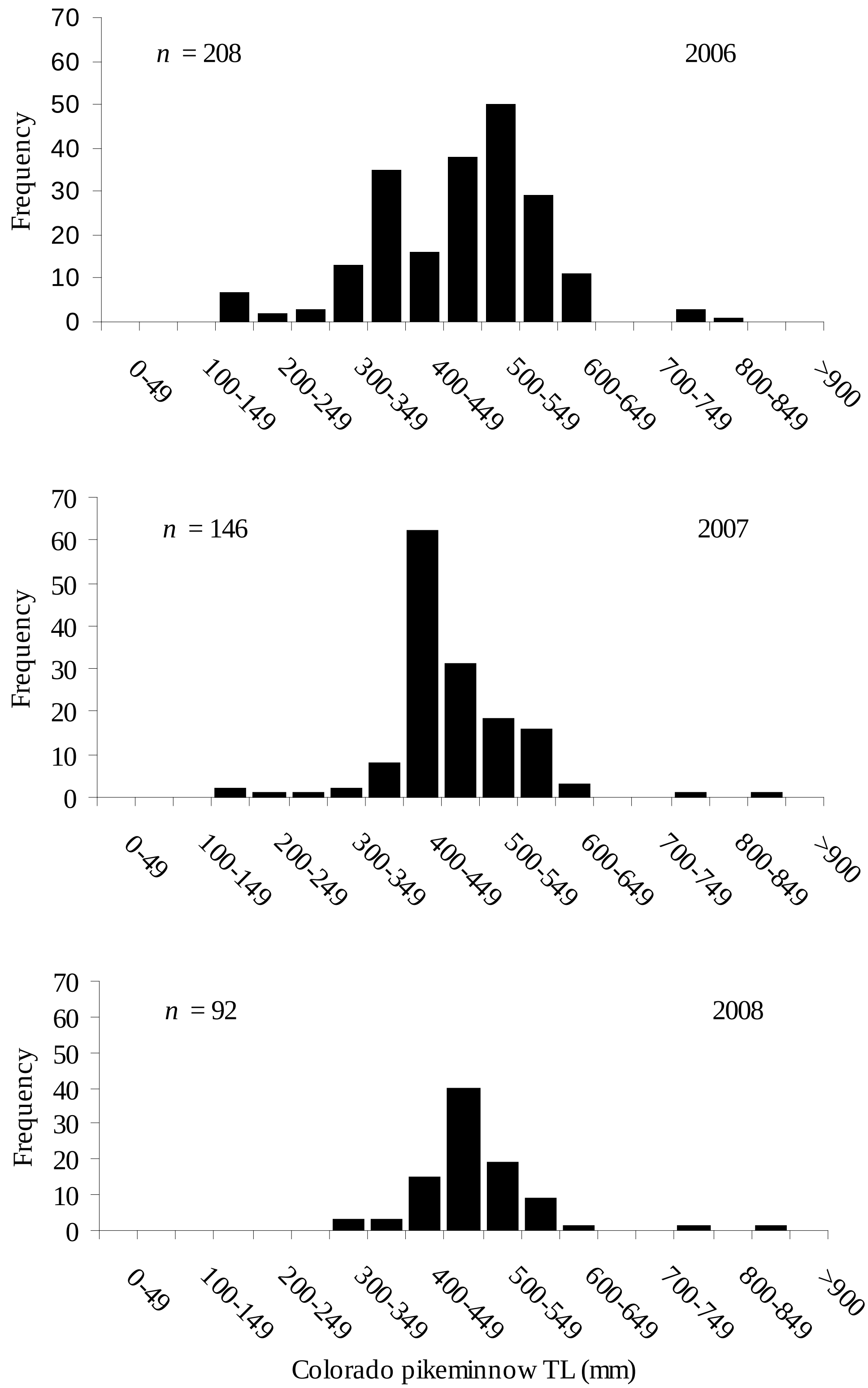

Figure 13. Length-frequency histograms for Colorado pikeminnow captured in the Desolation-Gray Canyon reach of the Green River, Utah, 2006 to 2008, during Green River abundance estimation sampling.

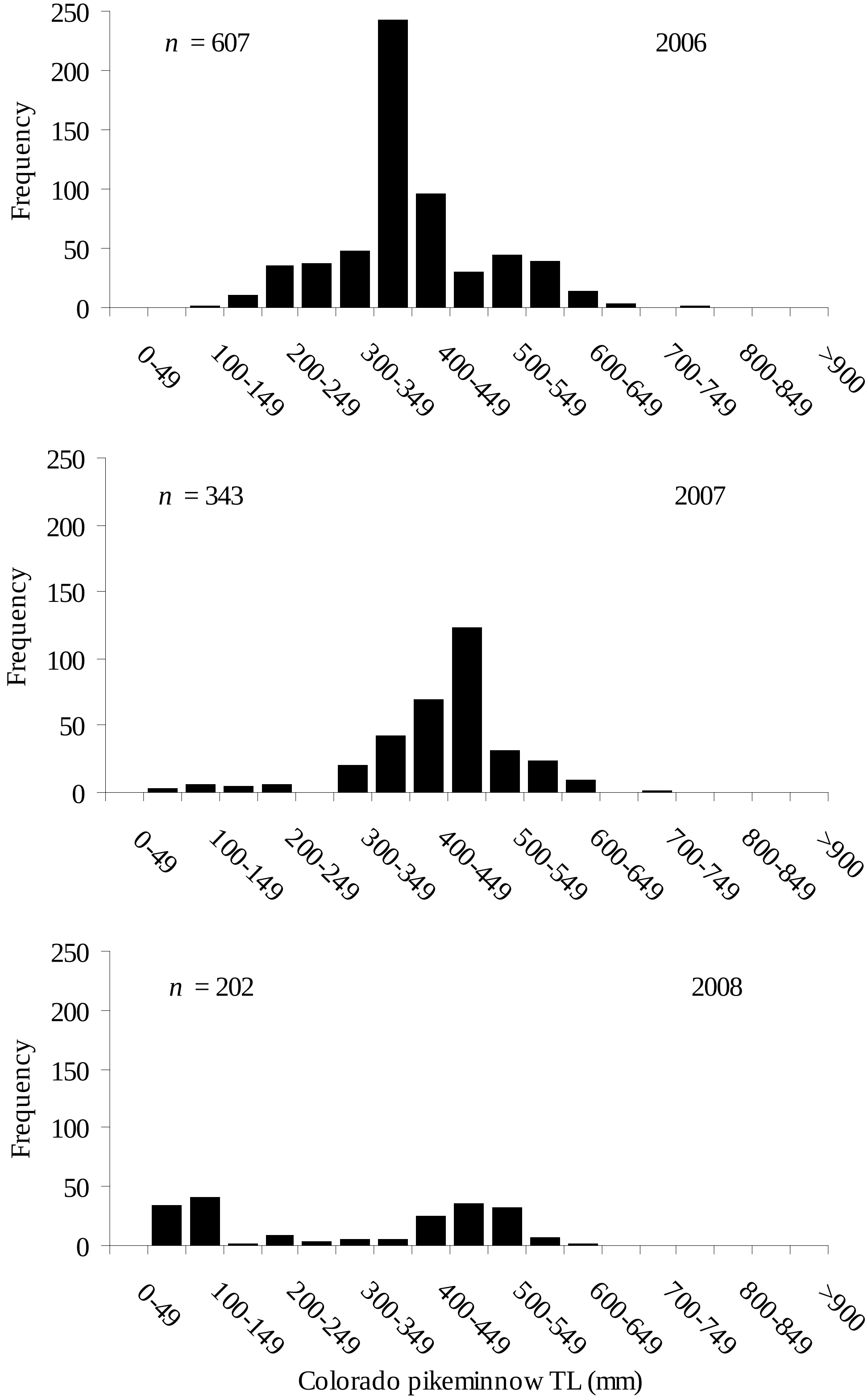

Figure 14. Length-frequency histograms for Colorado pikeminnow captured in the lower Green River reach, Utah, 2006 to 2008, during Green River abundance estimation sampling.

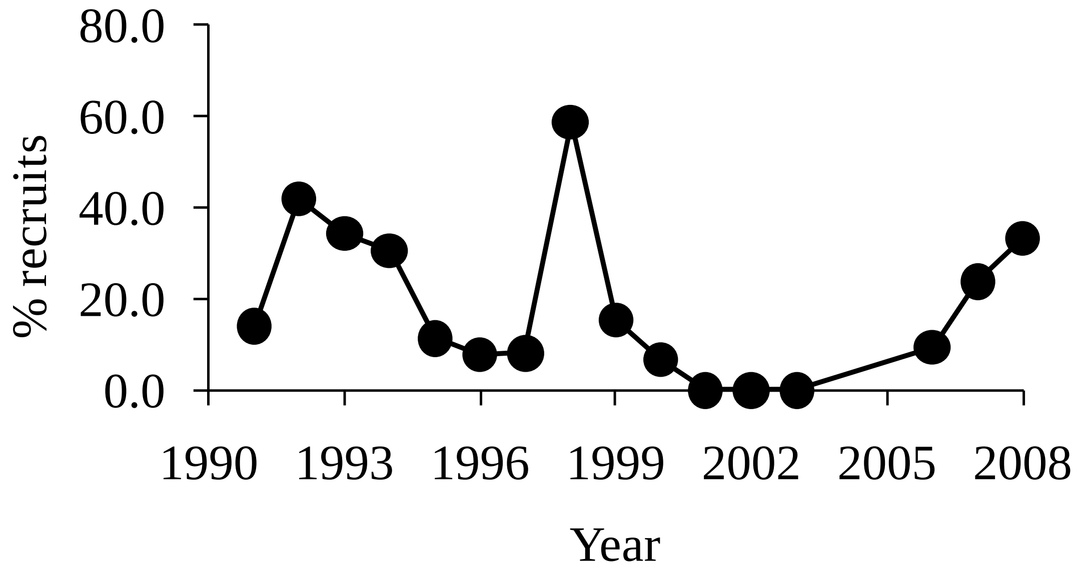

Figure 15. Percentage of recruit-sized (400 to 449 mm TL) Colorado pikeminnow relative to the number of adults ($\geq$ 450 mm TL) in Interagency Standardized Monitoring Program samples collected from the Green River Basin, Utah and Colorado, 1991 to 2003 and 2006 to 2008.

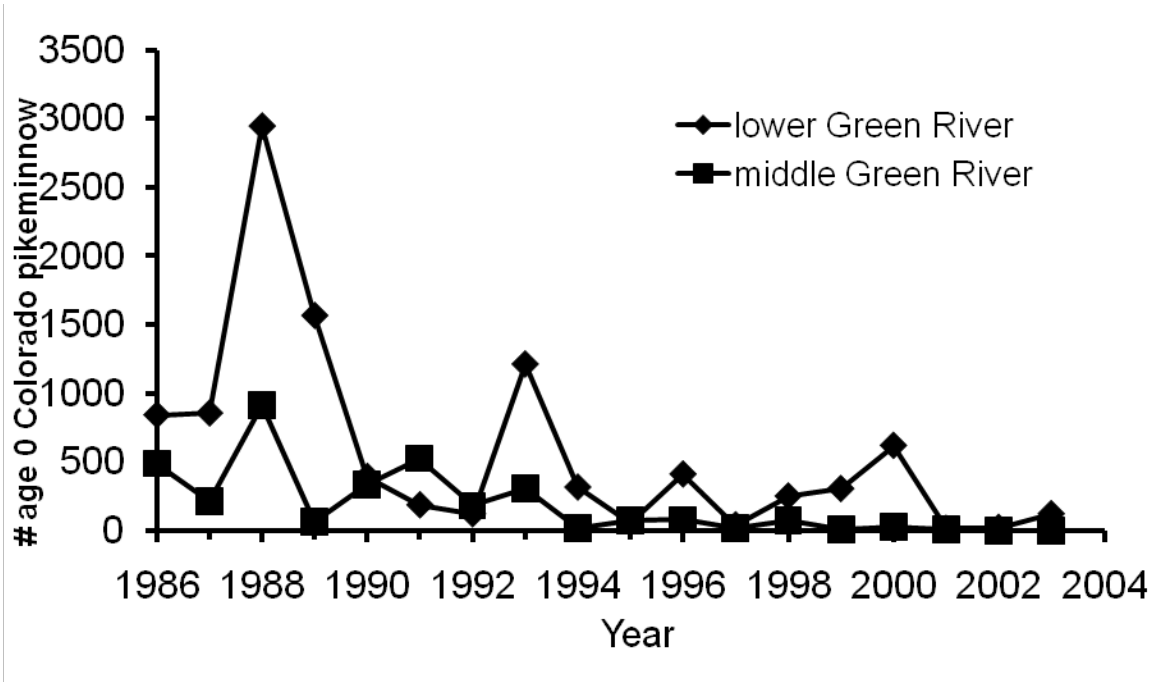

Figure 16. Abundance of age-0 Colorado pikeminnow in seine samples from backwaters in the middle and lower Green rivers, Utah, 1986 to 2003.

APPENDICES

Appendix I. Sampling dates, capture data, and effort for middle Green River, Yampa River, and White River abundance estimation sampling for Colorado pikeminnow, 2006. Electrofishing effort includes main channel and backwater sampling associated with trammel nets.

	Dates	Days Sampled	River km Sampled	Electrofishing Effort (hours)	Pikeminnow Captured [1]	Pikeminnow Recaptured [2]
Middle Green River						
Pass 1	April 17 - 27	9	537-396	56	53	0
2	May 2 - June 1	7	537-396	50	39	4
3	June 5 - 14	7	537-396	42	25	2
Total		23		148	117	6
Yampa River						
Pass 1	April 18 - May 3	15	216-82	85	11	0
2	May 3 - 12	11	216-83	74	6	1
3	May 9 - June 20	32	216-80	201	23	2
Total		58		360	40	3
White River						
Pass 1	April 28 - May 5	8	167-0	50	37	0
2	May 9 - 18	8	167-0	49	38	2
3	May 19 - June 2	8	167-0	47	30	8
Total		24		146	105	10

[1] All PIT tagged Colorado pikeminnow.
[2] Recaptured fish are those handled on previous sampling passes in 2006.

Appendix II. Sampling dates, capture data, and effort for Desolation-Gray and lower Green River abundance estimation sampling for Colorado pikeminnow, 2006. Electrofishing effort includes main channel and backwater sampling associated with trammel nets.

	Dates	Days Sampled	River km Sampled	Electrofishing Effort (hours)	Pikeminnow Captured [1]	Pikeminnow Recaptured [2]
Desolation-Gray Canyon, Green River						
Pass 1	March 27 - April 7	8	396-207	71	72	0
2	April 10 - 14	8	396-207	62	74	10
3	April 19 - 26	8	396-207	61	55	7
Total		24		194	201	17
Lower Green River						
Pass 1	May 3 - 10	8	193-0	76	232	0
2	May 24 - June 1	9	193-0	85	197	32
3	June 14 - 21	8	193-0	75	168	22
Total		25		236	597	54

[1] All PIT tagged Colorado pikeminnow.
[2] Recaptured fish are those handled on previous sampling passes in 2006.

Appendix III. Sampling dates, capture data, and effort for middle Green River, Yampa River, and White River abundance estimation sampling for Colorado pikeminnow, 2007. Electrofishing effort includes main channel and backwater sampling associated with trammel nets.

	Dates	Days Sampled	River km Sampled	Electrofishing Effort (hours)	Pikeminnow Captured [1]	Pikeminnow Recaptured [2]
Middle Green River						
Pass 1	April 11 - 27	9	538-396	43	22	0
2	April 30 - May 9	7	538-396	40	36	1
3	May 14 - 24	7	538-396	44	64	3
Total		23		127	122	4
Yampa River						
Pass 1	April 17 - 24	10	216-81	71	3	0
2	April 25 - May 8	14	216-81	107	6	0
3	May 15 - June 30	36	216-81	239	14	0
Total		60		417	23	0
White River						
Pass 1	April 30 - May 16	9	167-0	45	43	0
2	May 14 - 24	8	167-0	44	46	3
3	May 18 - June 6	8	167-0	44	46	6
Total		25		133	135	9

[1] All PIT tagged Colorado pikeminnow.
[2] Recaptured fish are those handled on previous sampling passes in 2007.

Appendix IV. Sampling dates, capture data, and effort for Desolation-Gray and lower Green River abundance estimation sampling for Colorado pikeminnow, 2007. Electrofishing effort includes main channel and backwater sampling associated with trammel nets.

	Dates	Days Sampled	River km Sampled	Electrofishing Effort (hours)	Pikeminnow Captured [1]	Pikeminnow Recaptured [2]
Desolation-Gray Canyon, Green River						
Pass 1	April 3 - 7	8	396-207	55	66	0
2	April 11 - 15	8	396-207	53	48	2
3	April 16 - 26	8	396-207	55	32	4
Total		24		163	146	6
Lower Green River						
Pass 1	May 9 - 17	9	193-0	81	154	0
2	May 23 - 31	9	193-0	80	123	14
3	June 6 - 13	8	193-0	71	55	14
Total		26		232	332	28

[1] All PIT tagged Colorado pikeminnow.
[2] Recaptured fish are those handled on previous sampling passes in 2007.

Appendix V. Sampling dates, capture data, and effort for middle Green River, Yampa River, and White River abundance estimation sampling for Colorado pikeminnow, 2008. Electrofishing effort includes main channel and backwater sampling associated with trammel nets.

	Dates	Days Sampled	River km Sampled	Electrofishing Effort (hours)	Pikeminnow Captured [1]	Pikeminnow Recaptured [2]
Middle Green River						
Pass 1	April 21 - 29	6	538-396	39	9	0
2	April 30 - May 8	6	538-396	43	26	0
3	May 13 - 21	6	538-396	44	37	3
Total		18		126	72	3
Yampa River						
Pass 1	April 15 - 22	13	216-80	90	5	0
2	April 23 - May 6	13	216-81	102	7	0
3	May 7 - June 25	46	216-81	306	20	2
Total		72		498	32	2
White River						
Pass 1	April 14 - 19	8	167-0	59	38	0
2	May 16 - 23	7	167-0	37	14	0
3	June 2 - 23	8	167-0	44	13	1
Total		23		140	65	1

[1] All PIT tagged Colorado pikeminnow.
[2] Recaptured fish are those handled on previous sampling passes in 2008.

Appendix VI. Sampling dates, capture data, and effort for Desolation-Gray and lower Green River abundance estimation sampling for Colorado pikeminnow, 2008. Electrofishing effort includes main channel and backwater sampling associated with trammel nets.

	Dates	Days Sampled	River km Sampled	Electrofishing Effort (hours)	Pikeminnow Captured [1]	Pikeminnow Recaptured [2]
Desolation-Gray Canyon, Green River						
Pass 1	April 24 -May 2	8	396-206	61	32	0
2	May 4 - 13	8	396-206	54	27	0
3	May 12 - 21	8	396-206	50	33	1
Total		24		165	92	1
Lower Green River						
Pass 1	April 22 - 30	9	193-0	82	42	0
2	May 6 - 14	9	193-0	80	45	4
3	May 20 - 27	8	193-11	69	40	4
Total		26		231	127	8

[1] All PIT tagged Colorado pikeminnow.
[2] Recaptured fish are those handled on previous sampling passes in 2008.

Appendix VII. Sampling dates, capture data, and effort for middle Green River, Yampa River, and White River abundance estimation sampling for Colorado pikeminnow, 2000. Electrofishing effort includes main channel and backwater sampling associated with trammel nets.

	Dates	Days Sampled	River km Sampled	Electrofishing Effort (hours)	Pikeminnow Captured [1]	Pikeminnow Recaptured [2]
Middle Green River						
Pass 1	April 11 - 27	10	538-395	61	173	0
2	May 2 - 9	4	538-394	41	197	8
3	May 18 - June 1	8	537-396	55	263	52
4	June 6 - 16	7	538-396	48	99	28
Total		29		205	732	88
Yampa River						
Pass 1	April 18 - 27	9	192-80	30	14	0
2	May 6 - 14	9	192-82	18	23	2
3	May 22 - June 1	11	192-73	29	44	4
4	June 20 - 24	5	192-82	15	8	1
Total		34		92	89	7
White River						
Pass 1	April 24 - May 10	6	168-0	62	109	0
2	May 10 - 25	7	168-0	Not available [3]	91	9
3	May 25 - June 9	9	168-0	64	113	17
Total		22		189 [3]	313	26

[1] All PIT tagged Colorado pikeminnow.
[2] Recaptured fish are those handled on previous sampling passes in 2000.
[3] All effort data not available.

Appendix VIII. Sampling dates, capture data, and effort for middle Green River, Yampa River, and White River abundance estimation sampling for Colorado pikeminnow, 2001. Electrofishing effort includes main channel and backwater sampling associated with trammel nets.

	Dates	Days Sampled	River km Sampled	Electrofishing Effort (hours)	Pikeminnow Captured [1]	Pikeminnow Recaptured [2]
Middle Green River						
Pass 1	April 16 - 24	6	537-396	48	64	0
2	May 1 - May 11	9	537-396	69	86	2
3	May 14 - 24	9	537-396	75	158	14
4	May 29 - June 6	7	538-395	59	85	19
Total		31		251	393	35
Yampa River						
Pass 1	April 24 - May 2	8	192-82	50	51	0
2	May 11 - 19	9	192-73	47	36	8
3	May 27 - June 4	9	192-73	47	44	9
4	June 12 - 19	7	192-82	41	9	3
Total		33		185	140	20
White River						
Pass 1	April 16 - 27	8	167-0	73	79	0
2	May 8 - 23	8	167-0	62	94	10
3	May 30 - June 5	8	167-0	69	63	14
Total		24		204	236	24

[1] All PIT tagged Colorado pikeminnow.
[2] Recaptured fish are those handled on previous sampling passes in 2001.

Appendix IX. Sampling dates, capture data, and effort for Desolation-Gray and lower Green River abundance estimation sampling for Colorado pikeminnow, 2001. Electrofishing effort includes main channel and backwater sampling associated with trammel nets.

	Dates	Days Sampled	River km Sampled	Electrofishing Effort (hours)	Pikeminnow Captured [1]	Pikeminnow Recaptured [2]
Desolation-Gray Canyon, Green River						
Pass 1	March 26 - April 9	10	396-207	91	104	0
2	April 17 - May 2	10	396-207	89 [3]	102	6
3	May 7 - 16	9	396-207	72	75	20
Total		29		252	281	26
Lower Green River						
Pass 1	March 12 - 21	8	193-0	77	42	0
2	April 1 - 11	9	193-0	83	53	4
3	April 22 - May 2	9	193-0	82	55	9
4	May 20 - 30	9	193-0	87	99	27
Total		35		329	249	40

[1] All PIT tagged Colorado pikeminnow.
[2] Recaptured fish are those handled on previous sampling passes in 2001.
[3] Some effort estimated.

Appendix X. Sampling dates, capture data, and effort for middle Green River, Yampa River, and White River abundance estimation sampling for Colorado pikeminnow, 2002. Electrofishing effort includes main channel and backwater sampling associated with trammel nets.

	Dates	Days Sampled	River km Sampled	Electrofishing Effort (hours)	Pikeminnow Captured [1]	Pikeminnow Recaptured [2]
Middle Green River						
Pass 1	April 30 - May 15	8	536-396	55	36	0
2	May 16 - 30	9	536-396	69	43	2
3	May 31 - July 11	8	536-396	59	30	4
Total		25		183	109	6
Yampa River						
Pass 1	April 25 - May 3	8	192-73	46	11	0
2	May 11 - 19	8	196-73	52	11	0
3	May 26 - June 3	9	196-81	58	9	0
4	June 12 - 16	5	192-84	10	2	0
Total		30		166	33	0
White River						
Pass 1	April 15 - 23	8	167-0	61	64	0
2	April 26 - May 3	9	167-0	64	49	7
3	May 8 - 24	9	167-0	55	71	14
Total		26		180	184	21

[1] All PIT tagged Colorado pikeminnow.
[2] Recaptured fish are those handled on previous sampling passes in 2002.

Appendix XI. Sampling dates, capture data, and effort for Desolation-Gray and lower Green River abundance estimation sampling for Colorado pikeminnow, 2002. Electrofishing effort includes main channel and backwater sampling associated with trammel nets.

	Dates	Days Sampled	River km Sampled	Electrofishing Effort (hours)	Pikeminnow Captured [1]	Pikeminnow Recaptured [2]
Desolation-Gray Canyon, Green River						
Pass 1	March 23 - April 11	10	396-208	81	47	0
2	April 20 - May 7	8	396-207	80	41	1
3	May 11 - 17	9	396-207	69	49	6
Total		27		230	137	7
Lower Green River						
Pass 1	April 7 - 17	9	193-2	86	48	0
2	April 21 - May 1	9	193-0	88	68	3
3	May 5 - 15	9	193-0	73	44	4
Total		27		247	160	7

[1] All PIT tagged Colorado pikeminnow.
[2] Recaptured fish are those handled on previous sampling passes in 2002.

Appendix XII. Sampling dates, capture data, and effort for middle Green River, Yampa River, and White River abundance estimation sampling for Colorado pikeminnow, 2003. Electrofishing effort includes main channel and backwater sampling associated with trammel nets.

	Dates	Days Sampled	River km Sampled	Electrofishing Effort (hours)	Pikeminnow Captured [1]	Pikeminnow Recaptured [2]
Middle Green River						
Pass 1	April 22 - May 12	10	538-396	67	41	0
2	May 13 - 27	10	538-396	65	65	3
3	May 28 - June 13	11	538-396	62	84	9
Total		31		194	190	12
Yampa River						
Pass 1	April 24 - May 3	9	193-80	48	4	0
2	May 12 - 20	8	192-80	58	5	0
3	May 28 - June 14	9	192-72	56	20	0
4	June 15 - 25	9	192-72	69	2	0
Total		35		231	31	0
White River						
Pass 1	April 21 - 30	8	167-0	61	55	0
2	April 29 - May 15	8	167-0	53	28	2
3	May 5 - 29	8	167-0	61	34	7
Total		24		175	117	9

[1] All PIT tagged Colorado pikeminnow.
[2] Recaptured fish are those handled on previous sampling passes in 2003.

Appendix XIII. Sampling dates, capture data, and effort for Desolation-Gray and lower Green River abundance estimation sampling for Colorado pikeminnow, 2003. Electrofishing effort includes main channel and backwater sampling associated with trammel nets.

	Dates	Days Sampled	River km Sampled	Electrofishing Effort (hours)	Pikeminnow Captured [1]	Pikeminnow Recaptured [2]
Desolation-Gray						
Pass 1	March 24 -April 2	9	396-207	62	49	0
2	April 14 - 23	9	396-207	72*	35	1
3	May 5 - 14	8	396-207	67*	44	2
4	June 2 - 6	8	396-207	67*	50	4
Total		34		190*	178	7
Lower Green River						
Pass 1	April 13 - 23	9	193-0	91	51	0
2	May 6 - 16	9	193-0	84	61	3
3	May 25 - June 4	9	193-0	78	96	8
Total		27		253	208	11

* Some effort not available due to lost data sheets and/or malfunctioning counters.
[1] All PIT tagged Colorado pikeminnow.
[2] Recaptured fish are those handled on previous sampling passes in 2003.